Gray, Hurst, Lewis, and Meyer

SOLUTIONS MANUAL TO ACCOMPANY

Analysis and Design of ANALOG INTEGRATED CIRCUITS

Prepared by

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FOURTH EDITION

Solutions Manual to Accompany

Analysis and Design of Analog Integrated Circuits

Fourth Edition

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CHAPTER 1

1.1

(a) From (1.1) the built-in potential is

$$\psi_o = V_T \ln \frac{N_A N_D}{n_i^2}$$

$$= 26 \ln \frac{8\times 10^{15} \times 10^{17}}{2.25\times 10^{20}} = 751 \text{ mV}$$

From (1.14) the depletion-layer depth in the p-type region is,

$$W_1 = \left[\frac{2\times 1.04\times 10^{-12} \times 5.75}{1.6\times 10^{-19} \times 8\times 10^{15}(1+0.08)}\right]^{1/2}$$

$$= 0.93\ \mu m$$

In the n-type region using (1.15)

$$W_2 = \left[\frac{2\times 1.04\times 10^{-12}\times 5.75}{1.6\times 10^{-19} \times 10^{17} \times 13.5}\right]^{1/2}$$

$$= 0.074\ \mu m$$

From (1.7) the maximum field is

$$\mathcal{E}_{MAX} = -q\frac{N_A}{\epsilon} W_1$$

$$= -1.6\times 10^{-19} \times \frac{8\times 10^{15} \times 0.93\times 10^{-4}}{1.04\times 10^{-12}}$$

$$= -11.4\times 10^4 \text{ V/cm}$$

(b) For zero volts bias,

$$\psi_o + V_R = \psi_o = 0.75$$

$$W_1 = 0.93\sqrt{\frac{0.75}{5.75}} = 0.34\ \mu m$$

$$W_2 = 0.074\sqrt{\frac{0.75}{5.75}} = 0.027\ \mu m$$

$$\mathcal{E}_{MAX} = -11.4\times 10^4 \times \frac{0.34}{0.93}$$

$$= -4.17\times 10^4 \text{ V/cm}$$

For 0.3V forward bias,

$$\psi_o + V_R = 0.45 \text{ V}$$

$$W_1 = 0.93\sqrt{\frac{0.45}{5.75}} = 0.26\ \mu m$$

$$W_2 = 0.074\sqrt{\frac{0.45}{5.75}} = 0.021\ \mu m$$

$$\mathcal{E}_{MAX} = -11.4\times 10^4 \times \frac{0.26}{0.93}$$

$$= -3.19\times 10^4 \text{ V/cm}$$

1.2

From (1.20), the zero bias junction capacitance is,

$$C_{jo} = A\left[\frac{q\varepsilon N_A N_D}{2(N_A+N_D)}\right]^{1/2} \frac{1}{\sqrt{\psi_o}}$$

$$= 2\times 10^{-5} \times \left[\frac{1.6\times 10^{-19} \times 1.04\times 10^{-12} \times 8\times 10^{15} \times 10^{17}}{2(8\times 10^{15} + 10^{17})}\right]^{1/2} \times \frac{1}{\sqrt{0.75}}$$

$$= 0.57 \text{ pF}$$

Using (1.20) with $V_D = -5$V we obtain,

$$C_j = \frac{C_{jo}}{\sqrt{7.7}} = 0.2 \text{ pF}$$

with $V_D = 0.3$ V

$$C_j = \frac{C_{jo}}{\sqrt{0.6}} = 0.74 \text{ pF}$$

1.3

The breakdown voltage can be calculated from (1.24) using

$$|\mathcal{E}_{MAX}| = \mathcal{E}_{CRIT} = 4\times10^5 \text{ V/cm}$$

Thus,

$$4\times10^5 = \left[\frac{2\times1.6\times10^{-19}\times8\times10^{15}\times10^{17}\times V_R}{1.04\times10^{-12}(8\times10^{15}+10^{17})}\right]^{1/2}$$

$$\therefore\ V_R = 70.2\text{ V}$$

1.4

Junction curvature causes (1.24) to become

$$|\mathcal{E}_{MAX}| = 1.5\left[\frac{2qN_AN_DV_R}{\varepsilon(N_A+N_D)}\right]^{1/2}$$

If $N_A >> N_D$, $|\mathcal{E}_{MAX}| = 3\times10^5$ V/cm and $V_R = 150$ V, then this equation gives

$$9\times10^{10} = 2.25\ \frac{2qN_DV_R}{\varepsilon}$$

$$\therefore\ N_D = \frac{9\times10^{10}\times1.04\times10^{-12}}{3.2\times10^{-19}\times150\times2.25}$$

$$= 8.7\times10^{14}\text{ atoms/cm}^3$$

1.5

The plane breakdown voltage is

$$BV_{CBO} = \frac{\varepsilon(N_A+N_D)}{2qN_AN_D}\mathcal{E}^2_{CRIT}$$

$$= \frac{1.04\times10^{-12}}{3.2\times10^{-19}\times6\times10^{15}}\times9\times10^{10} = 48.8\text{ V}$$

From (1.81),

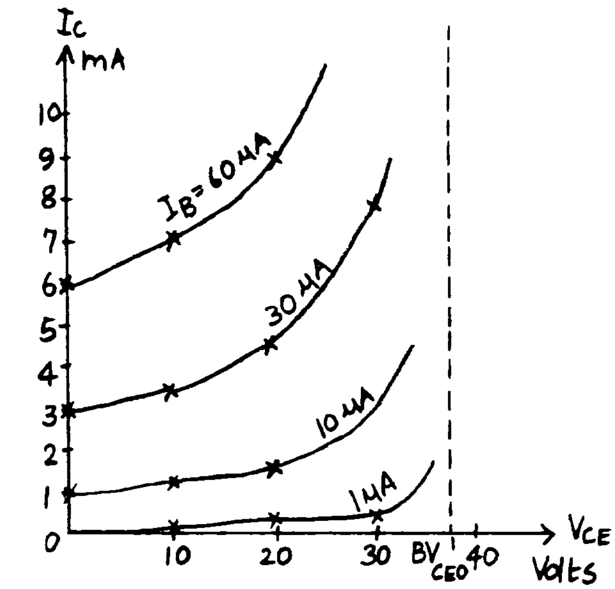
$$BV_{CEO} = \frac{48.8}{\sqrt[4]{200}} = 13\text{ V}$$

1.6

$$BV_{CBO} = \frac{1.04\times10^{-12}}{3.2\times10^{-19}\times10^{15}}\times9\times10^{10} = 293\text{ V}$$

$$BV_{CEO} = \frac{293}{\sqrt[4]{400}} = 65.5\text{ V}$$

1.7 (a)



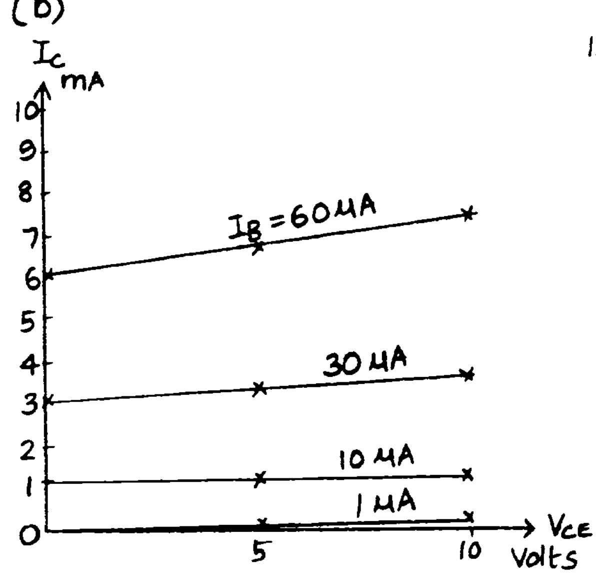
$$I_c = \left(1 + \frac{V_{CE}}{V_A}\right) \frac{M\alpha_F}{1 - M\alpha_F} I_B$$

$$M = \frac{1}{1 - \left(\frac{V_{CB}}{BV_{CBO}}\right)^n}$$

Where $\alpha_F = 0.99$, $V_A = 50\,V$

$BV_{CBO} = 120\,V$, $n = 4$

(b)



1.8

$$g_m = \frac{I_c}{V_T} = \frac{0.2\,mA}{26\,mV} = 7.69\ \frac{mA}{V}$$

$$r_o = \frac{1}{\eta g_m} = \frac{1}{10^{-3}(7.69m)} = 130\,K\Omega$$

$$r_\pi = \frac{\beta_o}{g_m} = \frac{100}{7.69\,m} = 13\,K\Omega$$

$$C_b = \tau_F g_m = (15\,ps)(7.69\,m) = 115\,fF$$

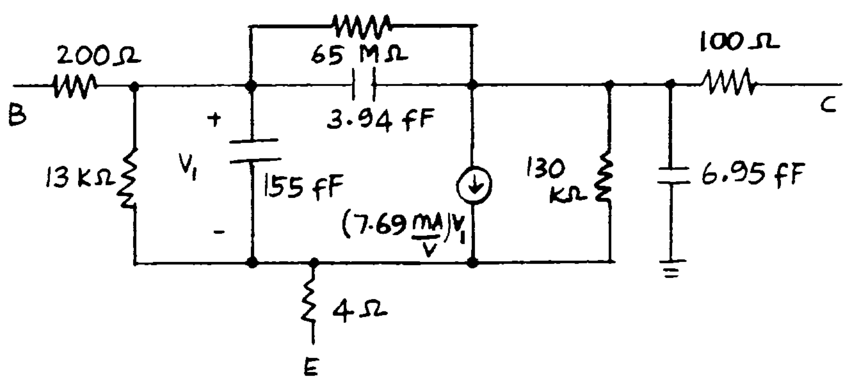
$$r_\mu = 5\beta_o r_o = 5\,(100)(130\,K) = 65\,M\Omega$$

$$C_{je} \cong 2\,C_{jeo} = 40\,fF$$

$$C_\mu = \frac{C_{\mu o}}{\sqrt{1 + \frac{V_{CB}}{\psi_o}}} = \frac{10\,fF}{\sqrt{1 + \frac{3}{0.55}}} = 3.94\,fF$$

$$C_{cs} = \frac{C_{cso}}{\sqrt{1 + \frac{V_{cs}}{\psi_o}}} = \frac{20\,fF}{\sqrt{1 + \frac{4}{0.55}}} = 6.95\,fF$$

$$C_\pi = C_b + C_{je} = 155\,fF$$



1.9

$$g_m = \frac{I_C}{V_T} = \frac{1\ mA}{26\ mV} = 38.5\ \frac{mA}{V}$$

$$r_o = \frac{1}{\eta g_m} = \frac{1}{10^{-3}(38.5m)} = 26\ K\Omega$$

$$r_\pi = \frac{\beta_o}{g_m} = \frac{100}{38.5m} = 2.6\ K\Omega$$

$$C_b = \tau_F g_m = (15ps)(38.5m) = 577\ fF$$

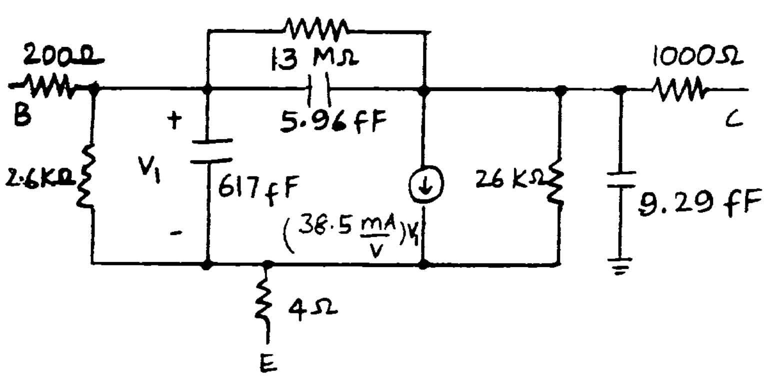
$$r_\mu = 5\beta_o r_o = 5(100)(26K) = 13\ M\Omega$$

$$C_{je} \simeq 2C_{jeo} = 40\ fF$$

$$C_\mu = \frac{C_{\mu o}}{\sqrt{1+\frac{V_{CB}}{\psi_o}}} = \frac{10\ fF}{\sqrt{1+\frac{1}{0.55}}} = 5.96\ fF$$

$$C_{cs} = \frac{C_{cso}}{\sqrt{1+\frac{V_{CS}}{\psi_o}}} = \frac{20\ fF}{\sqrt{1+\frac{2}{0.55}}} = 9.29\ fF$$

$$C_\pi = C_b + C_{je} = 617\ fF$$



1.10 At high frequencies,

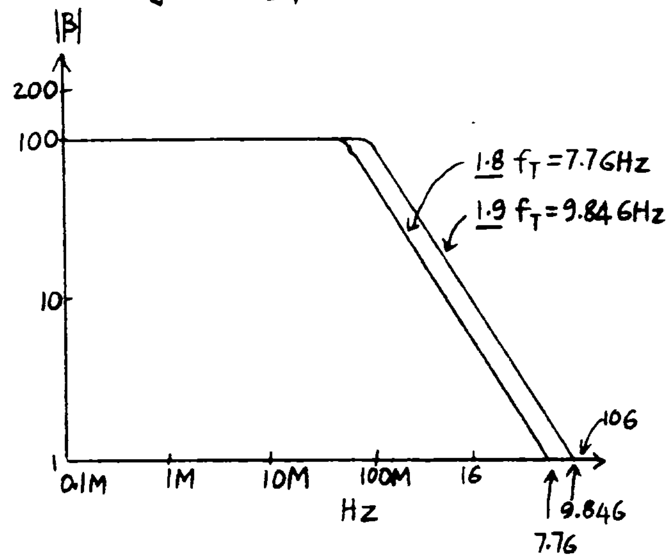
$$\beta(j\omega) = \frac{\omega_T}{j\omega} = \frac{g_m}{j\omega(C_\mu + C_\pi)}$$

For problem (1.8)

$$\beta(j\omega) = \frac{7.69\ mA/V}{j\omega\ 159\ fF} = \frac{48.4\ G}{j\omega} = \frac{7.7\ G}{jf}$$

For problem (1.9),

$$\beta(j\omega) = \frac{38.5\ mA/V}{j\omega\ 623\ fF} = \frac{61.8\ G}{j\omega} = \frac{9.84\ G}{jf}$$



1.11

(a) At $I_C = 1mA$, $\tau_{T_1} = \frac{1}{2\pi f_{T_1}} = \frac{1}{2\pi\, 600\times10^6}$

$= 0.265$ ns

At $I_C = 10$ mA, $\tau_{T_2} = \frac{1}{2\pi f_{T_2}} = \frac{1}{2\pi \times 10^9}$

$= 0.159$ ns

$\therefore\ 265 = \tau_F + 26\times(C_\mu + C_{je})$

$159 = \tau_F + 2.6\times(C_\mu + C_{je})$

$\therefore\ 106 = 23.4\,(C_\mu + C_{je})$

$\therefore\ C_\mu + C_{je} = 4.53$ pF

$\tau_F = 147$ ps

Since $C_\mu \simeq 0.15$ pF, $C_{je} = 4.4$ pF

$I_C = 0.1\,mA$

$g_m = \frac{0.1\times10^{-3}}{26\times10^{-3}} = 3.8$ mA/V

$r_\pi = \frac{100}{3.8}$ kΩ $= 26$ kΩ

$r_o = 500$ kΩ

$r_\mu = 5\times100\times500$ kΩ $= 250$ MΩ

$C_b = \tau_F g_m = 0.147\times10^{-9}\times3.8\times10^{-3}$

$= 0.56$ pF

$C_\pi = 0.56 + 4.4 = 5.0$ pF

$C_\mu = 0.15\sqrt{\frac{1+\frac{1.0}{0.55}}{1+\frac{2}{0.55}}} = 0.31$ pF

$C_{cs} = 1\sqrt{\frac{1+\frac{10}{0.55}}{1+\frac{15}{0.55}}} = 0.82$ pF

$r_b = 100\,\Omega$, $r_c = 100\,\Omega$

$I_C = 1\,mA$

$g_m = \frac{1}{26} = 38$ mA/V

$r_\pi = \frac{100}{38}$ kΩ $= 2.6$ kΩ

$r_o = 50$ kΩ, $r_\mu = 25$ MΩ

$C_b = 5.6$ pF

$C_\pi = 5.6 + 4.4 = 10$ pF

$C_\mu = 0.31$ pF, $C_{cs} = 0.82$ pF

$r_b = 100\,\Omega$, $r_c = 100\,\Omega$

$I_C = 5$ mA

$g_m = 190$ mA/V

$r_\pi = \frac{100}{190} = 530\,\Omega$

$r_o = 10$ kΩ, $r_\mu = 5$ MΩ

$C_b = 28$ pF

$C_\pi = 28 + 4.4 = 32.4$ pF

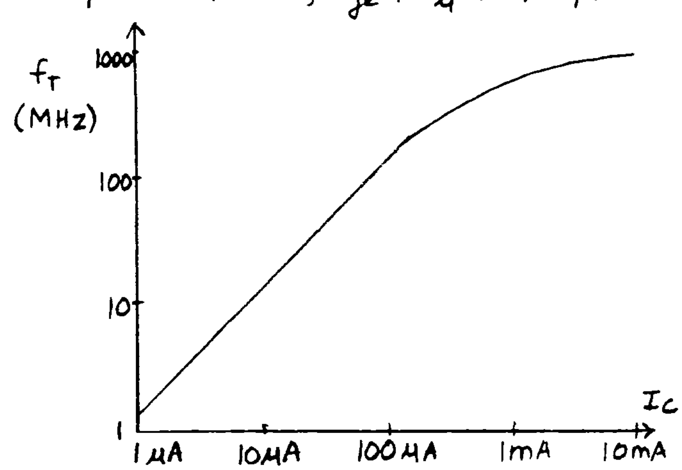
$C_\mu = 0.31$ pF, $C_{cs} = 0.82$ pF

$r_b = 100\,\Omega$, $r_b = 100\,\Omega$

(b) $f_T = \frac{1}{2\pi}\frac{g_m}{C_b + C_{je} + C_\mu}$

$= \frac{1}{2\pi}\frac{1}{\tau_F + \frac{V_T}{I_C}(C_{je}+C_\mu)}$

$\tau_F = 0.147$ ns, $C_{je} + C_\mu = 4.7$ pF



1.12

(a) $\tau_F = \dfrac{W_B^2}{2D_p} = \dfrac{10^{-6}}{26} = 38.5 \text{ ns}$

$$f_T = \frac{1}{2\pi}\,\frac{g_m}{C_b + C_{je}}$$

$$= \frac{1}{2\pi}\,\frac{1}{\tau_F + \frac{V_T C_{je}}{I_c}}$$

$$= \frac{1}{2\pi}\,\frac{1}{38.5 + 0.1} \times 10^9 = 4.1 \text{ MHz}$$

$$Q = \tau_F I_c = 38.5 \times 10^{-9} \times 0.5 \times 10^{-3}$$

$$= 19.3 \text{ pC}$$

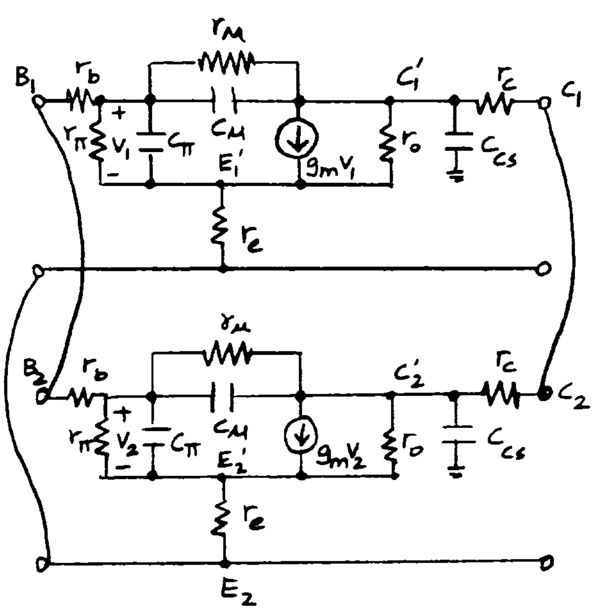
(b) $\dfrac{\Delta I_c}{I_c} = \dfrac{\Delta W_B}{W_B} = \dfrac{0.1}{10}$ per volt of V_{CE}

$\therefore \Delta I_c = 0.5 \times \dfrac{1}{100}$ mA per volt of V_{CE}

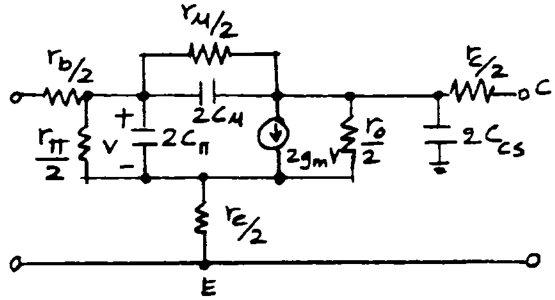
$\therefore r_o = \dfrac{\Delta V_{CE}}{\Delta I_c} = \dfrac{100}{0.5}\text{ K}\Omega = 200 \text{ k}\Omega$

1.13

Connect two transistors in parallel, each with a collector bias current $\frac{I_c}{2}$

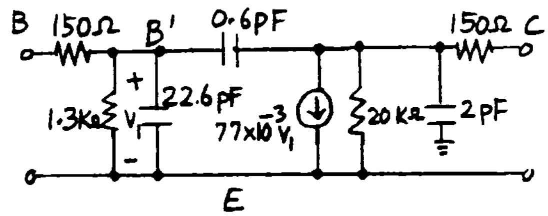


Points B_1' and B_2' will be at the same potential and can be connected. Also C_1' and C_2', E_1' and E_2'. Thus, the composite device becomes as shown with a collector bias current I_c.



Since r_b, r_c and r_e are assumed constant, the values of these resistors are <u>halved</u> in the composite device as compared to the original device at the same total current.

Since C_μ and C_{cs} are independent of bias current, the values of these capacitors are <u>doubled</u> in the composite device. Since r_π, r_o and r_μ are proportional to $1/I_c$, the values of these resistors are <u>unchanged</u> in the composite device as compared to the original device with the same total current. Since g_m is proportional to I_c, its value is unchanged in the composite device.



Finally, $C_\pi = C_{je} + C_b$ where C_{je} is assumed constant and C_b is proportional to I_C. Thus, in the composite device, C_{je} is doubled and C_b is unchanged. As a consequence, C_π in the composite is larger than in the original device at the same total current, but the increase in C_π is less than two times.

1.14

Since current gain is 9 at 50 MHz,

$f_T = 9 \times 50 = 450$ MHz at $I_C = 1$mA

$\therefore \tau_T = \frac{1}{2\pi f_T} = 0.354$ ns

From (1.130),

$$\tau_T = \tau_F + \frac{C_{je} + C_\mu}{g_m}$$

$\therefore 0.354 = 0.25 + (C_{je} + C_\mu) \times 26$

$\therefore C_{je} + C_\mu = 4$ pF

Given $C_\mu = 0.6$ pF, $\therefore C_{je} = 3.4$ pF

At $I_C = 2$ mA

$C_b = \tau_F g_m = 0.25 \times 10^{-9} \times \frac{1}{13} = 19.2$ pF

$\therefore C_\pi = C_{je} + C_b = 3.4 + 19.2 = 22.6$ pF

$g_m = \frac{1}{13} = 77$ mA/V

$r_o = \frac{V_A}{I_C} = \frac{40}{2}$ KΩ $= 20$ KΩ

$r_\pi = \frac{\beta_o}{g_m} = 1300\ \Omega$

1.15

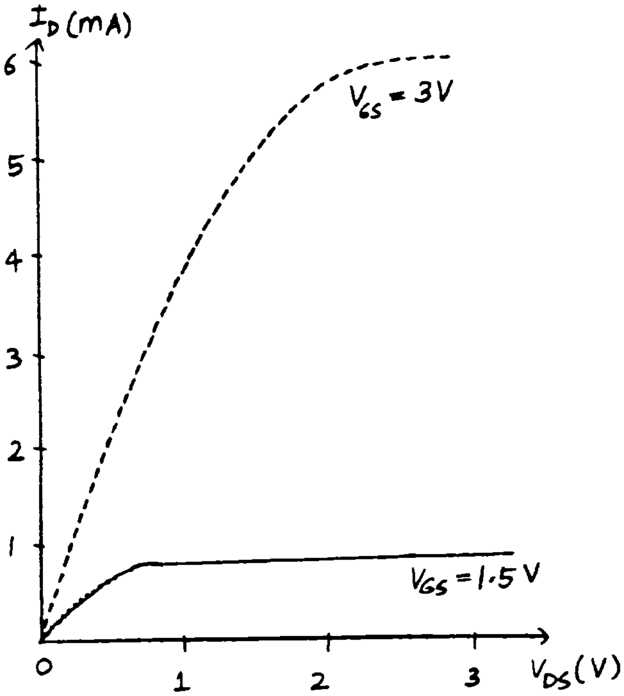
(a) $\frac{k'}{2}\frac{W}{L} = 97 \times 10 = 970\ \mu A/V^2$

so in triode region,

$I_D = 970\left[2(V_{GS}-0.6)V_{DS}-V_{DS}^2\right]\ \mu A$

In active region (saturation),

$I_D = 970\,(V_{GS}-0.6)^2(1+0.024V_{DS})\ \mu A$



(b) From (1.140),

$V_t = V_{t0} + \gamma\left(\sqrt{2\phi_F + V_{SB}} - \sqrt{2\phi_F}\right)$

From (1.141),

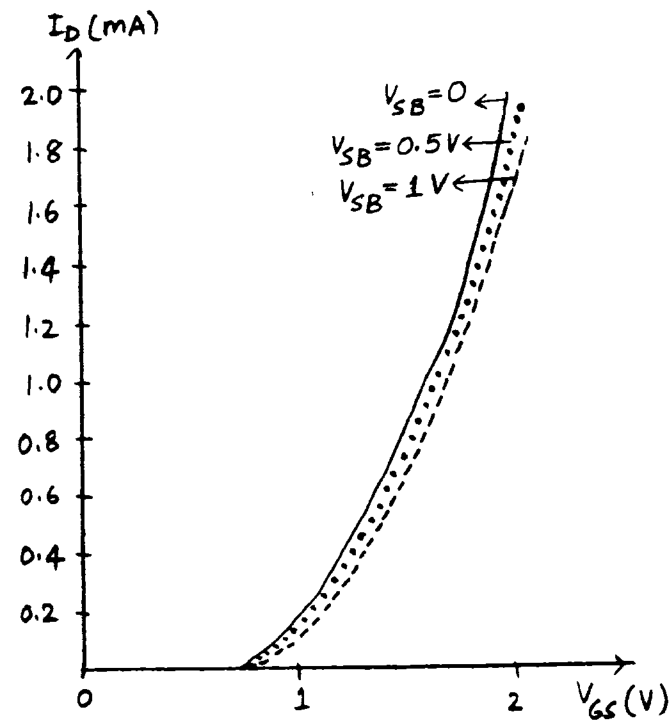
$\gamma = \frac{\sqrt{2q\varepsilon N_A}}{C_{ox}} = \frac{\sqrt{2\times1.6\times10^{-19}\times1.04\times10^{-12}\times5\times10^{15}}}{4.3\times10^{-7}}$

$= 0.094\sqrt{V}$

From (1.142),

$C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}} = \frac{3.9\times8.85\times10^{-14}}{80\times10^{-8}}\times10^{-8} = 4.3\ \frac{fF}{\mu m^2}$

$= 4.3\times10^{-7}\ \frac{F}{cm^2}$



When $V_{SB} = 0$, $V_t = 0.6\,V$

When $V_{SB} = 0.5\,V$, $V_t = 0.63\,V$

When $V_{SB} = 1\,V$, $V_t = 0.65\,V$

1.16

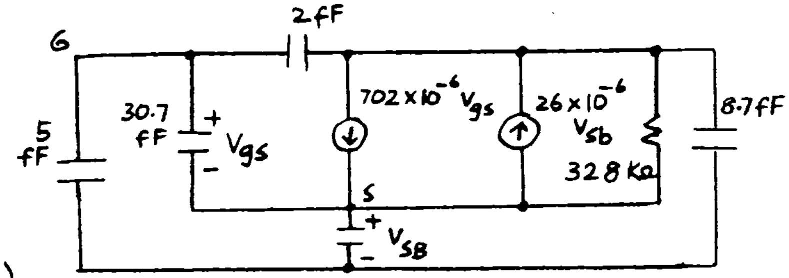
$V_t = 0.6 + 0.094\left(\sqrt{1.6} - \sqrt{0.6}\right)$

$\simeq 0.646\ \text{V}$

$I_D = \frac{k'}{2}\frac{W}{L}(V_{GS}-V_t)^2(1+\lambda V_{DS})$

$= \frac{194}{2}\ \frac{10}{1}(1-0.646)^2(1+0.024(2))$

$= 127\ \mu A$



From (1.180),

$g_m = \sqrt{2k'\frac{W}{L}I_D} = \sqrt{2(194)\,10\,(127)}$

$= 702\ \mu A/V$

From (1.199),

$g_{mb} = \gamma\sqrt{\frac{k' W/L\ I_D}{2(2\phi_F+V_{SB})}} = 0.094\sqrt{\frac{194(10)(127)}{2(0.6+1)}}$

$= 26\ \mu A/V$

From (1.194), $r_o = \frac{1}{\lambda I_D} = \frac{1}{0.024\,(127\mu)}$

$\simeq 328\ k\Omega$

From (1.201), $C_{sb} = \frac{C_{sbo}}{\sqrt{1+\frac{V_{SB}}{\psi_o}}} = \frac{20\ fF}{\sqrt{1+\frac{1}{0.7}}} = 13\ fF$

$V_{DB} = V_{DS} + V_{SB} = 2+1 = 3V$

From (1.202), $C_{db} = \frac{C_{dbo}}{\sqrt{1+\frac{V_{DB}}{\psi_o}}} = \frac{20\ fF}{\sqrt{1+\frac{3}{0.7}}} = 8.7\ fF$

$C_{gd} = 2\ fF$

From (1.191),

$C_{gs_i} = \frac{2}{3}WLC_{ox} = \frac{2}{3}(10)(1)(4.3\ f) = 28.7\ fF$

$C_{gs} = C_{gs_i} + C_{gs_{OL}} = 28.7 + 2 = 30.7\ fF$

1.17

From (1.208),

$f_T = \frac{1}{2\pi}\frac{g_m}{C_{gs}+C_{gd}+C_{gb}} = \frac{1}{2\pi}\frac{g_m}{37.7\times10^{-15}}$

From (1.179)

$g_m = k'\frac{W}{L}(V_{GS}-V_t)(1+\lambda V_{DS})$

$= 194\ \frac{10}{1}(V_{GS}-0.6)(1+\lambda V_{DS})$

Here, $1+\lambda V_{DS} = 1+0.024(3) = 1.072$

This term is usually ignored but is included here to demons-trate its use. Ignoring the term would cause a 7.2% error

V_{GS} (V)	$V_{GS}-V_t$ (V)	g_m (mA/V)	f_T (GHz)
1.0	0.4	0.83	3.5
1.5	0.9	1.87	7.9
2.0	1.4	2.91	12.3

1.18

In linear region, from (1.215)

$$I_D = \frac{\mu_n C_{ox}}{2\left(1+\frac{V_{DS}}{\mathcal{E}_c L}\right)} \frac{W}{L}\left[2(V_{GS}-V_t)V_{DS} - V_{DS}^2\right]$$

From (1.220),

$$V_{DS(act)} = \mathcal{E}_c L\left[\sqrt{1+\frac{2(V_{GS}-V_t)}{\mathcal{E}_c L}} - 1\right]$$

In active region, from (1.223)

$$I_D = \frac{\mu_n C_{ox}}{2} \frac{W}{L} V_{DS(act)}^2$$

$\mathcal{E}_c L = 15V$

(a)

V_{GS} (V)	$V_{GS}-V_t$ (V)	$V_{DS(act)}$ (V)
1.0	0.40	0.395
2.0	1.40	1.34
3.0	2.40	2.23

$V_{GS}=1V$

V_{DS}(V)	No vel. sat. I_D (μA)	Vel. sat. I_D (μA)
0	0	0
0.2	116.4	114.9
0.4	155.2	151.2

$V_{GS}=2V$

V_{DS}(V)	No vel. sat. I_D (μA)	Vel. sat. I_D (μA)
0	0	0
0.2	504.4	497.8
0.4	931.2	907.0
1.4	1901.2	1742.1

$V_{GS}=3V$

V_{DS}(V)	No vel. sat I_D (μA)	vel. sat I_D (μA)
0	0	0
0.2	892.4	880.7
0.4	1707.2	1662.9
1.4	4617.2	4223.0
2.4	5587.2	4839.7

(b) $\mathcal{E}_c L = 1.5V$

V_{GS}(V)	$V_{GS}-V_t$ (V)	$V_{DS(act)}$(V)
1.0	0.40	0.3574
2.0	1.40	1.0397
3.0	2.40	1.5741

$V_{GS}=1V$

V_{DS}(V)	No vel. sat. I_D(μA)	Vel. sat. I_D (μA)
0	0	0
0.2	116.4	102.7
0.4	155.2	123.9

$V_{GS}=2V$

V_{DS}(V)	No vel. sat I_D (μA)	vel. sat. I_D (μA)
0	0	0
0.2	504.4	445.1
0.4	931.2	735.2
1.4	1901.2	1048.5

$V_{GS}=3V$

V_{DS}(V)	No vel. sat I_D (μA)	vel. sat. I_D (μA)
0	0	0
0.2	892.4	787.4
0.4	1707.2	1347.8
1.4	4617.2	2388.2
2.4	5587.2	2403.4

(c) $\mathcal{E}_{cL} = 0.75V$

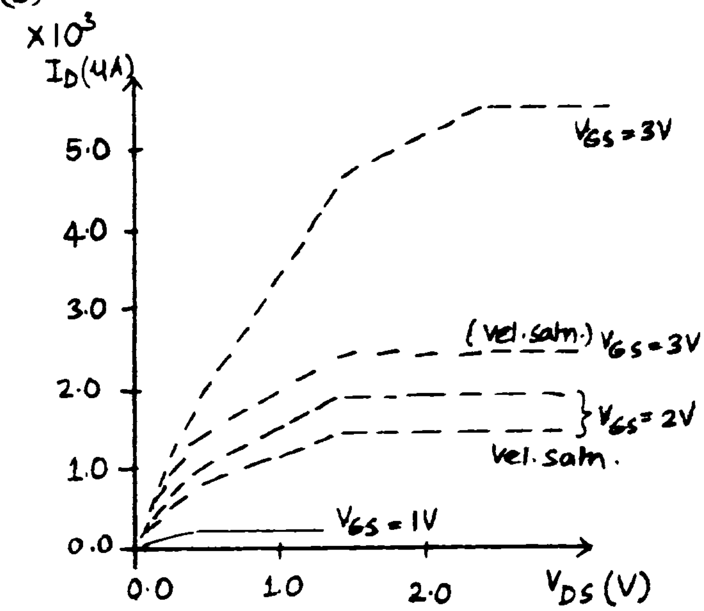
V_{GS}(V)	$V_{GS}-V_t$ (V)	$V_{DS(act)}$(V)
1.0	0.40	0.3282
2.0	1.40	0.8817
3.0	2.40	1.290

$V_{GS}=1V$

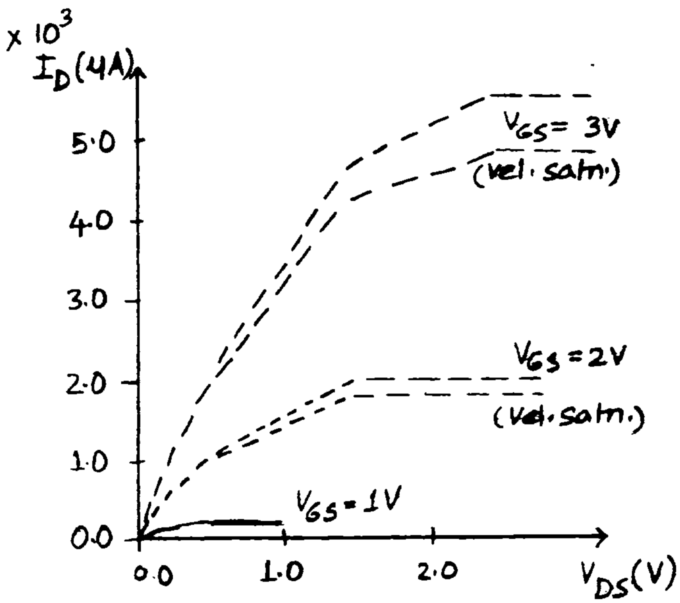
V_{DS} (V)	No vel. sat I_D (μA)	vel sat. I_D (μA)
0	0	0
0.2	116.4	91.89
0.4	155.2	104.5

	V_{DS} (V)	No velocity sat. I_D (μA)	vel. satn. I_D (μA)
$V_{GS} = 2V$	0	0	0
	0.2	504.4	398.2
	0.4	931.2	~~607.3~~
	1.4	1901.2	754.1
$V_{GS} = 3V$	V_{DS} (V)	No velocity sat. I_D (μA)	vel. satn. I_D (μA)
	0	0	0
	0.2	892.4	704.4
	0.4	1707.2	1113.4
	1.4	4617.2	1610.7
	2.4	5587.2	1614.7

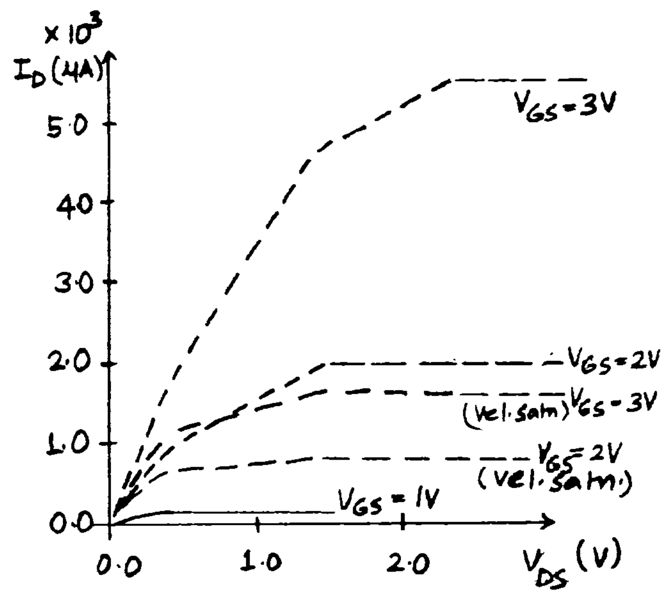
(b)



(a)



(c)



1.19

Direct calculation :

$$I_D = \frac{k'}{2}\frac{W}{L} V_{DS_{act}}^2$$

$$V_{DS_{act}} = \mathcal{E}_c L\left[\sqrt{1 + \frac{2(V_{GS}-V_t)}{\mathcal{E}_c L}} - 1\right]$$

$L = 0.5\ \mu m$

$\mathcal{E}_c L = 0.75$

$$\frac{k'}{2}\frac{W}{L} = \frac{194}{2}\frac{2}{0.5} = 388\ \frac{\mu A}{V^2}$$

$$V_{DS(act)} = 0.75\left[\sqrt{1 + \frac{2(V_{GS}-0.6)}{0.75}} - 1\right]$$

V_{GS} (V)	$V_{GS}-V_t$ (V)	$V_{DS\,act.}$ (V)	I_D (μA)
0.6	0.0	0	0
0.8	0.2	0.179	12.43
1.0	0.4	0.328	41.7
1.2	0.6	0.459	81.7
1.6	1.0	0.686	182.59
1.8	1.2	0.787	240.31
1.9	1.3	0.835	270.52
2.0	1.4	0.882	301.83

Now use (1.230),

$$\frac{k'}{2}\frac{W}{L} = \frac{194}{2}\frac{2}{0.5} = 388\ \frac{\mu A}{V^2}$$

$$R_{Sx} = \frac{1}{\mathcal{E}_c k' W} = \frac{1}{1.5\times10^6(194)2\mu} = 1718.2$$

$$k'\frac{W}{L} R_{Sx} = 194\times4\times1718.2\times10^{-6} = 1.333$$

V_{GS} (V)	$V_{GS}-V_t$ (V)	$\frac{1}{1+k'\frac{W}{L}R_{Sx}(V_{GS}-V_t)}$	I (μA)
0.6	0.0	1.0	0
0.8	0.2	0.790	12.4
1.0	0.4	0.652	40.9
1.2	1.6	0.556	78.4
1.6	1.0	0.429	168
1.8	1.2	0.385	217

10% error occurs when $V_{GS} = 1.8\,V$

Reasonable since,

$$(V_{GS}-V_t)^2 = (1.2)^2 = 1.44$$

$$(I_D R_{Sx})^2 = [242.8\times10^{-6}(1718.2)]^2 = 0.1740$$

0.17 is 12% of 1.44

1.20

simple calculation:

$$g_m = k' \frac{W}{L}(V_{GS}-V_t)$$

$$= \mu_n \frac{\epsilon_{ox}}{t_{ox}} \frac{W}{L}(V_{GS}-V_t)$$

$$= \frac{\mu_n \epsilon_{ox}}{L}(50)\frac{W}{L}(V_{GS}-V_t)$$

$$= 450 \frac{cm^2}{Vs}(3.9)(8.854\times10^{-14}\frac{F}{cm})$$

$$\times \frac{50(10\,\mu m)}{L^2} \times \frac{10^4\,\mu m}{1\,cm}(0.1)$$

$$= \frac{7.769\times10^{-4}}{L^2}(0.1)$$

L (μm)	g_m (μA/V²)	
0.4	485	(24% error)
0.5	310	(20% error)
1.0	77.7	(10% error)
2.0	19.4	
10.0	0.77	

Now with velocity saturation,

$$g_m = W C_{ox} \mu_n \mathcal{E}_c R \quad \text{where,}$$

$$R = \frac{\sqrt{1+\frac{2(V_{GS}-V_t)}{\mathcal{E}_c L}}-1}{\sqrt{1+\frac{2(V_{GS}-V_t)}{\mathcal{E}_c L}}}$$

$$g_m = (10\,\mu m)(3.9)\frac{(8.854\times10^{-14}\frac{F}{cm})}{L/50} 450 \frac{cm^2}{V sec}$$

$$\times 1.5\,R \times \frac{10^4\,\mu m}{1\,cm}$$

$$= \frac{7.77\times10^{-5}}{L} R(\mathcal{E}_c W)\ \mu A/V^2$$

$$= \frac{1.1654\times10^{-3}}{L} R \ \frac{\mu A}{V^2}$$

L (μm)	R	$g_m = \frac{1.1654\times10^{-3} R}{L}$ μA/V
10	6.6×10^{-3}	0.77
2	3.175×10^{-2}	18.5
1	6.066×10^{-2}	70.7
0.5	0.11148	260
0.4	0.134	390

1.21

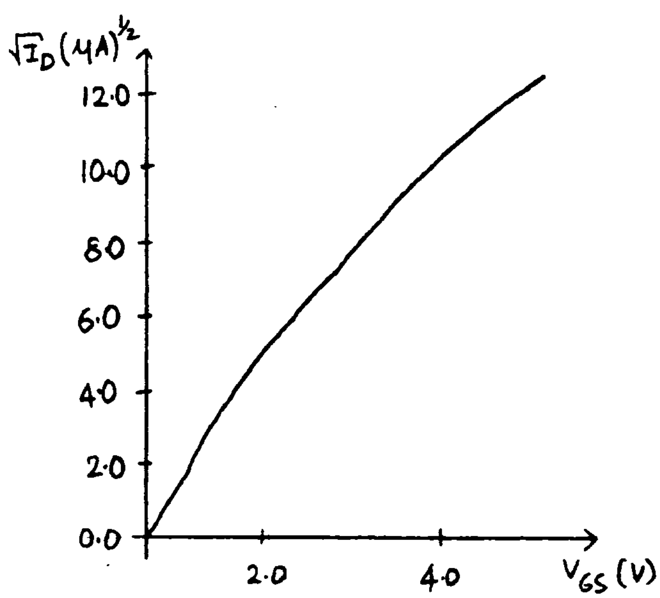
From (1.223), $I_D = \frac{\mu_n C_{ox}}{2} \frac{W}{L} \left[V_{DS(act)} \right]^2$

From (1.220), $V_{DS(act.)} = \mathcal{E}_c L \left[\sqrt{1 + \frac{2(V_{GS} - V_t)}{\mathcal{E}_c L}} - 1 \right]$

$\mathcal{E}_c L = 1.5 \qquad V_t = 0.7\ V$

V_{GS} (V)	$V_{DS(act.)}$ (V)	I_D (μA)	$\sqrt{I_D}$ $(\mu A)^{1/2}$	$\frac{k'}{2}\frac{W}{L}(V_{GS}-V_t)^2$ (μA)	$\sqrt{\frac{k'}{2}\frac{W}{L}(V_{GS}-V_t)^2}$ $(\mu A)^{1/2}$	$V_{GS}-V_t$ (V)
0.7	0.0	0.0	0.0	0.0	0.0	0.0
0.8	0.097	0.253	0.503	0.27	0.520	0.1
0.9	0.188	0.956	0.978	1.08	1.04	0.2
1.0	0.275	2.04	1.43	2.43	1.56	0.3
1.5	0.656	11.6	3.41	17.3	4.16	0.8
2.0	0.980	25.9	5.09	45.6	6.75	1.3
3.0	1.52	62.4	7.89	143	12.0	2.3
4.0	1.99	106.9	10.3	294	17.1	3.3
5.0	2.39	154.2	12.4	499	22.3	4.3

For large V_{GS}, current is limited by velocity saturation.



1.22

$$I_D = K_x \frac{W}{L} e^{V_{GS}/nV_T}(1 - e^{-V_{DS}/V_T})$$

$$g_m = \frac{\partial I_D}{\partial V_{GS}} = \frac{1}{nV_T} K_x \frac{W}{L} e^{V_{GS}/nV_T}(1 - e^{-V_{DS}/V_T})$$

$$= \frac{1}{nV_T} I_D = \frac{10 \times 10^{-9}}{1.5 \times 26 \times 10^{-3}} = 2.56 \times 10^{-7}$$

$$= 0.256 \ \mu A/V$$

$$f_T = \frac{g_m}{2\pi(C_{gs} + C_{gd} + C_{gb})} = \frac{0.256 \ \mu A/V}{2\pi(10 fF)}$$

$$= 4.076 \ MHz$$

CHAPTER 2

2.1

From Fig. (2.2)

For p-type Si,

$N_A = 1.5 \times 10^{16}$ atoms/cm³

For n-type Si,

$N_D = 6 \times 10^{15}$ atoms/cm³

2.2

$$R_\square = \frac{\rho}{T} = \frac{1\ \Omega\text{-cm}}{5\ \mu m} = \frac{1\ \Omega\text{-cm}}{5 \times 10^{-4} cm}$$

$$= 2000\ \Omega/\square$$

2.3

The doping profile has the form

$$N_D(x) = N_{DO} \exp\left(-\frac{x}{L}\right)$$

The first step is to determine N_{DO} and L. Since at $x = 0$,

$N_D(x) = 10^{17} cm^{-3}$, then

$N_{DO} = 10^{17} cm^{-3}$

At $x = 0.5\ \mu m$, $N_D(x) = \frac{1}{e} N_D(0)$

$$\therefore N_{DO} e^{-1} = N_{DO} \exp\left(-\frac{0.5\ \mu m}{L}\right)$$

$$\therefore L = 0.5\ \mu m$$

Thus,

$$N_D(x) = 10^{17} \exp\left(-\frac{x}{0.5 \mu m}\right)$$

The junction will exist at the point where the net doping

$$N_D(x) - N_A(x) = 0$$

$$\therefore 10^{17} \exp\left(-\frac{x_j}{0.5 \mu m}\right) = 10^{15}$$

$$\therefore x_j = 0.5\ \mu m\ \ln \frac{10^{17}}{10^{15}} = 2.3\ \mu m$$

The sheet resistance is given by:

$$R_\square = \left[q \bar{\mu}_n \int_0^{x_j} [N_D(x) - N_A(x)]\, dx \right]^{-1}$$

Since the effective doping is $N_D(x) - N_A(x)$

$$\therefore q \left[800 \frac{cm^2}{V\text{-}sec} \right] \int_0^{2.3 \mu m} \left[10^{17} e^{-\frac{x}{0.5 \mu m}} - 10^{15} \right] dx$$

$$= q \left[800 \frac{cm^2}{V\text{-}sec} \right] \left\{ \left[-0.5 \times 10^{11} - 2.3 \times 10^{11} \right] + 0.5 \times 10^{13} \right\}$$

$$= 1.6 \times 10^{-19} \times 800 \times 4.72 \times 10^{12}$$

$$= 1.6 \times 8 \times 4.72 \times 10^{-5}$$

$$\therefore R_\square = \left[6.04 \times 10^{-4} \right]^{-1} = 1655\ \Omega/\square$$

2.4

For the resistor $\frac{L}{W} = \frac{200\ \mu m}{5\ \mu m} = 40$

Base-diffused

$R = 40 \times 100\ \Omega/\square = 4\ K\Omega$

Emitter-diffused

$R = 40 \times 5\ \Omega/\square = 200\ \Omega$

Pinch

$R = 40 \times 5\ K\Omega/\square = 200\ K\Omega$

2.5

From (2.17), for an npn-transistor,

$$Q_B = \frac{A \bar{D}_n q n_i^2}{I_c} \exp\left(\frac{V_{BE}}{V_T}\right)$$

For $V_{BE} = 520$ mV,

$$Q_B = \frac{(10^{-4} cm^2)(13 \frac{cm^2}{sec})(1.6 \times 10^{-19})(2 \times 10^{20})}{10^{-5}} e^{(520/26)}$$

$= 2.02 \times 10^{12}$ atoms/cm²

For $V_{BE} = 580$ mV, same expression gives: $Q_B = 2 \times 10^{13}$ atoms/cm²

For $Q_B = 2.02 \times 10^{12}$

$$R_\square = [q \bar{\mu}_p Q_B]^{-1}$$

$$= \left[(1.6\times10^{-19})(150 \frac{cm^2}{V\text{-}sec})(2.02\times10^{12})\right]^{-1}$$

$$= (485 \times 10^{-17})^{-1} = 21\ k\Omega/\square$$

2.6

(a) Series base R :

Emitter periphery adjacent to a base contact is :

$p = 4 \times 40\ \mu m = 160\ \mu m$

Distance from base contact to emitter is : $10\ \mu m$

$$\therefore R_B = R_\square \left(\frac{10}{160}\right) = 100\ \Omega/\square \left(\frac{1}{16}\right)$$

$$= 6.2\ \Omega$$

(b) Series collector resistance :

For each of two emitters the effective buried layer dimensions are :

$$W_{BL} = (W + 2T) = 20\ \mu m + 2(10\ \mu m) = 40\ \mu m$$

$$L_{BL} = (L + 2T) = 40\ \mu m + 2(10\ \mu m) = 60\ \mu m$$

Using (2.18),

$$a = \left(\frac{20}{40}\right)^{-1}, \quad b = \left(\frac{40}{60}\right)^{-1}$$

$$2r_{c1} = \frac{(5\ \Omega\text{-cm})(10\ \mu m)}{(20\ \mu m)(40\ \mu m)} \ln \frac{2/1.5}{0.5}$$

$$= 360\ \Omega$$

$$\therefore r_{c1} = 180\ \Omega$$

$$r_{c2} = R_{BL\square}\left(\frac{L}{W}\right) = 20\ \frac{\Omega}{\square}\left(\frac{40}{140}\right) = 5.7\ \Omega$$

r_{c3} : for buried layer

$L_{eff} = 140\ \mu m$

$W_{eff} = 14\ \mu m + 2T = 34\ \mu m$

For top N^+: $L = 140\ \mu m$, $W = 14\ \mu m$

$$\therefore a = \frac{34}{14} = 2.43\ ;\ b = 1$$

$$\therefore r_{c3} = \frac{(5\ \Omega\text{-cm})(10\ \mu m)}{(140\ \mu m)(14\ \mu m)} \ln \frac{2.43}{2.43-1}$$

$$= 158\ \Omega$$

$$\therefore R_c = 158 + 180 + 5.7 = 344\ \Omega$$

(c) $C_{jc} = (A_{bottom} + A_{sidewall})\ C_{jc}/\text{area}$

$$= \left[(140\ \mu m)(60\ \mu m) + \frac{\pi}{2}\cdot 3\ \mu m(280\ \mu m + 120\ \mu m)\right] \times 10^{-4}\ pF/(\mu m)^2$$

$$= (8400 + 1885) \times 10^{-4}$$

$$= 1.03\ pF$$

(d) $C_{je} \approx (C_{jebottom} + C_{jesidewall})$

$$= 2\left[A_{bottom} + A_{sidewall}\right] C_{je}/\text{area}$$

$$= 2\left[(20\ \mu m)(40\ \mu m) + \frac{\pi}{2}\times 2\ \mu m(40\ \mu m + 80\ \mu m)\right] \times 10^{-4}\ pF/(\mu m)^2$$

$$= 2.4\ pF$$

(e) $C_{substrate} = C_{sidewall} + C_{epi\text{-}sub} + C_{BL\text{-}sub}$

$$C_{sidewall} = \frac{\pi}{2} \times (17\ \mu m)\left[175\ \mu m \times 2 + 140\ \mu m \times 2\right] \times 10^{-4}\ pF/(\mu m)^2$$

$$= 1.6\ pF$$

$$C_{epi\text{-}sub} = (175\times140 - 85\times126)\times10^{-4}\ \frac{pF}{(\mu m)^2}$$

$$= 1.4\ pF$$

$$C_{BL\text{-}sub} = (85\times126)\times 3.3\times10^{-4} = 3.5\ pF$$

$$\therefore C_{substrate} = 6.5\ pF$$

(f) $I_S = \dfrac{q n_i^2}{Q_B/\bar{D}_n} A_{EB}$

From text example,

$$\frac{Q_B}{\bar{D}_n} = 5.7 \times 10^{11}\ cm^{-4}\ sec$$

$$\therefore I_S = \frac{1.6\times10^{-19} \times 2\times10^{20} \times 1600\ \mu m^2 \times \left(10^{-8} \frac{cm^2}{\mu m^2}\right)}{5.7\times10^{11}}$$

$$= 0.9 \times 10^{-15}\ A$$

2.7

From (2.24), the β falloff begins at $I_C = qAN_D \dfrac{D_p}{W_B}$

For this structure, the area A is the product of the emitter diffusion periphery 120 μm, and the effective sidewall depth. Regarding the sidewall as a quarter-cylinder this effective depth is the emitter junction depth multiplied by $\pi/2$. Thus,

$$A_{eff} = (120\ \mu m)(3\ \mu m)(\pi/2) = 5.65\times10^{-6}\ cm^2$$

From Fig. (2.2), the donor density corresponding to a resistivity of 0.5 Ω-cm is $1.2\times10^{16} cm^{-3}$. Thus,

$$I_C = \frac{(1.6\times10^{-19})(5.65\times10^{-6})(1.2\times10^{16})(10)}{8\times10^{-4}}$$

$$= 13.56\times10^{-5} = 136\ \mu A$$

2.8

From (2.17), for a pnp transistor

$$Q_B = qA\bar{D}_p \frac{n_i^2}{I_C} \exp\left(\frac{V_{BE}}{V_T}\right)$$

For this device,

$$A = 2\times(30\mu m\times75\mu m) + 2\times(10\mu m\times30\mu m)$$

$$= 5100\ (\mu m)^2$$

For $V_{BE} = 525$ mV

$$Q_B = \frac{1.6\times10^{-19}\times5100\times10^{-8}\times10\times2\times10^{20}}{10^{-5}} \exp\left(\frac{525}{26}\right)$$

$$= 9.6\times10^{11}$$

Using Fig. (2.2), the donor density corresponding to 2 Ω-cm is $2.5\times10^{15} cm^{-3}$

Since, $Q_B = W_B N_D$, then

$$W_B = \frac{Q_B}{N_D} = \frac{9.6\times10^{11}}{2.5\times10^{15}} = 3.84\times10^{-4} cm$$

$$= 3.84\ \mu m$$

Since the p-diffusion depth is 3 μm, the total epi thickness is 6.84 μm, for $V_{BE} = 525$ mV. By a similar calculation, the total depth for $V_{BE} = 560$ mV is 17.45 μm

The same resistances are:

For $V_{BE} = 525$ mV

$$R_\square = [q\bar{\mu}_n Q_B]^{-1}$$

$$= [(1.6\times10^{-19})(800)(9.6\times10^{11})]^{-1}$$

$$= [12\times10^{-5}]^{-1} = 8\ k\Omega/\square$$

For $V_{BE} = 560$ mV

$$R_\square = 2.12\ k\Omega/\square$$

2.9

First consider the 6 μm resistor, For 10 kΩ we need 100 squares or 600 μm of length. The total resistor area is that of the body plus clubheads, or

$$A_{bottom} = 600\ \mu m \times 6\ \mu m + 2\ (26\ \mu m)^2$$
$$= 4952\ (\mu m)^2$$

The sidewall area is equal to the total periphery multiplied by $(3\mu m)(\pi/2)$.

The periphery is,

$$P = 600\ \mu m + 600\ \mu m + 6 \times 26\ \mu m + 2(26-6)\ \mu m$$
$$= 1396\ \mu m$$

Thus,

$$A_{sidewall} = 1396\ \mu m \times 3\ \mu m \times \frac{\pi}{2}$$
$$= 6578\ (\mu m)^2$$

The total area is,

$$A_{total} = 11{,}530\ (\mu m)^2$$

For the $10^{15}\ cm^{-3}$ epi concentration the capacitance per unit area for zero bias is from Fig.(2.29) equal to $10^{-4}\ pF/(\mu m)^2$

Thus, $C_{total} = 11{,}530\ (\mu m)^2 \times 10^{-4} \frac{pF}{(\mu m)^2}$

$$= 1.15\ pF$$

For the 12 μm resistor, we need 1200 μm of length

Thus, $A_{bottom} = 12\ \mu m \times 1200\ \mu m + 2(26\mu)^2$

$$= 15{,}750\ (\mu m)^2$$

$$A_{sidewall} = \frac{\pi}{2}\left[1200 \times 2 + 26 \times 6 + 2(26-12)\right] \times 3$$
$$= 12{,}177\ (\mu m)^2$$

$\therefore A_{total} = 27{,}929\ (\mu m)^2$

$\therefore C_{total} = 27{,}929\ (\mu m)^2 \times 10^{-4} \frac{pF}{(\mu m)^2} = 2.8\ pF$

2.10

(1) $I_S = A_{EB}\, q \frac{n_i^2}{Q_B} \bar{D}_{pb}$

$$= [90\ \mu m \times 75\ \mu m - 30\ \mu m \times 55\ \mu m] \times 10^{-8} \frac{cm^2}{\mu^2} \times \frac{(1.6 \times 10^{-19})(2 \times 10^{20})(10\ cm^2/sec)}{\left(10^{15} \frac{atoms}{cm^3}\right) \times 14\ \mu m \times 10^{-4} \frac{cm}{\mu m}}$$

$$= 1.17 \times 10^{-14}\ A$$

(2) $C_{je} = A_{bottom} \times 10^{-4}\ pF/(\mu m)^2 + A_{sidewall} \times 10^{-3}\ pF/(\mu m)^2$

$$= (90 \times 75 - 30 \times 55)(\mu m)^2 \times 10^{-4} \frac{pF}{(\mu m)^2} + \frac{\pi}{2}(60+110)(3)(\mu m)^2 \times 10^{-3} \frac{pF}{(\mu m)^2}$$

$$= 0.51 + 0.8 = 1.31\ pF$$

(3) $C_\mu = C_{epi\text{-}sidewall} + C_{bottom}$

$$= \frac{\pi}{2}(40 \times 2 + 125 \times 2) \times (17)(\mu m)^2 \times 10^{-4} \frac{pF}{(\mu m)^2} + (140 \times 125)(\mu m)^2 \times 10^{-4} \frac{pF}{(\mu m)^2}$$

$$= 1.4 + 1.75 = 3.15\ pF$$

(4) $\tau_F = \frac{W_B^2}{2D_p} = \frac{\left[(14\ \mu m)(10^{-4}\ cm/\mu m)\right]^2}{2 \times 10\ cm^2/sec}$

$$= 98\ nsec$$

2.11

For an npn transistor

$$Q_B = \frac{q A \bar{D}_n n_i^2}{I_c} \exp\left(\frac{V_{BE}}{V_T}\right)$$

$$= \frac{(1.6 \times 10^{-19})(10^{-4}\ cm^2)(13)(2 \times 10^{20})}{10^{-5}} e^{\frac{480}{26}}$$

$$= 4.3 \times 10^{11}\ atoms/cm^2$$

$$R_\square = [q \mu_p Q_B]^{-1}$$

$$= \left[1.6 \times 10^{-19} \times 150 \frac{cm^2}{V\text{-}sec} \times 4.3 \times 10^{11}\right]^{-1}$$

$$= 97\ k\Omega/\square$$

In order to contain 4.3×10^{11} atoms/cm^2 of the n-type epi-impurity, the width of the collector depletion layer at punch-thru is,

$$W_D = \frac{4.3\times10^{11} \text{ atoms/cm}^2}{10^{15}\ cm^{-3}}$$
$$= 4.3\times10^{-4}\ cm = 4.3\ \mu m$$

Using (1.15) and assuming that $N_A >> N_D$,

$$W_D = \sqrt{\frac{2\epsilon(\psi_0+\psi_R)}{q N_D}} = 4.3\ \mu m$$
$$= \sqrt{\frac{2\times1.04\times10^{-12}\times(0.55+V_R)}{1.6\times10^{-19}\times10^{15}}}$$

$\therefore V_R = 13.7$ V

For $V_{BE} = 560$ mV, same expressions give,

$Q_B = 9.4\times10^{12}$ atoms/cm^2

$R_\square = 4.43\ k\Omega/\square$

$W_D = 94\ \mu m$

$V_R = 6{,}796$ V

2.12 From (1.157),

$$I_D = \frac{\mu_n C_{ox}}{2}\frac{W}{L}(V_{GS}-V_t)^2$$

$$100\ \mu A = \frac{\mu_n C_{ox}}{2}\frac{W}{L}(1.5-V_t)^2 \rightarrow (1)$$

$$10\ \mu A = \frac{\mu_n C_{ox}}{2}\frac{W}{L}(0.8-V_t)^2 \rightarrow (2)$$

Divide (1) by (2) and solve for $V_t \rightarrow$ gives $V_t = 0.48$V.

Substituting for V_t in (1) gives,

$$\mu_n C_{ox}\frac{W}{L} = 191\ \mu A/V$$

2.13 $V_t = \phi_{MS} + 2\phi_f + \frac{Q_b}{C_{ox}} - \frac{Q_{ss}}{C_{ox}}$, (2.27)

(i) For unimplanted transistors, From Table 2.1, $\phi_{MS} = -0.1$ V

From (2.28),

$$\phi_f = \frac{KT}{q}\ln\frac{N_A}{n_i} = 0.026\ln\frac{10^{16}}{1.45\times10^{10}}$$
$$= 0.35.$$

From (2.30),

$C_{ox} = 0.86\ fF/(\mu m)^2$

$$\frac{Q_{ss}}{C_{ox}} = \frac{1.6\times10^{-19}\times10^{11}}{8.6\times10^{-8}} = 0.19\ V$$

From (1.137),

$$Q_{bo} = \sqrt{2qN_A\epsilon\cdot2\phi_f}$$
$$= [2\times1.6\times10^{-19}\times10^{16}\times11.6\times8.86\times10^{-14}\times2\times0.35]^{1/2} = 4.8\times10^{-8}\ \text{coulombs/cm}^2$$

$$\therefore V_t = -0.1-2\times0.35-\frac{4.8\times10^{-8}}{8.6\times10^{-8}}-0.19$$
$$= -1.55$$

(ii) For implanted transistors,

$N_A = 1\times10^{16} - 0.9\times10^{16} = 10^{15}\ cm^{-3}$

From Fig.(2.29), the depletion layer width corresponding to a doping level of $10^{15} cm^{-3}$ is $\sim 1\ \mu m$, while the implant depth is only 0.3 μm

$$\therefore V_{t(implant)} = -1.55 + \frac{0.9\times10^{16}\times0.3\times10^{-4}\times1.6\times10^{-19}}{8.6\times10^{-8}}$$
$$= -1.05$$

2.14

The metallurgical channel length is

$L = L_{drawn} - 2L_d = 7\,\mu m - 2(0.3) = 6.4\,\mu m$

The effective channel length is L minus the width of the depletion region at the drain. In the active region, the voltage at the drain end of the channel is $= V_{GS} - V_t = V_{ov}$

To calculate V_{ov}, assume at first that $L_{eff} \simeq L$. Then from (1.166)

$$V_{ov} = \sqrt{\frac{2I_D}{k' W/L}} = \sqrt{\frac{2(10\,\mu A)}{700\,\frac{cm^2}{V\cdot s} \cdot 0.86\,\frac{fF}{\mu^2}\left(\frac{100}{6.4}\right)}} = 0.15\ V$$

Thus, the voltage across the drain depletion region $= 5 - 0.15 = 4.85\ V$

To estimate the depletion-region width, assume it is a one-sided step junction that mainly exists in the lightly doped side. Since the channel and the drain are both n-type regions, the built in potential of the junction is near zero. Using (1.14) and assuming $N_D >> N_A$,

$$X_d = \sqrt{\frac{2\epsilon(V_{DS} - V_{ov})}{q N_A}} = \sqrt{\frac{2(1.04\times10^{-12})(5-0.15)}{1.6\times10^{-19}(2\times10^{16}+10^{15})}} = 0.55\,\mu m$$

So, $L_{eff} = 7\,\mu m - 2(0.3\,\mu m) - 0.55\,\mu m = 5.85\,\mu m$

Therefore, since $r_o = \frac{1}{\lambda I_D} = \frac{L_{eff}}{I_D} \Big/ \frac{dX_d}{dV_{DS}}$

$$\Rightarrow r_o = 5\,M\Omega = \frac{5.85\,\mu m}{10\,\mu A} \Big/ \frac{dX_d}{dV_{DS}}$$

So, $\frac{dX_d}{dV_{DS}} = 0.12\,\frac{\mu m}{V}$. Since, the other device uses the same technology, $\frac{dX_d}{dV_{DS}}$ is unchanged

But, should calculate V_{ov} for 2^{nd} transistor,

$$V_{ov} = \sqrt{\frac{2I}{k'\frac{W}{L}}} = \sqrt{\frac{2(30)}{(60.2)\frac{50}{12-2(0.3)}}} = 0.48\ V$$

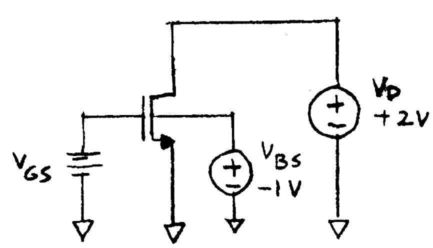
$$\text{So, } X_d = \sqrt{\frac{2(1.04\times10^{-12})(5-0.48)}{1.6\times10^{-19}(2.1\times10^{16})}} = 0.53\,\mu m$$

$L_{eff_2} = 12 - 2(0.3) - 0.53) = 10.87\,\mu m$

$$r_o = \frac{L_{eff}}{I_D} \Big/ \frac{dX_d}{dV_{DS}} = \frac{10.87\,\mu m}{30\,\mu A} \Big/ 0.12 = 3.02\,M\Omega$$

Note that using the same V_{ov} as for the 1^{st} transistor (0.15V) gives an answer of $3.1\,M\Omega$. (The change hardly matters)

2.15



First to estimate X_d and L_{eff}

$$L_{eff} = L_{drawn} - 2L_d - X_d \rightarrow (1)$$

$$X_d = \sqrt{\frac{2\epsilon_{si}(V_{DS} - V_{ov})}{q(N_A + N_i)}} \rightarrow (2)$$

$$I_D = \frac{\mu_n C_{ox}}{2}\frac{W}{L_{eff}}(V_{GS} - V_t)^2 \rightarrow (3)$$

L_{eff}, X_d and $V_{ov} = (V_{GS} - V_t)$ can be

found by solving (1), (2), (3).
To avoid solving non-linear equations, the following procedure is used: find X_d by substituting $L_{drawn} - 2L_d$ for L_{eff} in (3) and use the result in (2).

From (3),

$$V_{GS} - V_t = \sqrt{\frac{2I_D}{\mu_n C_{ox} W/L_{eff}}}$$

$$= \sqrt{\frac{2 \times 20\,\mu A}{450 \frac{cm^2}{V \cdot sec} 4.32 \frac{fF}{(\mu m)^2} \left(\frac{10\,\mu m}{1\,\mu m - 2(0.09\,\mu m)}\right)}}$$

$= 0.130$ V

From (2),

$$X_d = \sqrt{\frac{2 \times 11.6 \times 8.86 \times 10^{-14}(2-0.13)}{1.6 \times 10^{-19}(5 \times 10^{15} + 4 \times 10^{16})}}$$

$= 0.231\,\mu m$

From (1),

$L_{eff} \cong 1\,\mu m - 2(0.09)\,\mu m - 0.231\,\mu m$
$= 0.589\,\mu m$

(a) $$g_m = \sqrt{2K' \frac{W}{L_{eff}} I_D}$$

$$= \sqrt{2 \times 194 \frac{\mu A}{V^2} \times \frac{10}{0.589} \times 20\,\mu A}$$

$= 363\ \mu A/V$

(b) From (1.200), $$g_{mb} = \frac{\gamma g_m}{2\sqrt{2\phi_f + V_{SB}}} = \chi g_m$$

where $$\gamma = \frac{\sqrt{2q\varepsilon_{si} N_T}}{C_{ox}}$$ from (1.141) and

N_T is the effective dopant density at the bottom of the channel-substrate depletion layer, it can be either N_A (substrate doping) or $N_A + N_i$. To determine which one applies, we have to find $X'_{d\,max}$, i.e., the depletion depth under the channel,

$$X'_{d\,max} = \sqrt{\frac{2\varepsilon_{si}(2|\phi_p| + V_{SB})}{q(N_A + N_i)}}$$

But,

$$\phi_p = \frac{KT}{q} \ln \frac{N_A + N_i}{n_i}$$

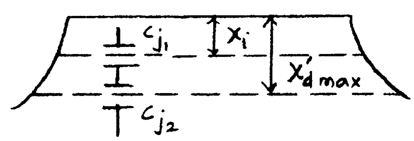
$$= 0.026 \ln \frac{4 \times 10^{16} + 5 \times 10^{15}}{1.45 \times 10^{10}} = 0.389$$

$$\therefore X'_{d\,max} = \sqrt{\frac{2 \times 11.6 \times 8.86 \times 10^{-14}(2 \times 0.389 + 1)}{1.6 \times 10^{-19}(4 \times 10^{16} + 5 \times 10^{15})}}$$

$= 0.225\,\mu m$

$> 0.16\,\mu m$ (effective implant depth)

since $X'_{d\,max} > X_i$, the depletion capacitor is the series combination of the capacitors as shown,



Now χ can be calculated from the following relationships,

$$\chi = \frac{C_{js}}{C_{ox}}, \quad C_{js} = \frac{C_{j1} C_{j2}}{C_{j1} + C_{j2}}$$

$$C_{j1} = \frac{\varepsilon_{si}}{X_i}, \quad C_{j2} = \frac{\varepsilon_{si}}{X_{d\,max} - X_i}$$

The actual depletion depth is

$$X_{d_{max.}} = \left[\frac{2\epsilon_{si}}{qN_A} \left(\phi_f + |\phi_p| + V_{SB} - x_i^2 \frac{N_i}{N_A} \right) \right]^{1/2}$$

(cf. Muller and kamins : Device Electronics for Integrated circuits, 2nd ed.; 1986; equation (10.6.2))

$$\phi_f = \frac{KT}{q} \ln \frac{N_A}{n_i} = 0.026 \ln \frac{5\times10^5}{1.45\times10^{10}} = 0.33\ V$$

$$X_{d_{max.}} = \left[\frac{2\times11.6\times8.86\times10^{-4}(0.33+0.389+1)}{1.6\times10^{-19}\times5\times10^{15}} - \frac{(0.16\times10^{-4}cm)^2(4\times10^{16})}{5\times10^{15}} \right]^{1/2}$$

$$= 0.453\ \mu m$$

$$C_{j1} = \frac{11.6\times8.86\times10^{-14}}{0.16\times10^{-4}} = 6.42\times10^{-8}\ F/cm^2$$

$$C_{j2} = \frac{11.6\times8.86\times10^{-14}}{(0.453-0.16)\times10^{-4}} = 3.51\times10^{-8}\ F/cm^2$$

$$C_{js} = 2.27\times10^{-8}\ F/cm^2$$

$$\therefore\ \chi = \frac{2.27\times10^{-8}}{4.32\times10^{-7}} = 0.0526$$

$$g_{mb} = \chi g_m = 0.0526\times363\times10^{-6} = 19.1\ \frac{\mu A}{V}$$

(c) From (2.37),

$$V_{ov} = \sqrt{\frac{2I_D}{K'(W/L_{eff})}} = \sqrt{\frac{2\times20\ \mu A}{194\ \mu A/V^2\ (10\mu/0.589\mu)}}$$

$$= 0.110\ V$$

$$X_d = \sqrt{\frac{2\epsilon_{si}(V_{DS}-V_{ov})}{q(N_A+N_i)}}$$

$$\frac{dX_d}{dV_{DS}} = \frac{X_d}{2(V_{DS}-V_{ov})} = \frac{0.231\ \mu m}{2(2-0.11)} = 0.061\ \mu m/V$$

$$\therefore\ r_o = \left(\frac{I_D}{L_{eff}} \frac{dX_d}{dV_{DS}} \right)^{-1} = \left(\frac{20\ \mu A}{0.589\mu m} \times 0.061\ \mu m/V \right)^{-1}$$

$$= 482.78\ k\Omega$$

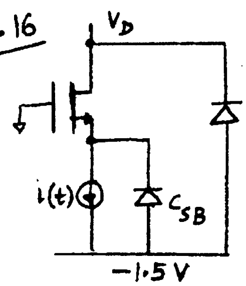
(d)
$$C_{gs} = \frac{2}{3} W L_{eff} C_{ox} + C_{OL}$$
$$= \frac{2}{3}\times10\times0.589\times4.32\times10^{-15} + 0.35\times10^{-15}\times10$$
$$= 20.5\ fF$$

(e)
$$C_{gd} = C_{OL} = 0.35\times10^{-15}\times10 = 3.5\ fF$$

(f)
$$C_{db} = \frac{C_{jo}\times(\text{drain area}) + C_{jswo}\times\text{periphery}}{\sqrt{1+V_{DB}/\phi_o}}$$
$$= \frac{0.2\times10\times1 + 1.2(10+1\times2)}{\sqrt{1+(3/0.7)}}\ fF$$
$$= 7.1\ fF$$

(g)
$$C_{sb} = \frac{C_{jo}\times(\text{source area}) + C_{jswo}\times\text{periphery}}{\sqrt{1+V_{SB}/\phi_o}}$$
$$= \frac{0.2\times10\times1 + 1.2(10+1\times2)}{\sqrt{1+(1/0.7)}}\ fF$$
$$= 10.5\ fF$$

2.16



$V_D(t=0) = V_s(t=0) = 1.5\ V$

(i) Initially transistor is off, current source discharges $C_{OL}+C_{SB}$. The rate of voltage change is,

$$\frac{V}{t} = \frac{I}{C}$$

$$\cong \frac{10\ \mu A}{0.35\frac{fF}{\mu m}\times10\mu m + 0.2\frac{fF}{\mu m^2}\times10\mu m\times(1\mu m+0.09\ \mu m) + 1.2\frac{fF}{\mu m}(12\mu m)}$$

$$= 500\ V/\mu sec$$

(ii) Transistor enters saturation region; drain current starts to flow, discharges $C_{OL}+C_{DB}$ and $\frac{2}{3}C_{ox}WL + C_{OL} + C_{SB}$. The discharge rate of drain voltage is

$$\frac{V}{t} \simeq \frac{10\,\mu A}{C_{OL}+C_{DB}}$$

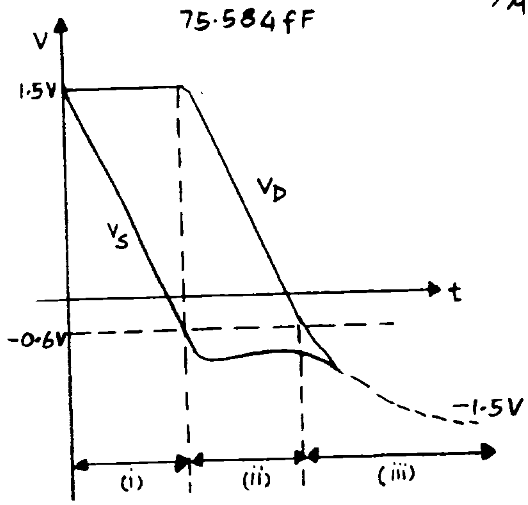
$$= \frac{10\,\mu A}{0.35\,\frac{fF}{\mu m}\times 10\,\mu m + 0.2\,\frac{fF}{\mu m^2}\times 10\,\mu m \times (1\,\mu m + 0.09\,\mu m) + 1.2\,\frac{fF}{\mu m}(12\,\mu m)}$$

$$= 500\ V/\mu s$$

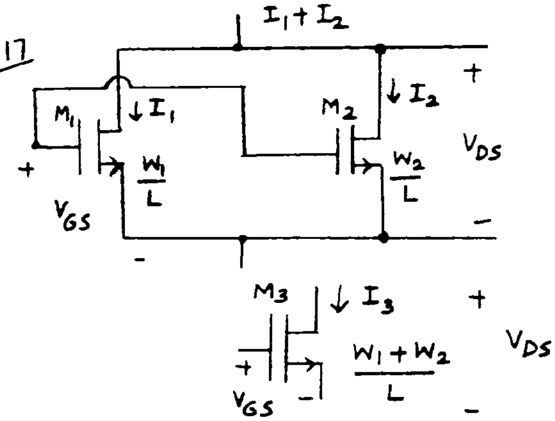
(iii) Transistor enters triode region, current discharges $C_{ox}WL + C_{DB} + C_{SB} + 2C_{OL}$ at a rate of,

$$\frac{V}{t} \simeq \frac{10\,\mu A}{\{4.32(10)(1-2(0.09)) + 0.2(10)(1+0.09)\,2 + 1.2(12)\,2 + \underbrace{0.35(2)(10)}_{2\ \text{overlaps}}\}}$$

$$= \frac{10\,\mu A}{75.584\,fF} = 132.30\ V/\mu s$$



2.17



Note that all the transistors have equal terminal voltages. so,

$$V_{GS_1} = V_{GS_2} = V_{GS_3} = V_{GS}$$

$$V_{DS_1} = V_{DS_2} = V_{DS_3} = V_{DS}$$

$$V_{SB_1} = V_{SB_2} = V_{SB_3} = V_{SB}$$

If $V_{SB} \neq 0$, there is a body effect but $V_{t_1} = V_{t_2} = V_{t_3} = V_t$

Case 1: All active

$$I_1 = \frac{k'}{2}\frac{W_1}{L}(V_{GS}-V_t)^2(1+\lambda V_{DS})$$

$$I_2 = \frac{k'}{2}\frac{W_2}{L}(V_{GS}-V_t)^2(1+\lambda V_{DS})$$

$$I_1 + I_2 = \frac{k'}{2}\left(\frac{W_1}{L}+\frac{W_2}{L}\right)(V_{GS}-V_t)^2(1+\lambda V_{DS})$$

$$I_3 = \frac{k'}{2}\left(\frac{W_1+W_2}{L}\right)(V_{GS}-V_t)^2(1+\lambda V_{DS})$$

$$= I_1 + I_2$$

Case 2: All triode

$$I_1 = \frac{k'}{2}\frac{W_1}{L}\left[2(V_{GS}-V_t)V_{DS} - V_{DS}^2\right]$$

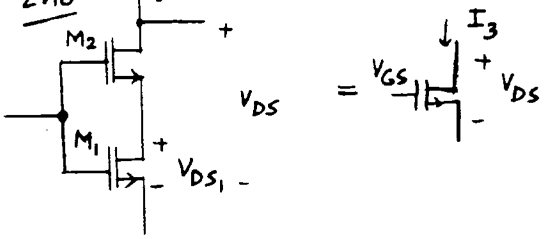
$$I_2 = \frac{k'}{2}\frac{W_2}{L}\left[2(V_{GS}-V_t)V_{DS} - V_{DS}^2\right]$$

$$I_1 + I_2 = \frac{k'}{2}\left(\frac{W_1}{L}+\frac{W_2}{L}\right)\left[2(V_{GS}-V_t)V_{DS} - V_{DS}^2\right]$$

$$I_3 = \frac{k'}{2}\left(\frac{W_1+W_2}{L}\right)\left[2(V_{GS}-V_t)V_{DS} - V_{DS}^2\right]$$

$$= I_1 + I_2$$

2.18



M_2 can operate in active or triode region. M_1 always operates in triode region

$$I_1 = \frac{K'}{2}\left(\frac{W}{L}\right)_1 \left[2(V_{GS}-V_t)V_{DS_1} - V_{DS_1}^2\right] = I_2$$

solve for V_{DS_1},

$$V_{DS_1}^2 - 2(V_{GS}-V_t)V_{DS_1} + \frac{2I_2}{K'\left(\frac{W}{L}\right)_1} = 0$$

$$V_{DS_1} = \frac{2(V_{GS}-V_t) \pm \sqrt{4(V_{GS}-V_t)^2 - 4\frac{2I_2}{K'\left(\frac{W}{L}\right)_1}}}{2}$$

V_{DS_1} must be $< V_{GS}-V_t$ or M_1 would be in active region.

$$V_{DS_1} = V_{GS}-V_t - \sqrt{(V_{GS}-V_t)^2 - \frac{2I_2}{K'\left(\frac{W}{L}\right)_1}}$$

Assume M_2 is active,

$$I_2 = \frac{K'}{2}\left(\frac{W}{L}\right)_2 (V_{GS}-V_{DS_1}-V_t)^2$$

$$= \frac{K'}{2}\left(\frac{W}{L}\right)_2 \left[V_{GS}-V_t-(V_{GS}-V_t)+\sqrt{(V_{GS}-V_t)^2 - \frac{2I_2}{K'\left(\frac{W}{L}\right)_1}}\right]^2$$

$$= \frac{K'}{2}\left(\frac{W}{L}\right)_2 (V_{GS}-V_t)^2 - \left(\frac{W}{L}\right)_2 \frac{I_2}{\left(\frac{W}{L}\right)_1}$$

$$I_2\left(1 + \left(\frac{W}{L}\right)_2 \Big/ \left(\frac{W}{L}\right)_1\right) = \frac{K'}{2}\left(\frac{W}{L}\right)_2 (V_{GS}-V_t)^2$$

$$I_2 = \left[\frac{K'}{2}\left\{\left(\frac{W}{L}\right)_2 \Big/ 1 + \left(\frac{W}{L}\right)_2 \Big/ \left(\frac{W}{L}\right)_1\right\}\right](V_{GS}-V_t)^2$$

$$= \frac{K'}{2}\left(\frac{W}{L_1+L_2}\right)(V_{GS}-V_t)^2$$

If M_2 and M_3 are active,

$$I_3 = \frac{K'}{2}\left(\frac{W}{L_1+L_2}\right)(V_{GS}-V_t)^2 = I_2$$

Assume M_2 is in triode region,

$$I_2 = \frac{K'}{2}\left(\frac{W}{L}\right)_2 \left[2(V_{GS}-V_{DS_1}-V_t)(V_{DS}-V_{DS_1}) - (V_{DS}-V_{DS_1})^2\right]$$

$$V_{DS_1} = V_{GS}-V_t - \sqrt{(V_{GS}-V_t)^2 - \frac{2I_2}{K'\left(\frac{W}{L}\right)_1}}$$

$$I_2 = \frac{K'}{2}\left(\frac{W}{L}\right)_2 \left[2\sqrt{(V_{GS}-V_t)^2 - \frac{I_2}{K'\left(\frac{W}{L}\right)_1}}\left[V_{DS} - (V_{GS}-V_t) + \sqrt{(V_{GS}-V_t)^2 - \frac{2I_2}{K'\left(\frac{W}{L}\right)_1}}\right] - \left[V_{DS}-(V_{GS}-V_t) + \sqrt{(V_{GS}-V_t)^2 - \frac{2I_2}{K'\left(\frac{W}{L}\right)_1}}\right]^2\right\}$$

Let $X = V_{DS} - (V_{GS}-V_t)$ and

$$Y = \sqrt{(V_{GS}-V_t)^2 - \frac{I_2}{K'\left(\frac{W}{L}\right)_1}}$$

Then,

$$I_2 = \frac{K'}{2}\left(\frac{W}{L}\right)_2 \left[2Y(X+Y) - (X+Y)^2\right]$$

$$I_2 = \frac{K'}{2}\left(\frac{W}{L}\right)_2 \left[2XY + 2Y^2 - X^2 - Y^2 - 2XY\right]$$

$$I_2 = \frac{K'}{2}\left(\frac{W}{L}\right)_2 \left[Y^2 - X^2\right]$$

$$= \frac{K'}{2}\left(\frac{W}{L}\right)_2 \left[(V_{GS}-V_t)^2 - \frac{I_2}{K'\left(\frac{W}{L}\right)_1} - \{V_{DS} - (V_{GS}-V_t)\}^2\right]$$

$$= \frac{K'}{2}\left(\frac{W}{L}\right)_2 \left[(V_{GS}-V_t)^2 - \frac{I_2}{K'\left(\frac{W}{L}\right)_1} - V_{DS}^2 - 2V_{DS}(V_{GS}-V_t) + (V_{GS}-V_t)^2\right]$$

$$I_2\left(1 + \frac{\left(\frac{W}{L}\right)_2}{\left(\frac{W}{L}\right)_1}\right) = \frac{K'}{2}\left(\frac{W}{L}\right)_2 \left\{-V_{DS}^2 + 2V_{DS}(V_{GS}-V_t)\right\}$$

$$I_2 = \frac{K'}{2}\frac{W}{L_1+L_2}\left[2(V_{GS}-V_t)V_{DS} - V_{DS}^2\right]$$

$$= I_3$$

2.19

(a) Curve B ;

(i) The cost of a 40,000 mil^2 chip is

$$C = \frac{C_W}{(N Y_{ws}) Y_{df} Y_{ft}} = \frac{100}{(47)(10.9)(0.8)} + \frac{0.6}{0.8}$$

$= 3.71$

$N Y_{ws} = 47$ is obtained from fig.(2.70)

(ii) The cost of two 20,000 mil^2 chips is,

$$C_{Y_2} = \frac{100}{(200)(0.9)(10.8)} + \frac{0.6}{0.8} = 1.44$$

$$C_{total} = C_{1/2} \times 2 = 2.88$$

∴ Putting the system on two chips is more economical

(b) Curve A ;

(i) For a 40,000 mil^2 chip,

$$C = \frac{100}{(115)(0.9)(0.8)} + \frac{0.6}{0.8} = 1.1$$

$$C_{total} = 1.1 \times 2 = 2.2$$

∴ one chip is more economical.

(c) Curve C :

(i) For a 40,000 mil^2 chip,

$$C = \frac{100}{12(0.9)(0.8)} + \frac{0.6}{0.8} = 12.3$$

(ii) For two 20,000 mil^2 chips,

$$C_{1/2} = \frac{100}{(80)(0.9)(0.8)} + \frac{0.6}{0.8} = 2.49$$

$$C_{total} = 2.49 \times 2 = 4.98$$

∴ using two chips is more economical.

2.20

Area $= (150 \text{ mils})^2 = 22,500 \; mil^2$

(a) Curve A ,

$$C = \frac{C_W}{(N Y_{ws})(Y_{df})(Y_{ft})} + \frac{C_P}{Y_{ft}}$$

$$= \frac{130}{(360)(0.8)(0.8)} + \frac{0.4}{0.8} = 1.06$$

$N Y_{ws} = 360$ is obtained from Fig.(2.70)

(b) Curve B,

$$C = \frac{130}{(140)(0.8)(0.8)} + \frac{0.4}{0.8} = 1.95$$

(c) Curve C,

$$C = \frac{130}{(60)(0.8)(0.8)} + \frac{0.4}{0.8} = 3.89$$

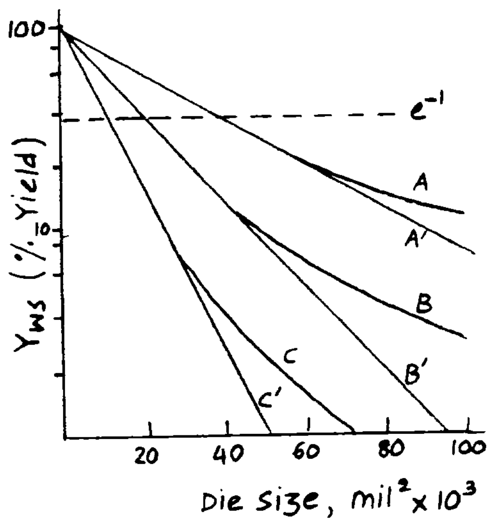
2.21

(a) When $Y_{ws} = e^{-1} = 0.37$

From curve A, $A_o = 38{,}000 \text{ mil}^2$

curve B, $A_o = 20{,}000 \text{ mil}^2$

curve C, $A_o = 11{,}000 \text{ mil}^2$



curves A', B' and C' are predicted by the equation.

(b) In fig (2.69), gross die/wafer is inversely proportional to the die size, i.e., $N = KA^{-1}$, K is the proportionality constant related to the wafer size (more specifically, K is the effective or usable area on the wafer). By (2.56), the cost per unit silicon area is,

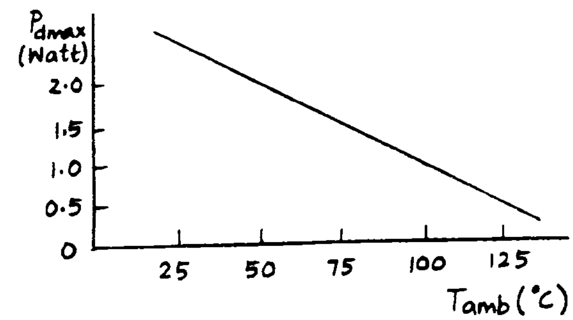
$$\frac{C}{A} = \frac{C_W}{A N Y_{ws} Y_{df} Y_{ft}} + \frac{C_P}{A Y_{ft}}$$

$$= \frac{C_W}{K e^{-A/A_o} Y_{df} Y_{ft}} + \frac{C_P}{A Y_{ft}}$$

Each K can be obtained from fig (2.69). e.g. $K \doteq 1.15 \times 10^5 \text{ mil}^2$ for 4' wafer.

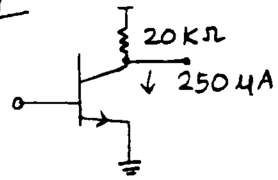
2.22 The total thermal resistance is 50°C/Watt.

$$P_{d\,max} = \frac{150°C - T_{ambient}}{50°C/W}$$



CHAPTER 3

3.1



$\beta = 200$ (from fig (2.30))

$$R_{IN} = r_\pi = \frac{\beta}{g_m}$$

$$= 100\Omega \times 200$$

$$= 20.8 \text{ k}\Omega$$

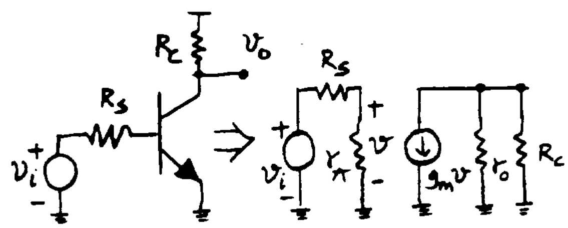
$$G_m = g_m = \frac{I_c}{V_T} = \frac{1}{104} \text{ A/V}$$

$$R_o = R_c \| r_o = 200k \| \frac{1}{\eta g_m}$$

$$= 20k \| \frac{104\Omega}{2 \times 10^{-4}} = 20k \| 520K$$

$$= 19.3 \text{ k}\Omega$$

3.2



$$A_v = \left(\frac{r_\pi}{R_s + r_\pi}\right) g_m (r_o \| R_c)$$

$$= \frac{\beta (r_o \| R_c)}{r_s + r_\pi} = \beta\left(\frac{V_A}{I_c} \| R_c\right)$$

Now, when

$I_c \to \infty$, $A_v \to 0$ because $R_c \to 0$

$I_c \to 0$, $A_v \to 0$ because $g_m \to 0$

$$A_v = \beta \left(\frac{\frac{V_A}{I_c} R_c}{\frac{V_A}{I_c} + R_c}\right)\left(\frac{1}{R_s + \frac{\beta V_T}{I_c}}\right)$$

$$= \beta\left(\frac{I_c R_c}{1 + \frac{I_c R_c}{V_A}}\right)\left(\frac{1}{R_s I_c + \beta V_T}\right)$$

$$\therefore A_v = \beta\left[\frac{\left(\frac{I_c R_c}{\beta V_T}\right)}{\left(1 + \frac{I_c R_c}{V_A}\right)\left(1 + \frac{R_s I_c}{\beta V_T}\right)}\right]$$

$$\frac{\partial A_v}{\partial I_c} = 0$$

$$\therefore 1 - \left(\frac{\frac{I_c R_c}{V_A}}{1 + \frac{I_c R_c}{V_A}}\right) - \left(\frac{\frac{I_c R_c}{\beta V_T}}{1 + \frac{I_c R_c}{\beta V_T}}\right) = 0$$

$$1 - \frac{ax}{1+ax} - \frac{bx}{1+bx} = 0$$

where $a = \frac{R_c}{V_A}$, $b = \frac{R_s}{\beta V_T}$, $x = I_c$

$$(1+ax)(1+bx) - (1+bx)ax - (1+ax)bx = 0$$

$$\therefore \left(1 + \frac{I_c R_c}{V_A}\right)\left(1 + \frac{I_c R_s}{\beta V_T}\right) - \left(1 + \frac{I_c R_s}{\beta V_T}\right)\left(\frac{I_c R_c}{V_A}\right)$$

$$- \left(1 + \frac{I_c R_c}{V_A}\right)\left(\frac{I_c R_s}{\beta V_T}\right) = 0$$

$$\therefore 1 - \left(\frac{I_c R_c}{V_A}\right)\left(\frac{I_c R_s}{\beta V_T}\right) = 0$$

$$I_c^2 \left(\frac{R_c}{V_A}\right)\left(\frac{R_s}{\beta V_T}\right) = 1$$

$$\therefore I_{c\,opt.} = \sqrt{\left(\frac{V_A}{R_c}\right)\left(\frac{\beta V_T}{R_s}\right)}$$

$$A_{v\,opt.} = \beta\left(\frac{I_{c\,opt.} R_c}{\beta V_T}\right)\left(\frac{1}{\left(1 + \frac{I_{c\,opt} R_c}{V_A}\right)\left(1 + \frac{I_{c\,opt} R_s}{\beta V_T}\right)}\right)$$

$$= \beta\left(\frac{\sqrt{V_A/R_s}}{\sqrt{\beta V_T/R_c}}\right)\left[\frac{1}{\left(1 + \frac{\sqrt{\beta V_T/R_s}}{\sqrt{V_A/R_c}}\right)\left(1 + \frac{\sqrt{V_A/R_c}}{\sqrt{\beta V_T/R_c}}\right)}\right]$$

Let $x' = \sqrt{\left(\frac{V_A}{\beta V_T}\right)\left(\frac{R_s}{R_c}\right)}$

Then,

$$A_{v\,OPT.} = \beta x' \left[\frac{1}{\left(1 + \frac{1}{x'}\right)(1 + x')}\right]\left(\frac{R_c}{R_s}\right)$$

3.3

$R_S = 50\,K\Omega$, $R_C = 50\,K\Omega$, $\beta = 200$

$V_A = 120\,V$

$$I_{C_{OPT.}} = \sqrt{\left(\frac{120V}{50K\Omega}\right)\left(\frac{26mV \times 200}{50\,K\Omega}\right)} = 0.5\ mA$$

$$A_{v_{OPT.}} = (200)\,x'\left[\frac{1}{\left(1+\frac{1}{x'}\right)\left(1+x'\right)}\right] \times \frac{50K}{50K}$$

where, $x' = \sqrt{\left(\frac{V_A}{\beta V_T}\right)\left(\frac{R_S}{R_C}\right)} = 4.8$

$$\therefore A_{v_{OPT.}} = 200 \times 4.8 \times \left[\frac{1}{\left(1+\frac{1}{4.8}\right)\left(1+4.8\right)}\right]$$

$$= 137$$

DC voltage on RC $= 0.5 \times 50 = 25\,V$

3.4

$$V_o = V_{DD} - R_D \frac{\mu C_{ox}}{2} \frac{W}{L} (V_{GS} - V_t)^2$$

Triode edge $V_{DS} = V_{GS} - V_t = V_o$

$$V_{DS} = V_{DD} - R_D \frac{\mu_{cox}}{2} \frac{W}{L} V_{DS}^2$$

$$V_{DS} = 3 - \frac{5K}{2} (200\mu)(10)\, V_{DS}^2$$

$$5V_{DS}^2 + V_{DS} - 3 = 0$$

$$V_{DS} = \frac{-1 + \sqrt{61}}{10} = 0.0681\,V = V_o$$

$0.681\,V = V_{GS} - V_t = V_i - V_t$

$0.681 = V_i - 0.6$

$1.281 = V_i$

S.S. $\frac{V_o}{V_i} = -g_m R_D = -6.81$

$$g_m = k' \frac{W}{L} (V_{GS} - V_t) = 200\mu (10)(0.681)$$
$$= 1.36\ \frac{mA}{V}$$

unity gain $g_m R_D = 1$,

$$g_m = \frac{1}{R_D} = \frac{1}{5K} = 200\mu(10)(V_{GS} - V_t)$$

$0.1 = V_{GS} - V_t$

$0.1 + 0.6 = 0.7\,V = V_i$

$$I_D = \frac{200\mu}{2}(10)(0.1)^2 = 10\,\mu A$$

$V_o = 3 - 10\,\mu A\,(5\,K\Omega) = 2.95\,V$

In active region:

$$g_m = k' \frac{W}{L} (V_{GS} - V_t)$$

$$g_m = \sqrt{2 k' \frac{W}{L} I_D}$$

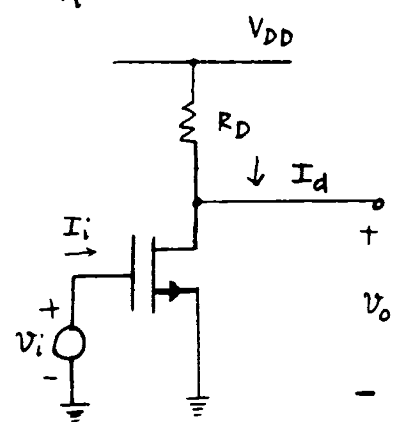
get maximum g_m at max. I_D just before I_D gets large enough to bring mosfet in linear region.

In linear region:

$g_m = k' \frac{W}{L} (V_{DS})$ which decreases as I_D increases

So, the maximum g_m occurs at the edge between active and linear regions.

$\frac{V_o}{V_i} = -6.81$ = maximum gain



```
COMMON SOURCE GAIN STAGE, MAX GAIN
******
VDD  100  0    3
M1   2    1    0    0    NMOS  W=10U  L=1U
RD   100  2    5K
VI   1    0    1.281
.MODEL NMOS NMOS LEVEL=1 VTO=0.6 KP=200U LAMBDA=0
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.TF  V(2) VI
.OP
.END

 ****  OPERATING POINT INFORMATION    TNOM=  27 TEMP=  27
   NODE =VOLTAGE       NODE =VOLTAGE       NODE =VOLTAGE
+0:1     = 1.281E+00 0:2     = 6.812E-01 0:100   = 3.000E+00

**** MOSFETS

SUBCKT
ELEMENT  0:M1
MODEL    0:NMOS
 ID       4.638E-04
 IBS        0.
 IBD      -6.812E-15
 VGS       1.281E+00
 VDS       6.812E-01
 VBS        0.
 VTH       6.000E-01
 VDSAT     6.810E-01
 BETA      2.000E-03
 GAM EFF    0.
 GM        1.362E-03
 GDS        0.

****      SMALL-SIGNAL TRANSFER CHARACTERISTICS
V(2)/VI                                    = -6.810E+00
INPUT RESISTANCE AT          VI            =  1.000E+20
OUTPUT RESISTANCE AT V(2)                  =  5.000E+03


COMMON SOURCE GAIN STAGE, UNITY GAIN
******

VDD  100  0    3
M1   2    1    0    0    NMOS  W=10U  L=1U
RD   100  2    5K
VI   1    0    0.7
.MODEL NMOS NMOS LEVEL=1 VTO=0.6 KP=200U LAMBDA=0
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.TF  V(2) VI
.OP
.END

 ****  OPERATING POINT INFORMATION    TNOM=  27 TEMP=  27
   NODE =VOLTAGE       NODE =VOLTAGE       NODE =VOLTAGE
+0:1     = 7.000E-01 0:2     = 2.950E+00 0:100   = 3.000E+00

SUBCKT
ELEMENT  0:M1
MODEL    0:NMOS
 ID        1.000E-05
 IBS        0.
 IBD      -2.950E-14
 VGS       7.000E-01
 VDS       2.950E+00
 VBS        0.
 VTH       6.000E-01
 VDSAT     1.000E-01
 BETA      2.000E-03
 GAM EFF    0.
 GM        2.000E-04
 GDS        0.

****      SMALL-SIGNAL TRANSFER CHARACTERISTICS
V(2)/VI                                    = -1.000E-00
INPUT RESISTANCE AT          VI            =  1.000E+20
OUTPUT RESISTANCE AT V(2)                  =  5.000E+03
```

3.5

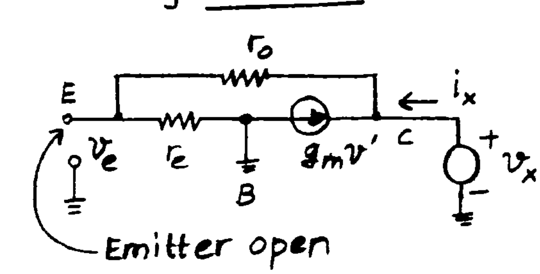
$$R_i = r_e \simeq \frac{1}{g_m} = \frac{V_T}{I_C} = 104\,\Omega$$

$$R_o = R_C = 10\,k\Omega$$

$$G_m = g_m = \frac{1}{104}\ A/V$$

3.6

Driven by current source:



$$v_e = v_x\left(\frac{r_e}{r_o + r_e}\right)$$

$$i_x = \frac{v_x}{r_o + r_e} - g_m v_e$$

$$= v_x\left[\frac{1}{r_o + r_e} - \frac{g_m r_e}{r_o + r_e}\right]$$

$$\therefore \frac{i_x}{v_x} = \frac{1}{R_o} = \frac{1 - g_m r_e}{r_o + r_e}$$

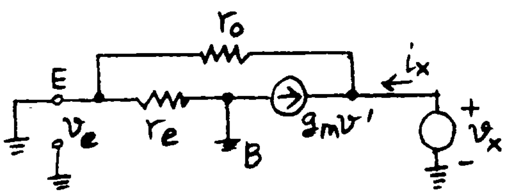
But, $g_m R_e = \alpha_F = \dfrac{\beta_F}{1 + \beta_F}$

$$\therefore \frac{i_x}{v_x} = \frac{1 - \dfrac{\beta_F}{1 + \beta_F}}{r_o + r_e} = \frac{1}{(1 + \beta_F)(r_o + r_e)}$$

Now, $r_o >> r_e$ and $\beta_F >> 1$, so

$$\frac{v_x}{i_x} = R_o = \beta_F R_o$$

For common-base driven from voltage source:

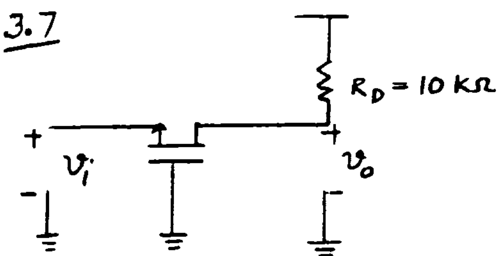


v_e is zero, since emitter shorted to ground for small signals.

Thus, $\frac{v_x}{i_x} = R_o = r_o$

Thus, we get much higher r_o when the CB stage is driven from a high source resistance.

3.7



From (3.54) → (without R_L and g_{mb}),

$$R_i = \frac{r_o + R_D}{1 + g_m r_o}$$

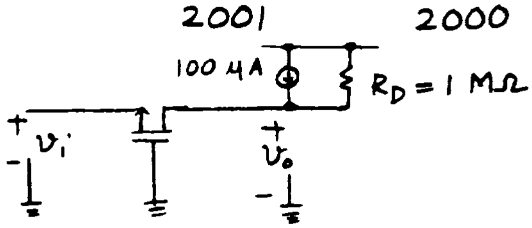
$$r_o = \frac{1}{\lambda I_D} = \frac{1}{(0.01)(100\mu)} = 1\,M\Omega$$

$$g_m = \sqrt{2K'\left(\frac{W}{L}\right) I_D} = \sqrt{2(200)\left(\frac{100}{1}\right)100}$$

$$= 2000\ \mu A/V$$

$$g_m r_o = 2000$$

$$R_i = \frac{1\,M\Omega + 10\,k\Omega}{2001} \approx \frac{1\,M\Omega}{2000} = \frac{1}{g_m} = 500\,\Omega$$



$$R_i \cong \frac{1\,M\Omega + 1\,M\Omega}{2001} \approx 1000\,\Omega$$

3.8

$$R_i = r_\pi + R_L(1+\beta)$$

$$= 200 \times 26\,\Omega + 500 \times 201\,\Omega$$

$$= 105.7\ k\Omega$$

$$R_o = \left(\frac{R_S}{1+\beta} + \frac{1}{g_m}\right) \| R_L$$

$$= \left(\frac{5k}{201} + 26\right) \| 500$$

$$= 51 \| 500$$

$$= 46\,\Omega$$

$$\text{Voltage gain} = \frac{1}{1 + \frac{R_S + r_\pi}{(1+\beta)R_L}}$$

$$= \frac{1}{1 + \frac{5.0K + 5.2K}{(201)(500)}}$$

$$= 0.91$$

3.9

(a) $V_o = 3 - V_t - (V_{GS} - V_t)$

$V_{GS} - V_t = \sqrt{\frac{2I}{k' W/L}}$; $k' = \mu_n C'_{ox}$

$C'_{ox} = \frac{3.9 \times 8.854 \times 10^{-14}}{250 \times 10^{-8} cm} = 1.38 \frac{fF}{\mu^2}$

$k' = 650 \frac{cm^2}{V \cdot S} \cdot 1.38 \times 10^{-7} \frac{F}{cm}$

$= 89.7 \mu A/V^2 \approx 90 \mu A/V^2$

$\therefore V_{GS} - V_t = \sqrt{\frac{2(200)}{90(10)}} \approx 0.67 V$

$\Rightarrow V_o = 3 - 0.7 - 0.67 = 1.63 V$

$\frac{v_o}{v_i} = \frac{g_m r_o}{1 + g_m r_o}$; $r = \infty$ since $\lambda = 0$

$\Rightarrow \frac{v_o}{v_i} = 1$

(b) V_t affects V_o and vice-versa, solve iteratively,

$V_t = V_{t_o} + \gamma \left(\sqrt{2\phi_F + V_{SB}} - \sqrt{2\phi_F} \right)$

$\gamma = \frac{\sqrt{2q\epsilon N_A}}{C'_{ox}}$

$\Rightarrow \gamma = \frac{\sqrt{2(1.6 \times 10^{-19})(11.7 \times 8.854 \times 10^{-14})(2 \times 10^{15})}}{1.38 \times 10^{-7}}$

$= 0.19 \sqrt{V}$

$V_{SB} = V_o$ - (use ans. from (a) to start)

$\phi_F = V_T \ln \frac{N_A}{N_i} = (26mV) \ln \frac{2 \times 10^{15}}{1.5 \times 10^{10}} \approx 0$

$V_t = 0.7 + 0.19 \left[\sqrt{0.6 + 1.63} - \sqrt{0.6} \right]$

$= 0.84 V$

So, $V_o = 3 - 0.84 - 0.6 = 1.49$

(Try again)

$V_t = 0.7 + 0.19 \left[\sqrt{0.6 + 1.63} - \sqrt{0.6} \right]$

$= 0.83$

(Not much change)

So, $V_o = 3 - 0.83 - 0.67 \cong 1.5 V$

$\frac{v_o}{v_i} = \frac{g_m}{g_m + g_{mb}} = \frac{1}{1 + X}$

$X = \frac{0.19}{2\sqrt{0.6 + 1.5}} \approx 0.07$

$\Rightarrow \frac{v_o}{v_i} = \frac{1}{1 + 0.07} \approx 0.93$

(c) Use V_o from (b) at first

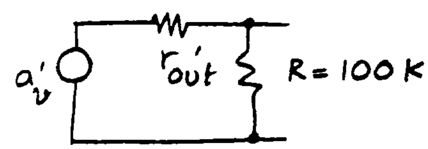
$\Rightarrow I = 200\mu + \frac{1.5}{100k} \approx 215 \mu A$

$V_o = 3 - 0.83 - \sqrt{\frac{2(215)}{90 \cdot 10}} = 1.48 V$

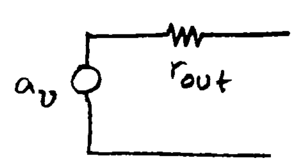
(Not much change from (b) so don't bother to recalculate V_t)

To find $a_v = \frac{v_o}{v_i}$, use

a'_v = OCVG from (b) = 0.93



⇓



$a_v = a'_v \frac{100k}{100k + r'_{out}}$

$$r'_{out} = \frac{1}{(g_m + g_{mb})} = \frac{1}{g_m(1+X)}$$

$$g_m = \sqrt{2(215)\,90.10} = 0.6\ mA/V$$

$$r'_{out} = \frac{1}{(0.62)(1.07)} = 1.5\ k\Omega$$

$$\Rightarrow a_v = 0.93\ \frac{100}{101.5} = 0.92$$

(d) Use V_o from (c) at first,

$$I = 200 + \frac{1.48}{10k} = 348\ \mu A$$

$$V_o = 3 - 0.83 - \sqrt{\frac{2(348)}{90.10}} = 1.29V$$

$$V_t = 0.7 + 0.19\left(\sqrt{0.6+1.29} - \sqrt{0.6}\right)$$
$$= 0.81\ V$$

$$I = 200 + \frac{1.29}{10k} = 329\ \mu A$$

$$V_o = 3 - 0.81 - \sqrt{\frac{2(329)}{90.10}} = 1.33\ V$$

$$a'_v = \frac{1}{1+x}\ ;\quad x = \frac{0.19}{2\left(\sqrt{0.6+1.33}\right)} \approx 0.07$$

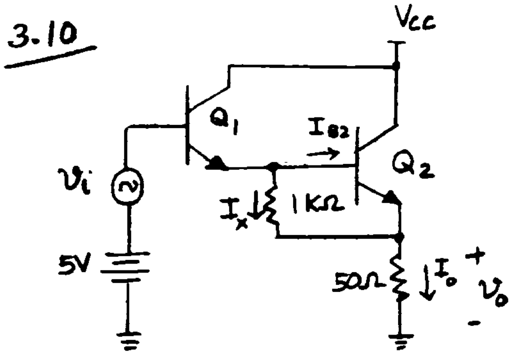
$$\Rightarrow a'_v \simeq 0.93$$

$$r'_{out} = \frac{1}{[g_m(1+x)]}\ ;\quad g_m = \sqrt{2(329)\,90(10)} = 0.77\ mA/V$$

$$r'_{out} = \frac{1}{0.77(1.07)} = 1.2k$$

$$\Rightarrow a_v = 0.93\ \frac{10K}{11.2K} = 0.83$$

3.10



The DC voltage across the 50Ω resistor is,

$$V_o = 5 - 0.7 - 0.7 = 3.6V$$

Thus, $I_o = \frac{3.6\ V}{50\Omega} = 72\ mA$

The current I_x is,

$$I_x = \frac{0.7\ V}{1\ k\Omega} = 0.7\ mA$$

The emitter current of Q_2 is

$$I_{E2} = I_o - I_x = 71.3\ mA$$

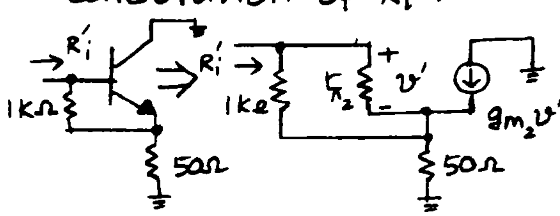
The base current of Q_2 is,

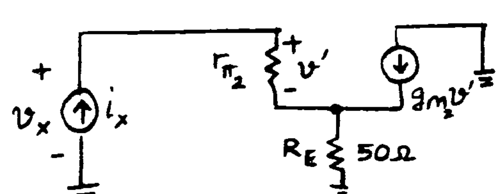
$$I_{B2} = \frac{I_{E2}}{1+\beta} = \frac{71.3}{201} = 0.35\ mA$$

Thus, the emitter current of Q_1 is

$$I_{E1} = I_x + I_{B2} = 0.7 + 0.35$$
$$= 1.05\ mA$$

calculation of R_i :





$$v_x = i_x r_{\pi_2} + (i_x + g_{m_2} r_{\pi_2} i_x) R_E$$

$$\frac{v_x}{i_x} = r_{\pi_2} + (1 + g_{m_2} r_{\pi_2}) R_E$$

Now, the $1\,k\Omega$ resistor is connected in parallel with r_{π_2}, so define a new effective r_{π_2},

$$r_{\pi_2}' = r_{\pi_2} \parallel 1K$$

$$R_i' = (r_{\pi_2} \parallel 1K) + \left[1 + g_{m_2}(r_{\pi_2} \parallel 1K)\right] R_E$$

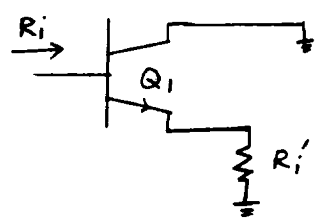
$$r_{\pi_2} = \frac{\beta}{g_{m_2}} = 200 \times \frac{26\,mV}{71\,mA} = 73\,\Omega$$

$$r_{\pi_2}' = 73 \parallel 1K = 68\,\Omega$$

$$\therefore R_i' = 68\,\Omega + \left[1 + \left(\frac{71\,mA}{26\,mV}\right)(68\,\Omega)\right] 50\,\Omega$$

$$= 9.4\,k\Omega$$

Now consider R_i



$$R_i = r_{\pi_1} + (1+\beta) R_i'$$

$$= 200 \left(\frac{26\,mV}{1.05\,mA}\right) + (201)(9.4\,k\Omega)$$

$$= (4.95\,k + 1.88\,M)\,\Omega$$

$$= 1.89\,M\Omega$$

Calculation of voltage gain,

(a) gain from input to emitter of Q_1 (use Eq. (3.20)

$$A_{v_1} = \frac{1}{1 + \dfrac{r_{\pi_1}}{(1+\beta) R_i'}}$$

$$A_{v_1} = \frac{1}{1 + \dfrac{r_{\pi_1}}{(1+\beta) R_i'}} = \frac{1}{1 + \dfrac{4.9\,K}{(201)(9.4\,K)}}$$

$$= 0.997$$

(b) Gain from base of Q_2 to output. Use Eq (3.20), substitute $g_m r_\pi'$ for β_o

$$A_{v_2} = \frac{1}{1 + \dfrac{r_\pi'}{(1 + g_m r_\pi') R_L}}$$

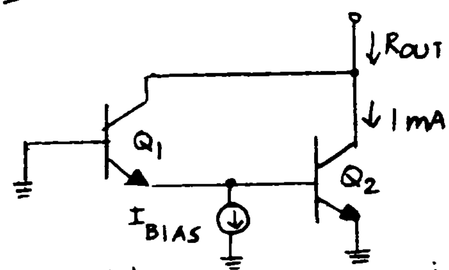
$$= \frac{1}{1 + \dfrac{68\,\Omega}{\left[68\,\Omega\left(\frac{71\,mA}{26\,mV}\right) + 1\right] 50\,\Omega}}$$

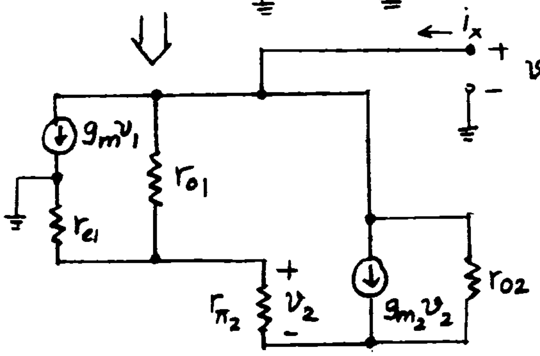
$$= 0.993$$

voltage gain $= 0.997 \times 0.993 = 0.990$

```
DARLINGTON EMITTER FOLLOWER
******
VCC  100  0    10
Q1   100  1    2    NPN
Q2   100  2    3    NPN
R1   2    3    1K
R2   3    0    50
VI   1    0    5
.MODEL NPN NPN IS=1E-14 BF=200 RB=0
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.TF  V(3) VI
.OP
.END
 ****  OPERATING POINT INFORMATION    TNOM=  27 TEMP=  27
   NODE =VOLTAGE       NODE =VOLTAGE       NODE =VOLTAGE
+0:1     = 5.000E+00 0:2     = 4.342E+00 0:3     = 3.577E+00
+0:100   = 1.000E+01
**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT  0:Q1        0:Q2
MODEL    0:NPN       0:NPN
 IB       5.558E-06  3.521E-04
 IC       1.112E-03  7.042E-02
 VBE      6.578E-01  7.651E-01
 VCE      5.657E+00  6.423E+00
 VBC     -5.000E+00 -5.657E+00
 VS      -1.000E+01 -1.000E+01
 POWER    6.293E-03  4.526E-01
 BETAD    2.000E+02  2.000E+02
 GM       4.298E-02  2.722E+00
 RPI      4.653E+03  7.345E+01
 RX         0.          0.
 RO       5.000E+14  5.657E+14
 BETAAC   2.000E+02  2.000E+02
****      SMALL-SIGNAL TRANSFER CHARACTERISTICS
V(3)/VI                                  =  9.903E-01
INPUT RESISTANCE AT         VI           =  1.900E+06
OUTPUT RESISTANCE AT V(3)                =  4.842E-01
```

3.11





$$v_2 = -v_1 = v_x\left[\frac{r_{e1} \| r_{\pi 2}}{r_{o1} + r_{e1} \| r_{\pi 2}}\right]$$

Assume $r_{o1} >> r_{e1} \| r_{\pi 2}$

$$i_x = g_{m1}v_1 + g_{m2}v_2 + \frac{v_x}{r_{o1} + (r_{e1} \| r_{\pi 2})} + \frac{v_x}{r_{o2}}$$

$$\frac{i_x}{v_x} = -g_{m1}\left(\frac{r_{e1} \| r_{\pi 2}}{r_{o1}}\right) + g_{m2}\left(\frac{r_{e1} \| r_{\pi 2}}{r_{o1}}\right) + \frac{1}{r_{o1}} + \frac{1}{r_{o2}}$$

$$= \frac{1}{r_{o2}} + \frac{1}{r_{o1}}\left[1 + (g_{m2} - g_{m1})(r_{e1} \| r_{\pi 2})\right]$$

$$R_o = \left\{\frac{1}{r_{o2}} + \frac{1}{r_{o1}}\left[1 + (g_{m2} - g_{m1})(r_{e1} \| r_{\pi 2})\right]\right\}^{-1}$$

① If $I_{BIAS} = 1\,mA$, then $g_{m1} \approx g_{m2}$

$$R_o = \left(\frac{1}{r_{o1}} + \frac{1}{r_{o2}}\right)^{-1}$$

② If $I_{BIAS} = 0$, then $I_{C1} = \frac{I_{C2}}{\beta}$

$\therefore\ r_{e1} \approx r_{\pi 2},\ g_{m2} >> g_{m1}$

$$R_o = \left\{\frac{1}{r_{o2}} + \frac{1}{r_{o1}}\left[1 + g_{m2}\frac{r_{\pi 2}}{2}\right]\right\}^{-1}$$

But, $r_{o1} = \beta r_{o2}$ (if $I_{C1} = I_{C2}/\beta$)

Thus,

$$R_o = \left\{\frac{1}{r_{o2}} + \frac{1}{\beta r_{o2}}\left[1 + \frac{\beta}{2}\right]\right\}^{-1}$$

$$\cong \left(\frac{1}{r_{o2}} + \frac{1}{2r_{o2}}\right)^{-1} = \frac{2}{3}r_{o2}$$

3.12

$V_o = 2\,V\ dc$

$I_C + I_D = 1\,mA$

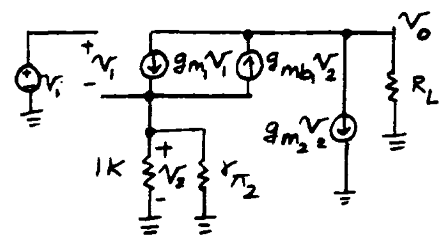
$I_D \approx \frac{0.1}{1K} = 0.7\,mA$

$I_C = 0.3\,mA$

$V_{BE} = V_T \ln \frac{0.3\,mA}{10^{-16}A} = 0.75\,V$

$I_D = 0.75\,mA$

$I_C = 0.25\,mA$



$$v_o = (g_{mb1}v_2 - g_{m1}v_1 - g_{m2}v_2)R_L$$

$$v_i = v_1 + v_2$$

$$g_m v_1 - g_{mb1}v_2 = \frac{v_2}{R}$$

$$R = 1K \| r_{\pi 2} = 912\,\Omega$$

$$r_{\pi 2} = \frac{\beta}{g_{m2}} = \frac{100}{\frac{0.25}{26}} = 10.4\,k\Omega$$

$$g_{m1}v_1 = v_2\left(g_{mb1} + \frac{1}{R}\right)$$

$$\frac{v_1}{v_2} = \frac{g_{mb1} + \frac{1}{R}}{g_{m1}}$$

$$v_i = v_2 + v_2\,\frac{g_{m1} + g_{mb1} + 1/R}{g_{m1}}$$

$$V_2 = V_i \frac{g_{m1}}{g_{m1} + g_{mb1} + \frac{1}{R}}$$

$$V_1 = V_i \frac{g_{mb1} + 1/R}{g_{m1} + g_{mb1} + \frac{1}{R_1}}$$

$$V_o = \left[(g_{mb1} - g_{m2}) V_2 - g_{m1} V_1 \right] R_L$$

$$\frac{V_o}{V_i} = \frac{(g_{mb1} - g_{m2}) g_{m1} - g_{m1}\left(g_{mb1} + \frac{1}{R}\right)}{\left(g_{m1} + g_{mb1} + \frac{1}{R}\right)} R_L$$

$$= \frac{-g_{m1} g_{m2} - g_{m1} \frac{1}{R}}{g_{m1} + g_{mb1} + \frac{1}{R}} R_L$$

$$\frac{V_o}{V_i} = -g_{m2} R_L \left(\frac{g_{m1} + \frac{g_{m1}}{g_{m2} R}}{g_{m1} + g_{mb1} + \frac{1}{R}} \right)$$

$$\frac{g_{mb1}}{g_{m1}} = \chi = \frac{\gamma}{2\sqrt{2\phi_f + V_{SB}}} = \frac{0.25}{2\sqrt{0.6 + 0.75}}$$

$$g_{m1} = \sqrt{2 K' \frac{W}{L} I_D} = \sqrt{2(200\mu)(10)(0.75m)}$$

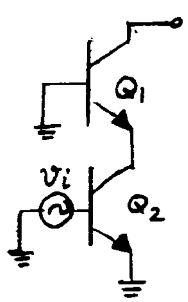
$$\frac{V_o}{V_i} = \frac{-0.25}{26} (1k) \frac{(1.73m)\left(1 + \frac{1}{\frac{0.25}{26} 912}\right)}{(1.73m)(1 + 0.108) + \frac{1}{912}}$$

$$= -9.6\ (0.64) = -6.2$$

```
BICMOS DARLINGTON
VCC  100  0    3
RL   100  2    1K
M1   2    1    4    0    NMOS  W=10U  L=1U
VI   1    0    2.296
Q2   2    4    0    NPN
RB   4    0    1K
.MODEL NMOS NMOS LEVEL=1 VTO=0.6 KP=200U
+ LAMBDA=0 GAMMA=0.25 PHI=0.6
.MODEL NPN NPN IS=1E-16 BF=100 RB=0
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.TF  V(2) VI
.DC  VI   2.2   2.3  0.01
.PLOT     DC   V(2)
.OP
.END
 ******  DC TRANSFER CURVES        TNOM=  27.000 TEMP=  27.000
    VOLT       V(2)
(A        )    1.900E+00     2.000E+00     2.100E+00     2.200E+00     2.300E+00
                   +             +             +             +             +
 2.200E+00 2.28E+00-+------+------+------+------+------+------+------+----A-+-
 2.210E+00 2.27E+00 +      +      +      +      +      +      +      +  A   +
 2.220E+00 2.25E+00 +      +      +      +      +      +      +      +A     +
 2.230E+00 2.24E+00 +      +      +      +      +      +      +     A+      +
 2.240E+00 2.21E+00 +      +      +      +      +      +      +  A   +      +
 2.250E+00 2.19E+00 +      +      +      +      +      +     A+      +      +
 2.260E+00 2.16E+00 +      +      +      +      +      + A    +      +      +
 2.270E+00 2.13E+00 +      +      +      +      +   A  +      +      +      +
 2.280E+00 2.08E+00 +      +      +      +    A +      +      +      +      +
 2.290E+00 2.03E+00 +      +      +    A +      +      +      +      +      +
 2.300E+00 1.97E+00-+------+--A---+------+------+------+------+------+------+-
                    +             +             +             +             +
 ****  OPERATING POINT INFORMATION     TNOM=  27 TEMP=  27
   NODE =VOLTAGE        NODE =VOLTAGE        NODE =VOLTAGE
+0:1     = 2.296E+00 0:2     = 2.000E+00 0:4     = 7.391E-01
+0:100   = 3.000E+00

**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT  0:Q2
MODEL    0:NPN
 IB        2.576E-06
 IC        2.576E-04
 VBE       7.391E-01
 VCE       2.000E+00
 VBC      -1.261E+00
 VS       -2.000E+00
 POWER     5.173E-04
 BETAD     1.000E+02
 GM        9.959E-03
 RPI       1.004E+04
 RX          0.
 RO        1.261E+16
 BETAAC    9.999E+01

**** MOSFETS
SUBCKT
ELEMENT  0:M1
MODEL    0:NMOS
 ID        7.417E-04
 IBS      -7.391E-15
 IBD      -2.001E-14
 VGS       1.556E+00
 VDS       1.261E+00
 VBS      -7.391E-01
 VTH       6.957E-01
 VDSAT     8.612E-01
 BETA      2.000E-03
 GAM EFF   2.500E-01
 GM        1.722E-03
 GDS         0.
 GMB       1.861E-04

 ****      SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(2)/VI                                        = -6.332E+00
INPUT RESISTANCE AT          VI                =  1.000E+20
OUTPUT RESISTANCE AT V(2)                      =  9.999E+02
```

```
BICMOS DARLINGTON
* NONZERO LAMBDA, NONZERO BASE RESISTANCE, AND FINITE VA
VCC  100  0    3
RL   100  2    1K
M1   2    1    4    0    NMOS  W=10U  L=1U
VI   1    0    2.268
Q2   2    4    0    NPN
RB   4    0    1K
.MODEL NMOS NMOS LEVEL=1 VT0=0.6 KP=200U
+ LAMBDA=0.05 GAMMA=0.25 PHI=0.6
.MODEL NPN NPN IS=1E-16 BF=100 RB=100 VA=20
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.TF  V(2) VI
.DC  VI   2.2   2.3  0.01
.PLOT     DC   V(2)
.OP
.END
 ******  DC TRANSFER CURVES      TNOM=  27.000 TEMP=  27.000
   VOLT      V(2)
(A        )    1.600E+00    1.800E+00    2.000E+00    2.200E+00   2.400E+00
                   +            +            +            +           +

 2.200E+00  2.23E+00-+------+------+------+------+------+------+-A----+------+-
 2.210E+00  2.21E+00 +      +      +      +      +      +      +A     +      +
 2.220E+00  2.18E+00 +      +      +      +      +      +     A+      +      +
 2.230E+00  2.16E+00 +      +      +      +      +      +   A  +      +      +
 2.240E+00  2.12E+00 +      +      +      +      +      + A    +      +      +
 2.250E+00  2.08E+00 +      +      +      +      +     A+      +      +      +
 2.260E+00  2.04E+00 +      +      +      +      +  A   +      +      +      +
 2.270E+00  1.98E+00 +      +      +      +     A+      +      +      +      +
 2.280E+00  1.92E+00 +      +      +      + A    +      +      +      +      +
 2.290E+00  1.85E+00 +      +      +   A  +      +      +      +      +      +
 2.300E+00  1.77E+00-+------+----A-+------+------+------+------+------+------+-
                   +            +            +            +           +
 ****  OPERATING POINT INFORMATION      TNOM=  27 TEMP=  27
   NODE =VOLTAGE       NODE =VOLTAGE        NODE =VOLTAGE
+0:1    = 2.268E+00 0:2    = 2.000E+00 0:4     = 7.380E-01
+0:100  = 3.000E+00

**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT  0:Q2
MODEL    0:NPN
 IB        2.438E-06
 IC        2.592E-04
 VBE       7.380E-01
 VCE       2.000E+00
 VBC      -1.262E+00
 VS       -2.000E+00
 POWER     5.204E-04
 BETAD     1.063E+02
 GM        1.001E-02
 RPI       1.060E+04
 RX        1.000E+02
 RO        8.202E+04
 BETAAC    1.061E+02

**** MOSFETS
SUBCKT
ELEMENT  0:M1
MODEL    0:NMOS
 ID        7.404E-04
 IBS      -7.380E-15
 IBD      -2.000E-14
 VGS       1.530E+00
 VDS       1.262E+00
 VBS      -7.380E-01
 VTH       6.955E-01
 VDSAT     8.345E-01
 BETA      2.126E-03
 GAM EFF   2.500E-01
 GM        1.774E-03
 GDS       3.482E-05
 GMB       1.918E-04

****      SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(2)/VI                                  = -5.557E+00
INPUT RESISTANCE AT          VI          =  1.000E+20
OUTPUT RESISTANCE AT V(2)                =  8.802E+02
```

3.13



$$R_i = r_{\pi_1} = \frac{\beta}{g_{m_1}}$$

$$= 200\left(\frac{26\text{ mV}}{250\,\mu\text{A}}\right)$$

$$= 20.8\text{ k}\Omega$$

$$G_m = g_{m_1} = \frac{250\,\mu\text{A}}{26\text{ mV}}$$

$$= \frac{1}{104}\ \text{A/V}$$

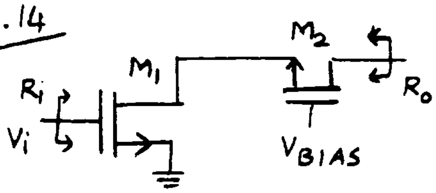
Using the results of 3.5, Q_1 is in effect a current source driving Q_2,

$$R_o = \beta r_{o2} = 200\left(\frac{1}{\eta g_{m_1}}\right)$$

$$= 200\left(\frac{26\text{ mV}}{250\,\mu\text{A}}\right)\left(\frac{1}{2\times10^{-4}}\right)$$

$$= 104\text{ M}\Omega$$

3.14



$R_i \to \infty$

$G_m = g_{m_1} = \sqrt{2(90)(100)(250)}$

$\simeq 2.1 \text{ mA/V}$

$R_o \approx (g_{m_2} + g_{mb_2}) r_{o2} r_{o1}$

$= g_{m_2}(1+\chi) r_{o2} r_{o1}$

$r_{o1} = r_{o2} = \frac{1}{\lambda I} = \frac{10}{250} = 40 \text{ k}\Omega$

$R_o \cong 2.1(1+0.1)(40k)^2 \simeq 3.7 \text{ M}\Omega$

3.15

From (3.133),

$R_o \approx [\, g_{m_2}(a+1) + g_{mb_2}] r_{o1} r_{o2}$

Ignore Body Effect,

$R_o \simeq g_{m_2}(a+1) r_{o1} r_{o2}$

From (1.163),

$V_A = L_{eff} \left(\frac{dX_d}{dV_{DS}} \right)^{-1}$

$L_{eff} = L_{drawn} - 2L_d - X_d$

$= 0.4 - 2(0.09) - (0.1) = 0.12 \mu m$

$V_A = \frac{0.12}{0.02} = 6V$

From (1.194),

$r_{o1} = r_{o2} = r_{o3} = \frac{V_A}{I_D} = \frac{6V}{100 \mu A} = 60 \text{ k}\Omega$

From (1.180)

$g_{m_1} = g_{m_2} = g_3 = \sqrt{2K' \frac{W}{L} I_D}$

$= 2\sqrt{2(194)\left(\frac{10 \mu m}{0.12 \mu m}\right)(100)}$

$\cong 1800 \mu A/V$

$a = g_{m_3} r_{o3} = 1.8 \frac{mA}{V} (60 \text{ k}\Omega)$

$= 108 = g_{m_2} r_{o2}$

$R_o \simeq (g_{m_2} r_{o2})(a+1) r_{o1}$

$= 108(109) 60 \text{ k}\Omega$

$= 706 \text{ M}\Omega$

SPICE gives $R_o = 1.15 \text{ G}\Omega$ for $V_o = 1.0 V$

The main difference between hand calculations and SPICE here stems from the fact that V_A is very small here.

As a result, V_{DS} is not negligible compared to V_A. So, $r_o = \frac{V_A + V_{DS}}{I_D}$ for each transistor

$V_{DS_1} = V_{GS_3} \simeq 0.7 V$

$V_{DS_2} = V_o - V_{DS_1}$

If $V_o = 1.0 V$, $V_{DS_2} \simeq 0.3V$

$V_{DS_3} = V_{GS_2} + V_{GS_3} \simeq 1.4 V$

$r_{o1} = \frac{V_A + V_{DS_1}}{I_{D1}} = \frac{6.7}{100 \mu A} = 67 \text{ K}\Omega$

$r_{o2} = \frac{6.3}{100 \mu A} = 63 \text{ K}\Omega$

$r_{o3} = \frac{7.4}{100 \mu A} = 74 \text{ K}\Omega$

$g_{m_3} r_{o3} = 1.8 \frac{mA}{V} (74K) \cong 133$

$R_o = \left(1.8 \frac{mA}{V}\right)(63)(134)(67K) = 1.02 G\Omega$

```
ACTIVE CASCODE
******

VDD 100 0  3
I   100 3  100U
VI 10   0  0.7053
* THE INPUT VOLTAGE IS ADJUSTED BY TRIAL AND ERROR
* SO THAT ID1 = 100 UA.

VO  2   0  1
* THE OUTPUT VOLTAGE IS BIASED HIGH ENOUGH
* TO OPERATE M1 AND M2 IN THE ACTIVE REGION.

M1  1  10  0  0 CMOSN W=10U L=0.3U
M2  2   3  1  1 CMOSN W=10U L=0.3U
M3  3   1  0  0 CMOSN W=10U L=0.3U
* THE CHANNEL LENGTH IS ENTERRED AS 0.3 MICRONS
* BECAUSE THE DRAWN LENGTH IS 0.4 MICRONS
* AND XD = 0.1 MICRONS
* NOTE THAT CONNECTING THE BODY TO THE SOURCE
* ELIMINATES THE BODY EFFECT.

.MODEL CMOSN NMOS LEVEL=1 LAMBDA=0.1667 KP=194U
+ VTO=0.6 LD=0.09U
*LEFF = LDRWN - 2LD - XD = 0.4 - 2(0.09) - 0.1 = 0.12U
*NOTE THAT LAMBDA = (DXD/DVDS)/LEFF = 0.02/0.12=0.1667

.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.TF V(2) VO
.END

 ****  OPERATING POINT INFORMATION      TNOM=  27 TEMP=  27
   NODE =VOLTAGE        NODE =VOLTAGE        NODE =VOLTAGE
+0:1     = 7.001E-01 0:2     = 1.000E+00 0:3     = 1.408E+00
+0:10    = 7.053E-01 0:100   = 3.000E+00

**** MOSFETS
SUBCKT
ELEMENT  0:M1       0:M2       0:M3
MODEL    0:CMOSN    0:CMOSN    0:CMOSN
 ID       1.001E-04  1.001E-04  1.000E-04
 IBS        0.         0.         0.
 IBD     -7.001E-15 -2.999E-15 -1.409E-14
 VGS      7.053E-01  7.086E-01  7.001E-01
 VDS      7.001E-01  2.999E-01  1.408E+00
 VBS        0.         0.         0.
 VTH      6.000E-01  6.000E-01  6.000E-01
 VDSAT    1.053E-01  1.086E-01  1.001E-01
 BETA     1.805E-02  1.697E-02  1.996E-02
 GAM EFF    0.         0.         0.
 GM       1.901E-03  1.843E-03  1.998E-03
 GDS      1.494E-05  1.589E-05  1.350E-05
 GMB        0.         0.         0.

****      SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(2)/VO                                  =  1.000E+00
INPUT RESISTANCE AT         VO           =  1.157E+09
OUTPUT RESISTANCE AT V(2)                =     0.
```

3.16

From (3.7), $G_m = -\dfrac{a_v}{z_o}$

At low frequency, $z_o \simeq R_o$

From (3.137), $R_o \simeq \dfrac{1}{g_{m1}+g_{mb1}}\left(\dfrac{1}{g_{m2} r_{o1}}\right)$

From (3.141), $a_v \simeq \dfrac{g_{m1}}{g_{m1}+g_{mb1}}$

$$\therefore\ G_m \simeq \frac{-\dfrac{g_{m1}}{g_{m1}+g_{mb1}}}{\dfrac{1}{g_{m1}+g_{mb1}}\left(\dfrac{1}{g_{m2} r_{o1}}\right)} = -(g_{m1} r_{o1})\, g_{m2}$$

From (1.163), $|V_{AP}| = L_{eff}\left(\dfrac{dX_d}{dV_{DS}}\right)^{-1}$

$L_{eff} = L_{drawn} - 2L_d - X_d = 0.4 - 2(0.09) - 0.1$

$= 0.12\ \mu m$

$|V_{AP}| = \dfrac{0.12}{0.04} = 3V$

From (1.194), $r_{o1} = \dfrac{|V_{AP}|}{|I_{D1}|} = \dfrac{3V}{100\ \mu A} = 30\, k\Omega$

$\because I_{D1} = -I_2 = -100\ \mu A$

From (1.180),

$g_{m1} = \sqrt{2 K_p' \dfrac{W_1}{L_1} |I_{D1}|}$

$= \sqrt{2(65)\left(\dfrac{30}{0.12}\right)(100)} = 1800\ \mu A/V$

$g_{m2} = \sqrt{2 K_n' \dfrac{W_2}{L_2} I_{D2}}$

$= \sqrt{2(194)\left(\dfrac{10}{0.12}\right)(100)} = 1800\ \mu A/V$

$(I_{D2} = I_1 - I_2 = 100\ \mu A)$

$G_m = -\left(1800\ \dfrac{\mu A}{V} \times 30\, K\right) 1800\ \dfrac{\mu A}{V}$

$\simeq -(54)\left(1800\ \dfrac{\mu A}{V}\right)$

$= -97.2\ \dfrac{mA}{V}$

3.17

$V_{CC} = I_{D_2}(10K) + V_{BE_2} + V_{GS_2}$

$5 = I_{D_2}(10K) + 0.7 + V_{GS_2}$

$5 = \frac{200\mu}{2}\ \frac{20}{1}\ (V_{GS_2} - 0.6)^2 (10K) + 0.7 + V_{GS_2}$

$5 = 20(V_{GS_2} - 0.6)^2 + 0.7 + V_{GS_2}$

$0 = 20 V_{GS_2}^2 - 23 V_{GS_2} + 2.9$

$V_{GS_2} = \frac{23 \pm \sqrt{(23)^2 - 4 \cdot 20 (2.9)}}{40}$

$= \frac{23 \pm 17.23}{40} = 1.006$ or 0.14 ← Too small for $I_{D_2} > 0$

$I_{D_2} = \frac{200}{2}\ \frac{20}{1}\ (1.006 - 0.6)^2$

$= 330\ \mu A$

$V_{BQ_2} = 5 - I_{D_2}(10K) = 1.7\ V$

$V_{EQ_1} = 1.7 - 0.7 = 1.0\ V$

$I_{RL_1} = \frac{5-1}{1K} = 4\ mA$

$I_{D_1} = \frac{K'}{2}\left(\frac{W}{L}\right)_1 (V_{GS_1} - V_t)^2 = I_{RL_1} + I_{RL_2}$

Assume the dc input is adjusted so that $I_{C_1} = I_{C_2}$. Then,

$V_{CQ_1} = 5 - I_{C_1}(10K) = 5 - 330\mu(10K)$
$= 1.7\ V$

so, Q_1 operates in the forward active region,

$I_{D_1} = \frac{200}{2}\ \frac{300}{1}\ (V_{GS_1} - 0.6)^2$
$= 4\ mA + 330\ \mu A = 4330\ \mu A = I_{D_1}$

$V_{GS_1} = 0.98\ V$

small signal parameters:

$g_m(M_1) = \sqrt{2(200)\frac{300}{1}(4330)}$
$= 22.8\ mA/V$

$g_m(M_2) = \sqrt{2(200)\frac{20}{1}(330)}$
$= 1.62\ \frac{mA}{V} = \frac{1}{615\Omega}$

$g_m(Q_1) = \frac{330\mu A}{26mV} = \frac{1}{79\Omega} = g_m(Q_2)$

$I_{C_3} = \frac{V_o}{1K} = \frac{V_C(Q_1) - V_{BE_3}}{1K}$
$= \frac{1.7 - 0.7}{1K} = 1\ mA$

$g_m(Q_3) = \frac{1\ mA}{26\ mV} = \frac{1}{26\Omega}$

$r_\pi(Q_3) = \frac{\beta}{g_m(Q_3)} = \frac{100}{1/26} = 2.6\ K\Omega$

M_1 converts changes in the input voltage to changes in the drain current of M_1. the conversion constant $= g_m(M_1)$

Let R_{i_1} = resistance looking into the emitter of Q_1.

$R_{i_1} = \frac{1}{g_m(Q_1)} + \frac{1/g_{m_2}(Q_2) + 1/g_{m_2}(M_2)}{\beta}$

$= 79 + \frac{79 + 615}{100} = 86\ \Omega$

Use current divider to find the small signal current flowing from the emitter of Q_1

$= -g_m(M_1) v_i \frac{R_{L_1}}{R_{L_1} + R_{i_1}}$

Then the small-signal collector current of $Q_1 = -g_m(M_1)\,v_i\,\dfrac{R_{L_1}}{R_{L_1}+R_{i_1}}\left(\dfrac{B}{B+1}\right)$

The resistance to small-signal ground at the collector of Q_1

$$= R_{L_2} \,\|\, \left(r_{\pi_3} + (B+1)\,R_{L_3} \right)$$

The gain of emitter follower Q_3

$$= \frac{g_m(Q_3)\,R_{L_3}}{1+g_m(Q_3)\,R_{L_3}}$$

$$\frac{v_o}{v_i} = -g_m(M_1)\frac{R_{L_1}}{R_{L_1}+R_{i_1}}\left(\frac{B}{B+1}\right)\left\{ R_{L_2} \,\|\, \left[r_{\pi_3} + (B+1)R_{L_3} \right] \right\} \times \frac{g_m(Q_3)\,R_{L_3}}{1+g_m(Q_3)\,R_{L_3}}$$

$$= -22.8\,\frac{mA}{V}\left(\frac{1000}{1086}\right)\left(\frac{100}{101}\right)\left\{ 10K \,\|\, \left[2.6K + 101(1K) \right] \right\}\left[\frac{1000/26}{1+\frac{1000}{26}} \right]$$

$$= -184$$

To model velocity saturation, use (1.232)

$$R_{SX_1} = \frac{1}{\mathcal{E}_c k' W_1} = \frac{1}{1.5\times 10^6 (200\mu)(300\mu)} = 11.1\,\Omega$$

$$R_{SX_2} = \frac{1}{\mathcal{E}_c k' W_2} = \frac{1}{1.5\times 10^6 (200\mu)(20\mu)} = 167\,\Omega$$

```
BICMOS AMPLIFIER (WITHOUT VELOCITY SATURATION)
******
VCC   100  0  5
* THE DC INPUT IS ADJUSTED BY TRIAL AND ERROR
*UNTIL THE DC OUTPUT IS ABOUT EQUAL TO THE DC INPUT.
VI    2    0  0.9793
M1    4    2  0  0  NMOS W=300U L=1U
Q1    3    5  4     NPN
Q2    5    5  6     NPN
RF    2    7  30K
RL1   100  4  1K
RL2   100  3  10K
RL3   7    0  1K
RBIAS 100  5  10K
Q3    100  3  7     NPN
M2    6    6  0  0  NMOS W=20U L=1U
.MODEL NMOS NMOS KP=200U LAMBDA=0 VT0=0.6
.MODEL NPN NPN IS=1E-16 BF=100 RB=0
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.TF V(7) VI
.END
```

```
****  OPERATING POINT INFORMATION    TNOM=  27 TEMP=  27
  NODE  =VOLTAGE       NODE  =VOLTAGE       NODE  =VOLTAGE
+0:2    = 9.793E-01 0:3    = 1.756E+00 0:4    = 1.001E+00
+0:5    = 1.746E+00 0:6    = 1.001E+00 0:7    = 9.825E-01
+0:100  = 5.000E+00

**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT  0:Q1       0:Q2       0:Q3
MODEL    0:NPN      0:NPN      0:NPN
 IB      3.147E-06  3.191E-06  9.729E-06
 IC      3.147E-04  3.191E-04  9.729E-04
 VBE     7.443E-01  7.447E-01  7.735E-01
 VCE     7.543E-01  7.447E-01  4.017E+00
 VBC    -9.965E-03  0.        -3.244E+00
 VS     -1.756E+00 -1.746E+00 -5.000E+00
 POWER   2.397E-04  2.400E-04  3.916E-03
 BETAD   1.000E+02  1.000E+02  1.000E+02
 GM      1.217E-02  1.234E-02  3.762E-02
 RPI     8.219E+03  8.106E+03  2.658E+03
 RX      0.         0.         0.
 RO      3.802E+14  2.586E+14  3.244E+16
 BETAAC  9.999E+01  9.999E+01  9.999E+01

**** MOSFETS

SUBCKT
ELEMENT  0:M1       0:M2
MODEL    0:NMOS     0:NMOS
 ID      4.316E-03  3.222E-04
 IBS     0.         0.
 IBD    -1.002E-14 -1.001E-14
 VGS     9.793E-01  1.001E+00
 VDS     1.001E+00  1.001E+00
 VBS     0.         0.
 VTH     6.000E-01  6.000E-01
 VDSAT   3.793E-01  4.014E-01
 BETA    6.000E-02  4.000E-03
 GAM EFF 0.         0.
 GM      2.276E-02  1.606E-03
 GDS     0.         0.
 GMB     0.         0.

****     SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(7)/VI                                   = -1.833E+02
INPUT RESISTANCE AT        VI             =  1.627E+02
OUTPUT RESISTANCE AT V(7)                 =  1.109E+02
```

```
BICMOS AMPLIFIER (WITH VELOCITY SATURATION MODEL)
******
VCC   100  0  5
* THE DC INPUT IS ADJUSTED BY TRIAL AND ERROR
*UNTIL THE DC OUTPUT IS ABOUT EQUAL TO THE DC INPUT.
VI    2    0  1.0242
M1    4    2  11 0  NMOS W=3000U L=1U
RSX1  11   0  11.1
Q1    3    5  4     NPN
Q2    5    5  6     NPN
RF    2    7  30K
RL1   100  4  1K
RL2   100  3  10K
RL3   7    0  1K
RBIAS 100  5  10K
Q3    100  3  7     NPN
M2    6    6  12 0  NMOS W=20U L=1U
RSX2  12   0  167
.MODEL NMOS NMOS KP=200U LAMBDA=0 VT0=0.6
.MODEL NPN NPN IS=1E-16 BF=100 RB=0
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.TF V(7) VI
.END

 ****  OPERATING POINT INFORMATION     TNOM=  27 TEMP=  27
   NODE =VOLTAGE        NODE =VOLTAGE        NODE =VOLTAGE
+0:2    = 1.024E+00 0:3    = 1.797E+00 0:4    = 1.051E+00
+0:5    = 1.795E+00 0:6    = 1.051E+00 0:7    = 1.023E+00
+0:11   = 4.730E-02 0:12   = 5.300E-02 0:100  = 5.000E+00

**** BIPOLAR JUNCTION TRANSISTORS

SUBCKT
ELEMENT  0:Q1        0:Q2        0:Q3
MODEL    0:NPN       0:NPN       0:NPN
 IB       3.101E-06  3.142E-06  1.013E-05
 IC       3.101E-04  3.142E-04  1.013E-03
 VBE      7.439E-01  7.443E-01  7.745E-01
 VCE      7.460E-01  7.443E-01  3.976E+00
 VBC     -2.051E-03   0.        -3.202E+00
 VS      -1.797E+00 -1.795E+00 -5.000E+00
 POWER    2.336E-04  2.362E-04  4.036E-03
 BETAD    1.000E+02  1.000E+02  1.000E+02
 GM       1.199E-02  1.215E-02  3.916E-02
 RPI      8.340E+03  8.231E+03  2.553E+03
 RX        0.          0.          0.
 RO       2.799E+14  2.586E+14  3.202E+16
 BETAAC   9.999E+01  9.999E+01  9.999E+01

**** MOSFETS

SUBCKT
ELEMENT  0:M1        0:M2
MODEL    0:NMOS      0:NMOS
 ID       4.262E-03  3.173E-04
 IBS     -4.730E-16 -5.300E-16
 IBD     -1.052E-14 -1.051E-14
 VGS      9.769E-01  9.983E-01
 VDS      1.004E+00  9.983E-01
 VBS     -4.730E-02 -5.300E-02
 VTH      6.000E-01  6.000E-01
 VDSAT    3.769E-01  3.983E-01
 BETA     6.000E-02  4.000E-03
 GAM EFF   0.          0.
 GM       2.261E-02  1.593E-03
 GDS       0.          0.
 GMB       0.          0.

****      SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(7)/VI                                    = -1.454E+02
INPUT RESISTANCE AT          VI            =  2.048E+02
OUTPUT RESISTANCE AT V(7)                  =  1.101E+02
```

3.18

We first neglect the DC current through the 10 MΩ resistor.

$$A_{dm} = -g_m R_C = -\left(\frac{10\mu A}{26\,mA}\right) 100\,k\Omega$$

$$= -38$$

$$A_{cm} = \frac{-g_m R_C}{1 + 2 g_m R_{TAIL}\left(1+\frac{1}{\beta}\right)}$$

$$= \frac{-38}{1 + 20\times 10^6\left(\frac{10\mu A}{26\,mV}\right)\left(1+\frac{1}{200}\right)} = -0.005$$

$$CMRR = \frac{A_{dm}}{A_{cm}} = 7.6\times 10^3 = 78\ dB$$

$$R_{id} = 2r_\pi = 2\times 200 \times \frac{26\,mV}{10\,\mu A} = 2\times 520K$$

$$= 1.04\ M\Omega$$

$$R_{ic} = r_\pi + 2R_{TAIL}(1+\beta)$$

$$= 520K + 2\times 10^6 \times 201 = 402\ M\Omega$$

```
EMITTER-COUPLED PAIR (DIFFERENTIAL-MODE INPUT)
******
VCC    100  0    5
VEE    200  0    -5
RC1    100  2    100K
RC2    100  5    100K
Q1     2    3    4    NPN
Q2     5    0    4    NPN
ITAIL 4     200  20U
RTAIL 4     200  10MEG
VI     3    0    0
.MODEL NPN NPN BF=200 RB=0
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.TF    V(2, 5)    VI
.OP
.END
 ****  OPERATING POINT INFORMATION     TNOM=  27 TEMP=  27
   NODE =VOLTAGE        NODE =VOLTAGE        NODE =VOLTAGE
+0:2    = 3.983E+00 0:3    =  0.        0:4    =-6.555E-01
+0:5    = 3.983E+00 0:100  = 5.000E+00 0:200  =-5.000E+00
****       SMALL-SIGNAL TRANSFER CHARACTERISTICS
V(2,5)/VI                                  = -3.930E+01
INPUT RESISTANCE AT          VI            =  1.017E+06
OUTPUT RESISTANCE AT V(2,5)                =  2.000E+05

EMITTER-COUPLED PAIR (COMMON-MODE INPUT)
******
VCC    100  0    5
VEE    200  0    -5
RC1    100  2    100K
RC2    100  5    100K
Q1     2    3    4    NPN
Q2     5    13   4    NPN
ITAIL 4     200  20U
RTAIL 4     200  10MEG
VI     3    0    0
ECM    13   0    3    0    1
```

```
.MODEL NPN NPN BF=200 RB=0
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.TF   V(2) VI
.OP
.END
 ****  OPERATING POINT INFORMATION    TNOM=  27 TEMP=  27
   NODE =VOLTAGE       NODE =VOLTAGE       NODE =VOLTAGE
+0:2     = 3.983E+00 0:3     =    0.       0:4     =-6.555E-01
+0:5     = 3.983E+00 0:13    =    0.       0:100   = 5.000E+00
+0:200   =-5.000E+00
****       SMALL-SIGNAL TRANSFER CHARACTERISTICS
V(2)/VI                                    = -4.974E-03
INPUT RESISTANCE AT          VI            =  4.004E+09
OUTPUT RESISTANCE AT V(2)                  =  9.999E+04

EMITTER-COUPLED PAIR (DIFFERENTIAL-MODE INPUT)
* WITH NONZERO RB AND FINITE VA
******
VCC   100   0    5
VEE   200   0    -5
RC1   100   2    100K
RC2   100   5    100K
Q1    2     3    4    NPN
Q2    5     0    4    NPN
ITAIL 4     200  20U
RTAIL 4     200  10MEG
VI    3     0    0
.MODEL NPN NPN BF=200 RB=200 VA=130
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.TF   V(2, 5)   VI
.OP
.END
 ****  OPERATING POINT INFORMATION    TNOM=  27 TEMP=  27
   NODE =VOLTAGE       NODE =VOLTAGE       NODE =VOLTAGE
+0:2     = 3.983E+00 0:3     =    0.       0:4     =-6.548E-01
+0:5     = 3.983E+00 0:100   = 5.000E+00 0:200   =-5.000E+00
****       SMALL-SIGNAL TRANSFER CHARACTERISTICS
V(2,5)/VI                                  = -3.899E+01
INPUT RESISTANCE AT          VI            =  1.048E+06
OUTPUT RESISTANCE AT V(2,5)                =  1.984E+05
```

3.19

With 4 kΩ resistors (emitter degeneration)

$$A_{dm} = \frac{-g_m R_C}{1 + g_m R_E\left(1+\frac{1}{\beta}\right)}$$

$$= \frac{-38}{1 + \left(\frac{10\,\mu A}{26\,mV}\right) 4k \left(1+\frac{1}{200}\right)}$$

$$= -14.9$$

$$A_{cm} = \frac{-g_m R_C}{1 + g_m (4k + 2R_{TAIL})\left(1+\frac{1}{\beta}\right)}$$

$$\simeq -0.005$$

$$CMRR = \frac{A_{dm}}{A_{cm}} = 2980 = 69\,dB$$

```
EMITTER-COUPLED PAIR WITH EMITTER DEGENERATION (DIFF MODE)
VCC   100   0    5
VEE   200   0    -5
RC1   100   2    100K
RC2   100   5    100K
RE1   14    4    4K
RE2   15    4    4K
Q1    2     3    14   NPN
Q2    5     0    15   NPN
ITAIL 4     200  20U
RTAIL 4     200  10MEG
VI    3     0    0
.MODEL NPN NPN BF=200 RB=0
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.TF   V(2, 5)   VI
.END
 ****  OPERATING POINT INFORMATION    TNOM=  27 TEMP=  27
   NODE =VOLTAGE       NODE =VOLTAGE       NODE =VOLTAGE
+0:2     = 3.983E+00 0:3     =    0.       0:4     =-6.964E-01
+0:5     = 3.983E+00 0:14    =-6.555E-01 0:15    =-6.555E-01
+0:100   = 5.000E+00 0:200   =-5.000E+00
****       SMALL-SIGNAL TRANSFER CHARACTERISTICS
V(2,5)/VI                                  = -1.523E+01
INPUT RESISTANCE AT          VI            =  2.624E+06
OUTPUT RESISTANCE AT V(2,5)                =  2.000E+05

EMITTER-COUPLED PAIR WITH EMITTER DEGENERATION (COMMON MODE)
VCC   100   0    5
VEE   200   0    -5
RC1   100   2    100K
RC2   100   5    100K
RE1   14    4    4K
RE2   15    4    4K
Q1    2     3    14   NPN
Q2    5     13   15   NPN
ITAIL 4     200  20U
RTAIL 4     200  10MEG
VI    3     0    0
ECM   13    0    3    0    1
.MODEL NPN NPN BF=200 RB=0
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.TF   V(2) VI
.END
 ****  OPERATING POINT INFORMATION    TNOM=  27 TEMP=  27
   NODE =VOLTAGE       NODE =VOLTAGE       NODE =VOLTAGE
+0:2     = 3.983E+00 0:3     =    0.       0:4     =-6.964E-01
+0:5     = 3.983E+00 0:13    =    0.       0:14    =-6.555E-01
+0:15    =-6.555E-01 0:100   = 5.000E+00 0:200   =-5.000E+00
****       SMALL-SIGNAL TRANSFER CHARACTERISTICS
V(2)/VI                                    = -4.973E-03
INPUT RESISTANCE AT          VI            =  4.005E+09
OUTPUT RESISTANCE AT V(2)                  =  9.999E+04

EMITTER-COUPLED PAIR WITH EMITTER DEGENERATION (DIFF MODE)
* WITH NONZERO RB AND FINITE VA
VCC   100   0    5
VEE   200   0    -5
RC1   100   2    100K
RC2   100   5    100K
RE1   14    4    4K
RE2   15    4    4K
Q1    2     3    14   NPN
Q2    5     0    15   NPN
ITAIL 4     200  20U
RTAIL 4     200  10MEG
VI    3     0    0
.MODEL NPN NPN BF=200 RB=200 VA=130
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.TF   V(2, 5)   VI
.END
 ****  OPERATING POINT INFORMATION    TNOM=  27 TEMP=  27
   NODE =VOLTAGE       NODE =VOLTAGE       NODE =VOLTAGE
+0:2     = 3.983E+00 0:3     =    0.       0:4     =-6.956E-01
+0:5     = 3.983E+00 0:14    =-6.548E-01 0:15    =-6.548E-01
+0:100   = 5.000E+00 0:200   =-5.000E+00
****       SMALL-SIGNAL TRANSFER CHARACTERISTICS
V(2,5)/VI                                  = -1.518E+01
INPUT RESISTANCE AT          VI            =  2.690E+06
OUTPUT RESISTANCE AT V(2,5)                =  1.994E+05
```

3.20

First consider the balanced case in which the 10K resistor is present in the collector of Q_1. For this,

$$I_{C_1} = I_{C_2} = \frac{1}{2}\left(\frac{15V - 0.7V}{10k\Omega}\right) = 0.71\,mA$$

$$A_{dm} = -g_m R_C = -10K\left(\frac{0.71\,mA}{26\,mV}\right)$$

$$= -273$$

$$A_{cm} = \frac{-g_m R_C}{1 + 2g_m R_E(1+\frac{1}{\beta})} \approx \frac{-R_C}{2R_{TAIL}} = -\frac{1}{2}$$

Now, we are applying a signal to the V_{i_1} input, and taking the V_{o2} output only.

$$V_{o2} = V_{oc} - \frac{V_{od}}{2} = A_{cm}V_{ic} - \frac{1}{2}A_{dm}V_{id}$$

$$\text{Now, } V_{ic} = \frac{V_{i_1} + V_{i2}}{2} = \frac{1}{2}V_i$$

$$V_{id} = V_{i_1} - V_{i2} = V_i$$

$$\text{Thus, } V_{o2} = A_{cm}\left(\frac{1}{2}V_i\right) - \frac{1}{2}A_{dm}V_i$$

$$\frac{V_{o2}}{V_i} = \frac{1}{2}(A_{cm} - A_{dm})$$

$$= \frac{1}{2}\left(-\frac{1}{2} - (-273)\right) = 136$$

The common mode input resistance is much larger than the D.M. input resistance, so

$$R_i \approx R_{id} = 2r_\pi = 2\beta\left(\frac{26\,mV}{0.71\,mA}\right)$$

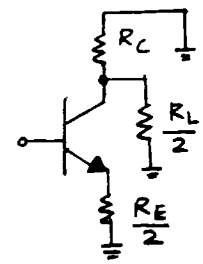
$$\therefore R_i = 14.6\,k\Omega$$

By inspection, if we neglect r_o,

$$R_{OUT} = R_C = 10\,k\Omega$$

3.21

The D.M. Half circuit is :



$$R_{C_{eff}} = R_C \parallel \frac{R_L}{2}$$

$$R_{E_{eff}} = \frac{R_E}{2}$$

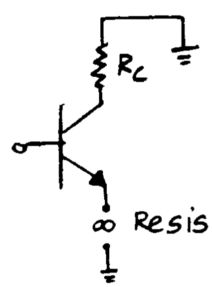
$$A_{dm} = \frac{g_m R_{C_{eff}}}{1 + g_m R_{E_{eff}}(1+\frac{1}{\beta})}$$

$$= \frac{g_m (R_C \parallel \frac{R_L}{2})}{1 + g_m \frac{R_E}{2}(1+\frac{1}{\beta})}$$

Similarly,

$$R_{id} = 2\left[r_\pi + (1+\beta)\frac{R_E}{2}\right]$$

The C.M. half-circuit looks like:



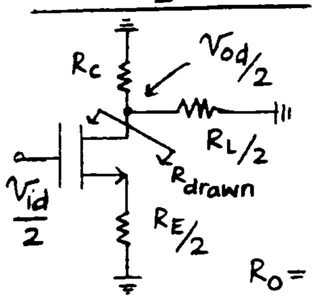
since $R_E = \infty$

$A_{CM} = 0$

$R_{iC} = \infty$

3.22

D.M. ½ circuit :



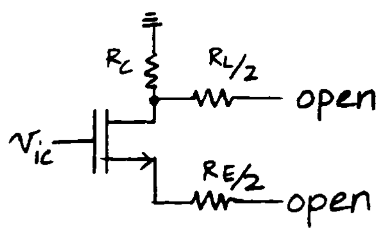
$A_{dm} = -G_m R_o$

$G_m = \dfrac{g_m}{1 + g_m \frac{R_E}{2}}$

$R_o = R_C \parallel \frac{R_L}{2} \parallel \underbrace{R_{drawn}}_{\infty}$

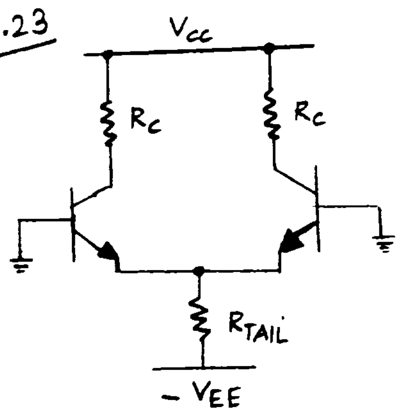
$$A_{dm} = \frac{-g_m (R_C \parallel R_L/2)}{1 + g_m R_E/2}$$

C.M. ½ circuit :



Since the resistance connected to the source → ∞, G_m here = 0 and $A_{cm} = 0$

3.23



For, $R_{id} = 2M\Omega$, $r_\pi = 1\ M\Omega = \dfrac{\beta}{g_m}$

$\therefore\ g_m = \dfrac{\beta}{10^6\Omega} = \dfrac{200}{10^6\Omega} = \dfrac{1}{5\ K\Omega}$

$\therefore\ I_C = V_T/5K\Omega = 5.2\ \mu A$

Now, $A_{dm} = -g_m R_C = -500$

$\therefore\ R_C = 500/\frac{1}{5K\Omega} = 2.5\ M\Omega$

The DC voltage drop across R_C is $I_C R_C = (5.2\times10^{-6})(2.5\times10^{6}) = 13V$

For a transistor V_{CE} of 1 V, when the bases are grounded,

$V_{CB} = V_{CE} - V_{BE} = 0.3\ V$

$\therefore\ V_{CC} = 0.3V + 13V = 13.3V$

$A_{cm} \approx -\dfrac{R_C}{2R_{TAIL}}$; $A_{dm} = -g_m R_C$

$CMRR = \dfrac{A_{dm}}{A_{cm}} = \dfrac{-g_m R_C}{-R_C/2R_{TAIL}} = 2 g_m R_{TAIL}$

For CMRR = 500, $2 g_m R_{TAIL} = 500$

$R_{TAIL} = \dfrac{500}{2(1/5k)} = 1.25\ M\Omega$

since $I_{C_1} + I_{C_2} = 10.4\ \mu A$, the voltage drop in R_{TAIL} is :

$(I_{C_1} + I_{C_2}) R_{TAIL} = 10.4 \times 1.25 = 13\ V$

and $V_{EE} = 13 + V_{BE} = 13.7\ V$

3.24

From Table (2.4),

$$\mu_n C_{ox} = 450 \times \frac{3.9 \times 8.854 \times 10^{-14}}{0.08 \times 10^{-5}}$$

$$= 194\ \mu A/V^2 = k'$$

$$\Delta I_d = 0.85\ I_{TAIL}$$

$$= \frac{k'}{2}\frac{W}{L_{eff}}(0.2)\sqrt{\frac{2I_{TAIL}}{\frac{k'}{2}\frac{W}{L_{eff}}} - (0.2)^2} \rightarrow ①$$

Also, $G_m = 1.0\ \frac{mA}{V} = \sqrt{I_{TAIL}k'\frac{W}{L_{eff}}}$

$$\Rightarrow k'\frac{W}{L_{eff}} = \frac{1 \times 10^{-6}\ A/V^2}{I_{TAIL}} \rightarrow ②$$

substituting ② in ①,

$$0.85\ I_{TAIL} = \frac{1 \times 10^{-6}}{2 I_{TAIL}}(0.2)\sqrt{\frac{2I_{TAIL}}{\frac{k'}{2}\frac{W}{L_{eff}}} - (0.2)^2}$$

Solve for I_{TAIL}^2:

$$7.225 \times 10^{13} I_{TAIL}^4 - 4 \times 10^6 I_{TAIL}^2 + 0.04 = 0$$

$$I_{TAIL}^2 = \sqrt{\frac{4 \times 10^6 \pm (4 \times 10^6)^2 - 4(7.225 \times 10^{13})(0.04)}{2(7.225 \times 10^{13})}}$$

$$= 2.768 \times 10^{-8} \pm 1.458 \times 10^{-8}$$

$$I_{TAIL}^2 = 4.226 \times 10^{-8} \text{ or } 1.310 \times 10^{-8}$$

$$I_{TAIL} = 205.6\ \mu A \text{ or } 114.4\ \mu A$$

If $I_{TAIL} = 205.6\ \mu A$,

$$\frac{W}{L_{eff}} = \frac{1 \times 10^{-6}}{194 \times 10^{-6}(205.6 \times 10^{-6})} = 25.1$$

$$V_{OV} = \sqrt{\frac{205.6}{194(25)}} = 0.206\ V$$

If $I_{TAIL} = 114.4\ \mu A$,

$$\frac{W}{L_{eff}} = \frac{1 \times 10^{-6}}{194 \times 10^{-6}(114.4 \times 10^{-6})} = 45.0$$

$$V_{OV} = \sqrt{\frac{114.4}{194(45)}} = 0.114\ V$$

This overdrive is too small because the range would be only $\pm\sqrt{2}(0.14)$ which is 162 mV which is less than the 200 mV input.

$$L_{eff} = L_{drawn} - 2L_d - X_d = 1\ \mu m - 2(0.09) - 0$$

$$= 0.82\ \mu m$$

$$\Rightarrow \frac{W}{L_{eff}} = \frac{W}{0.82\ \mu m} = 25.1$$

$$\Rightarrow W = 20.6\ \mu m\ ;\ I_{TAIL} = 205.6\ \mu A$$

3.25

For the emitter coupled pair, using (3.216),

$$|V_{OS}| = V_T\left(\frac{\Delta I_S}{I_S} + \frac{\Delta R_C}{R_C}\right)$$

But, for uniform-base transistor,

$$\left|\frac{\Delta I_S}{I_S}\right| = \left|\frac{\Delta W_B}{W_B}\right|$$

Thus, in this case,

$$|V_{OS}| = V_T\left(\frac{\Delta W_B}{W_B}\right) = 26\ mV \times 0.1$$

$$= 2.6\ mV$$

3.26

From (3.248),

$$V_{os} = \Delta V_t + \frac{(V_{GS}-V_t)}{2}\left(-\frac{\Delta R_L}{R_L} - \frac{\Delta(W/L)}{W/L}\right)$$

$$V_{GS}-V_t = \sqrt{\frac{I_{TAIL}}{k' \, W/L_{eff}}}$$

$$k' = \frac{450 \times 3.39 \times 8.86 \times 10^{-14}}{80 \times 10^{-8}} = 194 \ \mu A/V^2$$

$$L_{eff} = 1-2(0.09) = 0.82 \ \mu m$$

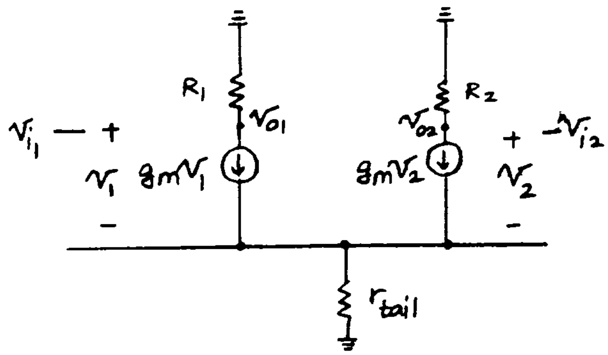
$$V_{GS}-V_t = \sqrt{\frac{50 \mu}{194 \mu \left(\frac{10}{0.82}\right)}} = 0.145$$

If $(W/L)_1 > (W/L)_2$, $V_{os} < 0$

since we don't know whether $(W/L)_1 > (W/L)_2$ or $(W/L)_2 > (W/L)_1$, we can only calculate the magnitude of V_{os}

$$|V_{os}| = 0 + \frac{0.145}{2}(0 + 0.02) = 1.45 \ mV$$

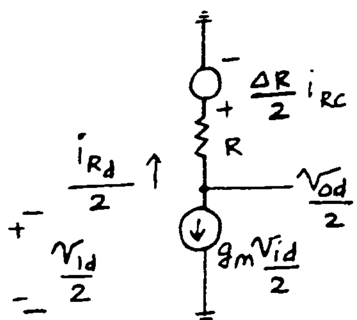
3.27



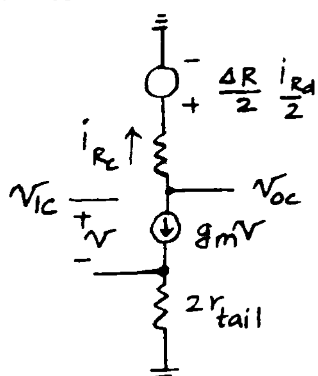
Let $R = \dfrac{R_1 + R_2}{2}$

$\Delta R = R_1 - R_2$

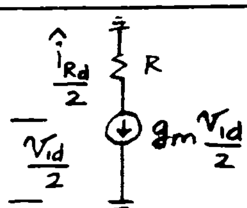
Exact D.M. ½ circuit:



Exact C.M. ½ circuit :

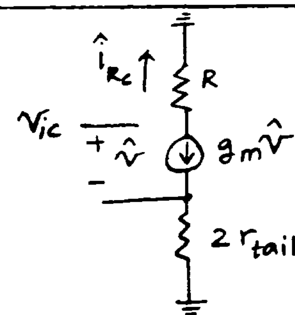


D.M. ½ circuit without mismatch:



$$\frac{\hat{i}_{Rd}}{2} = -g_m \frac{v_{id}}{2}$$

C.M. ½ circuit without mismatch:



$$\hat{i}_{Rc} = \frac{-g_m v_{ic}}{1 + 2 g_m r_{tail}}$$

From exact ½ circuits ;

$$v_{od} = \frac{\Delta R}{2} i_{Rc} + R \frac{i_{Rd}}{2} \simeq \frac{\Delta R}{2} \hat{i}_{Rc} + R \frac{\hat{i}_{Rd}}{2}$$

$$= -\frac{\Delta R}{2} \frac{g_m v_{ic}}{1 + 2 g_m r_{tail}} - R \frac{g_m v_{id}}{2}$$

$$\therefore \; A_{dm} \simeq -g_m R = -1(10) = -10$$

$$A_{cm\text{-}dm} \simeq \frac{-g_m \Delta R}{1 + 2 g_m r_{tail}} = \frac{-1(0.2)}{1 + 2(1)(1000)}$$

$$= -1 \times 10^{-4}$$

$$v_{oc} = \frac{\Delta R}{2} \frac{i_{Rd}}{2} + R i_{Rc} \simeq \frac{\Delta R}{2} \frac{\hat{i}_{Rd}}{2} + R \hat{i}_{Rc}$$

$$= -\frac{\Delta R}{2} g_m \frac{v_{id}}{2} - \frac{R g_m v_{ic}}{1 + 2 g_m r_{tail}}$$

$$\therefore \; A_{dm\text{-}cm} \simeq -\frac{g_m \Delta R}{4} = \frac{-1(0.2)}{4}$$

$$= -0.05$$

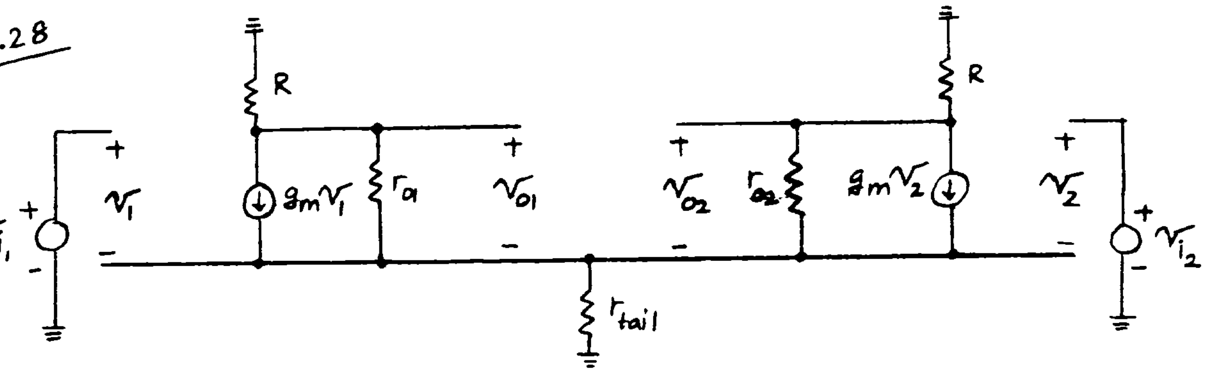
$$A_{cm} = \frac{-g_m R}{1 + 2 g_m r_{tail}} = \frac{-1(10)}{1 + 2(1)(1000)} \simeq -0.005$$

$$\frac{A_{dm}}{A_{cm}} \simeq \frac{10}{0.005} = 2000$$

$$\frac{A_{dm}}{A_{cm\text{-}dm}} \simeq \frac{10}{1 \times 10^{-4}} = 100{,}000$$

$$\frac{A_{dm}}{A_{dm\text{-}cm}} \simeq \frac{10}{0.05} = 200$$

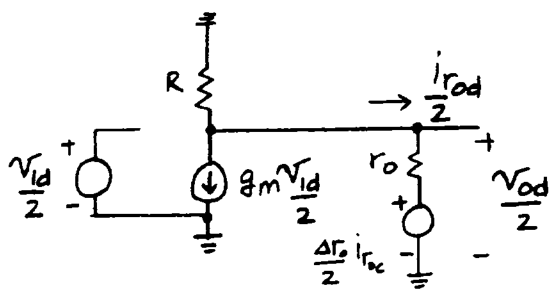
3.28



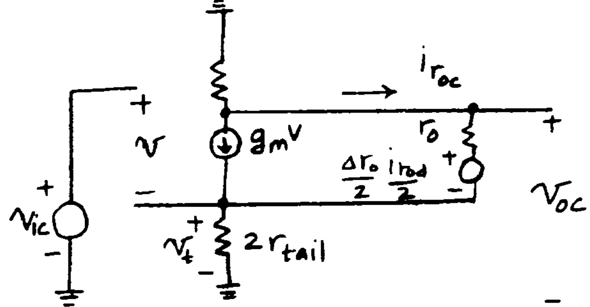
Let $r_o = \dfrac{r_{o1} + r_{o2}}{2}$

$\Delta r_o = r_{o1} - r_{o2}$

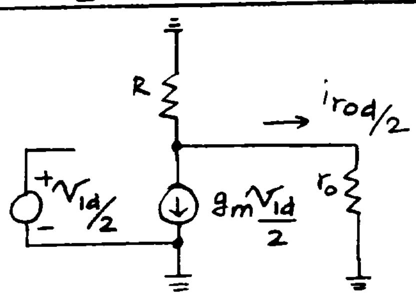
Exact D.M. ½ circuit:



Exact C.M. ½ circuit:

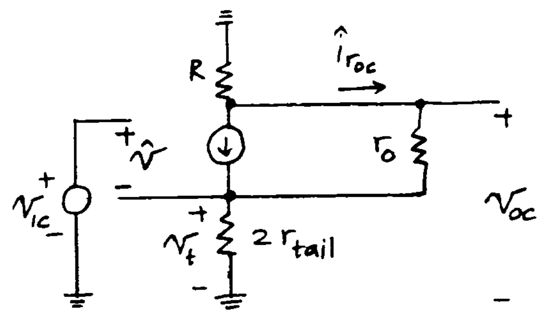


D.M. ½ circuit without mismatch:



$$\frac{\hat{i}_{rod}}{2} = -g_m \frac{v_{id}}{2}\left(\frac{R}{R + r_o}\right)$$

C.M. ½ circuit without mismatch:



The bottom of the CM ½ circuit is essentially a source follower, since $g_m(2r_{tail}) \gg 1$, $v_t \approx v_{ic}$. Also, the current that flows in R is equal to the current that flows in $2r_{tail}$. So,

$$\frac{-v_{oc}}{R} = \frac{v_t}{2r_{tail}}$$

$$\hat{i}_{roc} = \frac{v_{oc} - v_t}{r_o} = \frac{-v_t\left(\frac{R}{2r_{tail}} + 1\right)}{r_o}$$

$$\approx -v_t/r_o = -v_{ic}/r_o$$

From exact D.M. ½ circuit,

$$\frac{v_{od}}{2} = \frac{\Delta r_o}{2}\, i_{roc} \frac{R}{R+r_o} + \frac{i_{rod}\, r_o}{2}$$

$$\approx \frac{\Delta r_o}{2}\, \hat{i}_{roc} \frac{R}{R+r_o} + \frac{\hat{i}_{rod}\, r_o}{2}$$

$$\approx \frac{\Delta r_o}{2}\left(\frac{-v_{ic}}{r_o}\right) \frac{R}{R+r_o} - g_m \frac{v_{id}}{2} \frac{R}{R+r_o}\, r_o$$

$$A_{dm} = \frac{v_{od}}{v_{id}} = -g_m r_o \frac{R}{R+r_o} = 1m\,(500k)\left(\frac{10}{510}\right)$$

$$= -9.8$$

$$A_{cm\text{-}dm} = \frac{v_{od}}{v_{ic}} = -\frac{\Delta r_o}{r_o} \frac{R}{R+r_o} = \frac{-10k}{500k}\, \frac{10}{510}$$

$$= -3.9 \times 10^{-4}$$

From exact C.M. ½ circuit,

Use superposition,

First, set $i_{rod} = 0$,

$$v_{oc} = \frac{-R}{2 r_{tail}} v_t \approx \frac{-R}{2 r_{tail}} v_{ic}$$

$$A_{cm} = \frac{v_{oc}}{v_{ic}} \approx \frac{-R}{2 r_{tail}} = \frac{-10}{2000} = -0.005$$

Second, set $v_{ic} = 0$,

From KCL (with $v = 0 - v_t$)

$$g_m v_t + \frac{v_t}{2 r_{tail}} + \frac{v_t + \frac{\Delta r_o}{2} \frac{i_{rod}}{2} - v_{oc}}{r_o} = 0$$

$$v_t \underbrace{\left(g_m + \frac{1}{2 r_{tail}} + \frac{1}{r_o}\right)}_{\approx\, g_m} + \frac{\Delta r_o}{r_o} \frac{i_{rod}}{4} - \frac{v_{oc}}{r_o} = 0$$

Also, $v_t = -\frac{2 r_{tail}}{R} v_{oc}$

$$\frac{\Delta r_o}{r_o} \frac{i_{rod}}{4} = \frac{v_{oc}}{r_o} + \frac{2 r_{tail}}{R} g_m v_{oc}$$

Use $i_{rod} \approx \hat{i}_{rod} = -g_m v_{id} \frac{R}{R+r_o}$

$$\frac{\Delta r_o}{r_o}\left(-g_m \frac{v_{id}}{4} \frac{R}{R+r_o}\right) = v_{oc}\left(\frac{1}{r_o} + \frac{2 r_{tail}}{R} g_m\right)$$

$$\approx v_{oc} \frac{2 r_{tail}}{R} g_m$$

$$A_{dm\text{-}cm} = \frac{v_{oc}}{v_{id}} \approx \frac{-1}{4} \frac{\Delta r_o}{r_o} \frac{R}{R+r_o} \frac{R}{2 r_{tail}}$$

$$= \frac{-1}{4}\, \frac{10}{500}\, \frac{10}{510}\, \frac{10}{2000}$$

$$= -4.9 \times 10^{-7}$$

As $r_{tail} \to \infty$

$$A_{dm} = -g_m r_o \left(\frac{R}{R+r_o}\right) = -9.8$$

$$A_{cm\text{-}dm} = \frac{-\Delta r_o}{r_o} \frac{R}{R+r_o} = -3.9 \times 10^{-4}$$

Both of these values are unchanged from the case with finite r_{tail}

$$A_{cm} \approx \frac{-R}{2 r_{tail}} = 0 \text{ as } r_{tail} \to \infty$$

$$A_{dm\text{-}cm} \approx -\frac{1}{4} \frac{\Delta r_o}{r_o} \frac{R}{R+r_o} \frac{R}{2 r_{tail}}$$

$$= 0 \text{ as } r_{tail} \to \infty$$

CHAPTER 4

4.1

Assume

(1) All transistors are identical

$I_{S_1} = I_{S_2} = I_{S_3} = I_{S_4} = I_{S_5} = I_S$

(2) $V_{BE(on)} = 0.7\text{ V}$

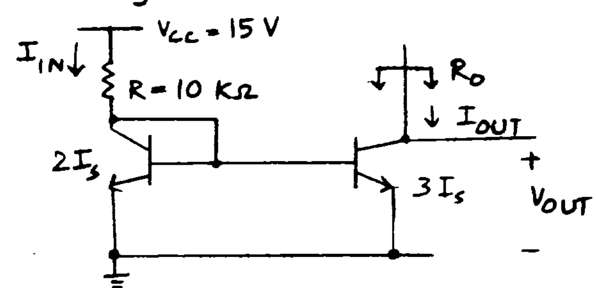
(3) $V_A = 130\text{ V}$

(4) $\beta_F \to \infty$ (to ignore base currents)

Transistors Q_1 and Q_2 operate in parallel and can be replaced by one equivalent transistor Q_A with a saturation current of $2I_S$

Similarly, transistors Q_3-Q_5 operate in parallel and can be replaced by one equivalent transistor Q_B with a saturation current of $3I_S$.

Redrawing the circuit,



From (4.8) with $\beta_F \to \infty$

$$I_{OUT} = \frac{I_{SB}}{I_{SA}} I_N \left(1 + \frac{V_{CEB} - V_{CEA}}{V_A}\right)$$

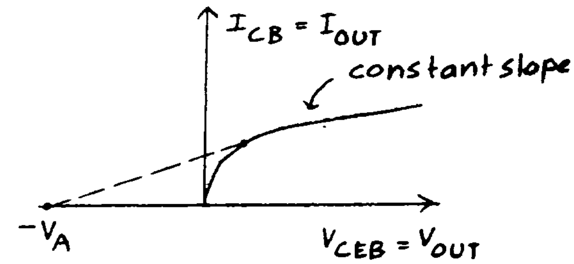
$$I_{IN} = \frac{15 - 0.7}{10\text{ K}} = 1.43\text{ mA}$$

$$I_{OUT} = \frac{3I_S}{2I_S}(1.43\text{ mA})\left(1 + \frac{V_{OUT} - 0.7}{130}\right)$$

$$I_{OUT}(V_{OUT} = 1\text{V}) = \frac{3}{2}(1.43)\left(1 + \frac{0.3}{130}\right) = 2.15\text{ mA}$$

$$I_{OUT}(V_{OUT} = 5\text{V}) = \frac{3}{2}(1.43)\left(1 + \frac{4.3}{130}\right) = 2.22\text{mA}$$

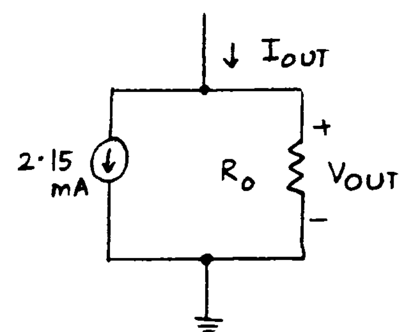
$$I_{OUT}(V_{OUT} = 30\text{V}) = \frac{3}{2}(1.43)\left(1 + \frac{29.3}{130}\right) = 2.63\text{ mA}$$



$$R_o = r_{oB} = \frac{1}{\text{slope}} = \frac{V_A + V_{CEB}}{I_{CB}}$$

$$\simeq \frac{V_A}{I_{OUT}(V_{OUT} = 1\text{V})} = \frac{130}{2.15\text{ mA}} = 60.5\text{ k}\Omega$$

We can model the output of the current mirror as,



```
SIMPLE CURRENT MIRROR SIMULATION (IGNORE BASE CURRENTS)
VCC 100 0  15
R   100 1  10K
Q1  1   1  0   NPN
Q2  1   1  0   NPN
Q3  2   1  0   NPN
Q4  2   1  0   NPN
Q5  2   1  0   NPN
VO  2   0  1
.MODEL NPN NPN BF=10000 VAF=130
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.DC VO 1 30 1
.PLOT I(VO)
.TF V(2) VO
.END

 ******  DC TRANSFER CURVES      TNOM=  27.000 TEMP=  27.000
   VOLT      I(VO)
(A      )      -2.800E-03    -2.600E-03    -2.400E-03    -2.200E-03    -2.000E-03
                    +             +             +             +             +
1.000E+00 -2.14E-03-+------+------+------+------+------+------+---A--+------+-
2.000E+00 -2.15E-03 +      +      +      +      +      +      +  A   +      +
3.000E+00 -2.17E-03 +      +      +      +      +      +      + A    +      +
4.000E+00 -2.19E-03 +      +      +      +      +      +      +A     +      +
5.000E+00 -2.20E-03 +      +      +      +      +      +      A      +      +
6.000E+00 -2.22E-03 +      +      +      +      +      +     A+      +      +
7.000E+00 -2.24E-03 +      +      +      +      +      +   A  +      +      +
8.000E+00 -2.25E-03 +      +      +      +      +      +  A   +      +      +
9.000E+00 -2.27E-03 +      +      +      +      +      + A    +      +      +
1.000E+01 -2.29E-03 +      +      +      +      +      +A     +      +      +
1.100E+01 -2.30E-03-+------+------+------+------+------A------+------+------+-
1.200E+01 -2.32E-03 +      +      +      +      +     A+      +      +      +
1.300E+01 -2.34E-03 +      +      +      +      +   A  +      +      +      +
1.400E+01 -2.35E-03 +      +      +      +      +  A   +      +      +      +
1.500E+01 -2.37E-03 +      +      +      +      + A    +      +      +      +
1.600E+01 -2.38E-03 +      +      +      +      +A     +      +      +      +
1.700E+01 -2.40E-03 +      +      +      +      A      +      +      +      +
1.800E+01 -2.42E-03 +      +      +      +     A+      +      +      +      +
1.900E+01 -2.43E-03 +      +      +      +    A +      +      +      +      +
2.000E+01 -2.45E-03 +      +      +      +  A   +      +      +      +      +
2.100E+01 -2.47E-03-+------+------+------+-A----+------+------+------+------+-
2.200E+01 -2.48E-03 +      +      +      +A     +      +      +      +      +
2.300E+01 -2.50E-03 +      +      +      A      +      +      +      +      +
2.400E+01 -2.52E-03 +      +      +     A+      +      +      +      +      +
2.500E+01 -2.53E-03 +      +      +    A +      +      +      +      +      +
2.600E+01 -2.55E-03 +      +      +  A   +      +      +      +      +      +
2.700E+01 -2.57E-03 +      +      + A    +      +      +      +      +      +
2.800E+01 -2.58E-03 +      +      +A     +      +      +      +      +      +
2.900E+01 -2.60E-03 +      +      A      +      +      +      +      +      +
3.000E+01 -2.61E-03 +      +     A+      +      +      +      +      +      +
                    +             +             +             +             +

 ****  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
   NODE     =VOLTAGE       NODE     =VOLTAGE       NODE     =VOLTAGE
+0:1        = 7.654E-01 0:2         = 1.000E+00 0:100       = 1.500E+01

**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT  0:Q1       0:Q2       0:Q3       0:Q4       0:Q5
MODEL    0:NPN      0:NPN      0:NPN      0:NPN      0:NPN
 IB      7.116E-08  7.116E-08  7.116E-08  7.116E-08  7.116E-08
 IC      7.116E-04  7.116E-04  7.128E-04  7.128E-04  7.128E-04
 VBE     7.654E-01  7.654E-01  7.654E-01  7.654E-01  7.654E-01
 VCE     7.654E-01  7.654E-01  1.000E+00  1.000E+00  1.000E+00
 VBC     0.         0.        -2.346E-01 -2.346E-01 -2.346E-01
 VS     -7.654E-01 -7.654E-01 -1.000E+00 -1.000E+00 -1.000E+00
 POWER   5.447E-04  5.447E-04  7.129E-04  7.129E-04  7.129E-04
 BETAD   9.999E+03  9.999E+03  1.001E+04  1.001E+04  1.001E+04
 GM      2.751E-02  2.751E-02  2.756E-02  2.756E-02  2.756E-02
 RPI     3.634E+05  3.634E+05  3.634E+05  3.634E+05  3.634E+05
 RX      0.         0.         0.         0.         0.
 RO      1.827E+05  1.827E+05  1.827E+05  1.827E+05  1.827E+05
 BETAAC  9.998E+03  9.998E+03  1.001E+04  1.001E+04  1.001E+04

****      SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(2)/VO                                   =  1.000E+00
INPUT RESISTANCE AT        VO             =  6.090E+04
```

4.2

Assume

(1) All transistors are identical

$$I_{S_1} = I_{S_2} = I_{S_3} = I_{S_4} = I_{S_5} = I_S$$

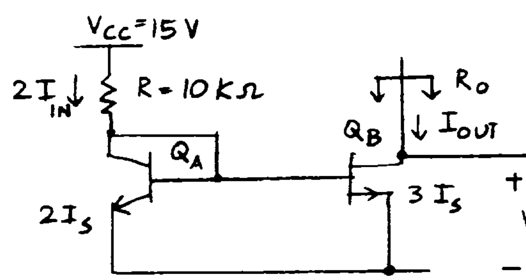
(2) $V_{BE(on)} = 0.7\text{ V}$

(3) $V_A = 130\text{ V}$

(4) $\beta_F = 200$

Transistors Q_1 and Q_2 operate in parallel and can be replaced by an equivalent transistor with a saturation current of $2I_S$. Similarly, transistors Q_3-Q_5 operate in parallel and can be replaced by an equivalent transistor Q_B with a saturation current of $3I_S$.

Redrawing the circuit,



$$I_{IN} = \frac{15-0.7}{10\text{ k}} = 1.43\text{ mA}$$

From (4.8),

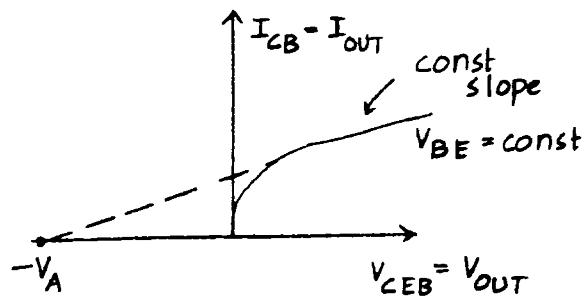
$$I_{OUT} = \frac{\dfrac{I_{SB}}{I_{SA}} I_{IN}\left(1 + \dfrac{V_{CEB}-V_{CEA}}{V_A}\right)}{1 + \dfrac{1 + I_{SB}/I_{SA}}{\beta_F}}$$

$$I_{OUT} = \frac{\frac{3}{2}(1.43\text{ mA})\left(1 + \dfrac{V_{OUT}-0.7}{130}\right)}{1 + \dfrac{1+3/2}{200}}$$

$I_{OUT}(V_{OUT}=1V) = 2.12\ mA$

$I_{OUT}(V_{OUT}=5V) = 2.19\ mA$

$I_{OUT}(V_{OUT}=30V) - 2.60\ mA$

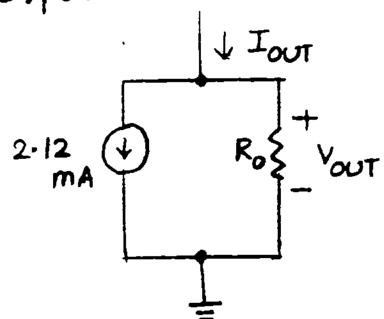


$R_O = r_{OB} = 1/slope$

$= \dfrac{V_A + V_{CEB}}{I_C} \approx \dfrac{V_A}{I_{OUT}}$

$\approx \dfrac{130}{2.12\ mA} = 61.3\ k\Omega$

output model:




```
SIMPLE CURRENT MIRROR SIMULATION (INCLUDE BASE CURRENTS)
******
VCC 100 0  15
R   100 1  10K
Q1  1   1  0   NPN
Q2  1   1  0   NPN
Q3  2   1  0   NPN
Q4  2   1  0   NPN
Q5  2   1  0   NPN
VO  2   0  1
.MODEL NPN NPN BF=200 VAF=130
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.DC VO 1 30 1
.PLOT I(VO)
.TF V(2) VO
.END

******  DC TRANSFER CURVES      TNOM=  27.000 TEMP=  27.000
   VOLT       I(VO)
(A       )    -2.600E-03   -2.400E-03   -2.200E-03   -2.000E-03   -1.800E-03
                  +            +            +            +            +
1.000E+00 -2.11E-03-+------+------+------+------+-----A+-----+------+------+-
2.000E+00 -2.13E-03 +      +      +      +      +    A +     +      +      +
3.000E+00 -2.15E-03 +      +      +      +      +   A  +     +      +      +
4.000E+00 -2.16E-03 +      +      +      +      +  A   +     +      +      +
5.000E+00 -2.18E-03 +      +      +      +      + A    +     +      +      +
6.000E+00 -2.19E-03 +      +      +      +      A      +     +      +      +
7.000E+00 -2.21E-03 +      +      +      +     A+      +     +      +      +
8.000E+00 -2.23E-03 +      +      +      +    A +      +     +      +      +
9.000E+00 -2.24E-03 +      +      +      +   A  +      +     +      +      +
1.000E+01 -2.26E-03 +      +      +      +  A   +      +     +      +      +
1.100E+01 -2.27E-03-+------+------+------+-A----+------+-----+------+------+-
1.200E+01 -2.29E-03 +      +      +      +A     +      +     +      +      +
1.300E+01 -2.31E-03 +      +      +     A+      +      +     +      +      +
1.400E+01 -2.32E-03 +      +      +    A +      +      +     +      +      +
1.500E+01 -2.34E-03 +      +      +   A  +      +      +     +      +      +
1.600E+01 -2.36E-03 +      +      +  A   +      +      +     +      +      +
1.700E+01 -2.37E-03 +      +      + A    +      +      +     +      +      +
1.800E+01 -2.39E-03 +      +      +A     +      +      +     +      +      +
1.900E+01 -2.40E-03 +      +      A      +      +      +     +      +      +
2.000E+01 -2.42E-03 +      +     A+      +      +      +     +      +      +
2.100E+01 -2.44E-03-+------+---A--+------+------+------+-----+------+------+-
2.200E+01 -2.45E-03 +      +  A   +      +      +      +     +      +      +
2.300E+01 -2.47E-03 +      + A    +      +      +      +     +      +      +
2.400E+01 -2.49E-03 +      +A     +      +      +      +     +      +      +
2.500E+01 -2.50E-03 +      A      +      +      +      +     +      +      +
2.600E+01 -2.52E-03 +     A+      +      +      +      +     +      +      +
2.700E+01 -2.53E-03 +    A +      +      +      +      +     +      +      +
2.800E+01 -2.55E-03 +  A   +      +      +      +      +     +      +      +
2.900E+01 -2.57E-03 + A    +      +      +      +      +     +      +      +
3.000E+01 -2.58E-03 +A     +      +      +      +      +     +      +      +
                  +            +            +            +            +
 ****  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
   NODE      =VOLTAGE        NODE      =VOLTAGE        NODE      =VOLTAGE
+0:1         = 7.651E-01 0:2           = 1.000E+00 0:100         = 1.500E+01

**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT  0:Q1        0:Q2        0:Q3        0:Q4        0:Q5
MODEL    0:NPN       0:NPN       0:NPN       0:NPN       0:NPN
 IB       3.515E-06   3.515E-06   3.515E-06   3.515E-06   3.515E-06
 IC       7.030E-04   7.030E-04   7.042E-04   7.042E-04   7.042E-04
 VBE      7.651E-01   7.651E-01   7.651E-01   7.651E-01   7.651E-01
 VCE      7.651E-01   7.651E-01   1.000E+00   1.000E+00   1.000E+00
 VBC       0.          0.        -2.349E-01  -2.349E-01  -2.349E-01
 VS      -7.651E-01  -7.651E-01  -1.000E+00  -1.000E+00  -1.000E+00
 POWER    5.405E-04   5.405E-04   7.069E-04   7.069E-04   7.069E-04
 BETAD    2.000E+02   2.000E+02   2.003E+02   2.003E+02   2.003E+02
 GM       2.717E-02   2.717E-02   2.722E-02   2.722E-02   2.722E-02
 RPI      7.358E+03   7.358E+03   7.358E+03   7.358E+03   7.358E+03
 RX        0.          0.          0.          0.          0.
 RO       1.849E+05   1.849E+05   1.849E+05   1.849E+05   1.849E+05
 BETAAC   1.999E+02   1.999E+02   2.003E+02   2.003E+02   2.003E+02

****      SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(2)/VO                                      =   1.000E+00
INPUT RESISTANCE AT         VO               =   6.164E+04
```

4.3

From Table (2.4),

$$k' = \mu_n C_{ox}$$
$$= \frac{450 \times 3.9 \times 8.86 \times 10^{-14}}{0.08 \times 10^{-5}}$$
$$= 194\ \mu A/V^2$$

$$I_{OUT} = 50\ \mu A\,(1 + \lambda \Delta V_{DS})$$

From condition (c), $\lambda \Delta V_{DS} \leq 0.01$

and $\Delta V_{DS} = 1V \Rightarrow \lambda \leq 0.01\ V^{-1}$

From conditions (a) and (b)

$$50\ \mu A = \frac{k'}{2} \frac{W}{L_{eff}} (V_{GS} - V_t)^2 \text{ where}$$

$$V_{GS} - V_t = 0.2\ V$$

$$50\ \mu = \frac{194}{2} \frac{W}{L_{eff}} (0.2)^2 \Rightarrow \frac{W}{L_{eff}} = 12.9$$

$\lambda \leq \frac{1}{100V}$; Also from the table

$$\frac{dX_d}{dV_{DS}} = 0.02\ \mu m/V$$

$$\lambda = \frac{1}{V_A} = \frac{dX_d/dV_{DS}}{L_{eff}} \leq \frac{1}{100V}$$

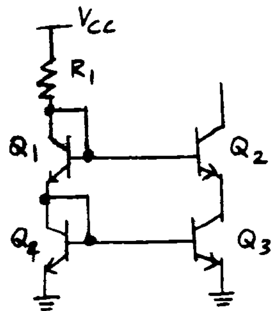
$$\Rightarrow L_{eff} \geq 2\ \mu m$$

$$L_{drawn} = 2\ \mu m + 2(0.09) = 2.18\ \mu m$$
$$\approx 2.2\ \mu m$$

The minimum length that satisfies the constraints minimizes the required gate area

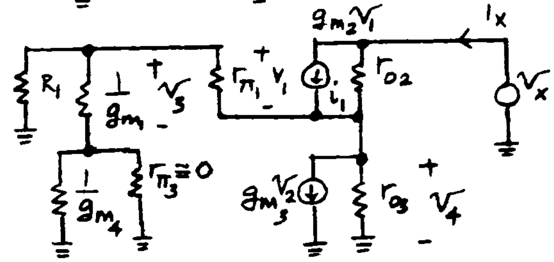
Then $W = 12.9 \times 2.2\ \mu m = 28\ \mu m$

4.4



$$\frac{1}{g_{m_4}} \| r_{\pi_3} \approx \frac{1}{g_{m_4}}$$

assume $r_{\pi_3} \cong 0$



$$i_1 = \frac{V_4}{r_{\pi_1} + R_1 \| \frac{2}{g_{m_1}}} = \frac{V_4}{R}$$

$$I_{C_1} = I_{C_2} = I_{C_3} = I_{C_4}$$

$$g_{m_1} = g_{m_2} = g_{m_3} = g_{m_4} = g_m$$

$$r_{o1} = r_{o2} = r_{o3} = r_{o4} = r_o$$

$$V_2 = i_1 \frac{R_1}{R_1 + \frac{2}{g_m}} \cdot \frac{1}{g_m} = K i_1 \frac{1}{g_m}$$

$$V_1 = -i_1 r_{\pi_1}$$

$$g_{m_2} V_1 + \frac{V_x - V_4}{r_{o2}} = i_1 + \frac{V_4}{r_{o3}} + g_{m_3} V_2$$
$$= i_1 + \frac{V_4}{r_{o3}} + k i_1$$

$$-\beta i_1 + \frac{V_x}{r_o} - \frac{V_4}{r_o} = (1 + K) i_1 + \frac{V_4}{r_o}$$

$$i_1 \left(\beta + 1 + K + \frac{2R}{r_o}\right) = \frac{V_x}{r_o}$$

$$i_x = g_{m_2} V_1 + \frac{V_x - V_4}{r_{o2}}$$
$$= -g_{m_2} r_{\pi_1} i_1 + \frac{V_x}{r_{o2}} - \frac{V_4}{r_{o2}}$$
$$= -\beta i_1 + \frac{V_x}{r_o} - \frac{R}{r_o} i_1$$

$$= \frac{v_x}{r_o} - \left(\beta + \frac{R}{r_o}\right)\frac{v_x}{r_o}\frac{1}{\beta+1+K+\frac{2R}{r_o}}$$

$$\frac{i_x}{v_x} = \frac{1}{r_o}\left(1 - \frac{\beta + \frac{R}{r_o}}{\beta+1+K+\frac{2R}{r_o}}\right)$$

$$= \frac{1}{r_o}\frac{\beta+1+K+2\frac{R}{r_o} - \beta - \frac{R}{r_o}}{\beta+1+K+\frac{2R}{r_o}}$$

$$= \frac{1}{r_o}\frac{1+K+R/r_o}{\beta+1+K+\frac{2R}{r_o}}$$

$$R_o = \frac{v_x}{i_x} = r_o\frac{\beta+1+K+2\frac{R}{r_o}}{1+K+\frac{R}{r_o}}$$

$$K = \frac{R_1}{R_1 + 2/g_m} = 1 \text{ for } R_1 \to \infty$$

$$R = r_{\pi_1} + R_1 \| \frac{2}{g_{m_1}} \cong r_{\pi_1} \text{ for } R_1 \to \infty$$

$$\frac{r_{\pi_1}}{r_o} << 1$$

$$R_o \simeq r_o\frac{2+\beta}{2} \simeq \frac{\beta r_o}{2} \text{ for large } R$$

$$V_{BE} = V_T \ln\frac{I_c}{I_s}$$

$$I_c = \frac{5-2(0.8)}{10\text{ K}} = 340\ \mu A$$

$$V_{BE} = 26m \ln\frac{340\ \mu A}{5\ fA} = 0.65\text{ V}$$

$$I_c = \frac{5-2(0.65)}{10\text{ K}} = 370\ \mu A$$

$$\frac{1}{g_m} = 70\,\Omega$$

$$K = \frac{10{,}000}{10{,}140} = 0.986$$

$$R = r_{\pi_1} + R_1 \| \frac{2}{g_{m_1}} = 200(70) + 10\text{k} \| 140$$

$$= 14\text{ K} + 140 = 14.2\text{ K}$$

$$r_o = \frac{130}{0.37}\text{ k}\Omega = 351\text{ k}\Omega$$

$$R_o = (351\text{ k})\frac{200+1+0.99+2\frac{14.2}{351}}{1+0.99+\frac{14.2}{351}}$$

$$= 34.9\text{ M}\Omega \text{ very close to } \frac{\beta r_o}{2}$$

R_o will decrease when Q_2 is saturated.

$$V_o = V_{BE(on)} + V_{CE(sat)}$$

$$\simeq 0.65 + 0.1 \simeq 0.75\text{ V}$$

```
BJT CASCODE CURRENT MIRROR
VCC 100 0  5
R1      100 2  10K
Q1      2   2  3      NPN
Q2      5   2  4      NPN
Q3      4   3  0      NPN
Q4      3   3  0      NPN
VO      5   0  2
.MODEL NPN NPN IS=5E-15 BF=200 RB=200 VAF=130
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.DC VO 0 5 0.2
.PLOT I(VO)
.TF V(5) VO
.END

 ******  DC TRANSFER CURVES        TNOM=  27.000 TEMP=  27.000
   VOLT        I(VO)
(A      )     -1.000E-03    -5.000E-04       0.          5.000E-04    1.000E-03
                   +            +            +            +            +
  0.        4.26E-04-+------+------+------+------+------+---A-+------+------+-
2.000E-01  4.06E-04 +      +      +      +      +      +  A +      +      +
4.000E-01  3.61E-04 +      +      +      +      +      + A  +      +      +
6.000E-01 -2.23E-05 +      +      +      +     A+      +      +      +      +
8.000E-01 -3.61E-04 +      +      +  A   +      +      +      +      +      +
1.000E+00 -3.63E-04 +      +      +  A   +      +      +      +      +      +
1.200E+00 -3.63E-04 +      +      +  A   +      +      +      +      +      +
1.400E+00 -3.63E-04 +      +      +  A   +      +      +      +      +      +
1.600E+00 -3.63E-04 +      +      +  A   +      +      +      +      +      +
1.800E+00 -3.63E-04 +      +      +  A   +      +      +      +      +      +
2.000E+00 -3.63E-04-+------+------+--A---+------+------+------+------+------+-
2.200E+00 -3.63E-04 +      +      +  A   +      +      +      +      +      +
2.400E+00 -3.63E-04 +      +      +  A   +      +      +      +      +      +
2.600E+00 -3.63E-04 +      +      +  A   +      +      +      +      +      +
2.800E+00 -3.63E-04 +      +      +  A   +      +      +      +      +      +
3.000E+00 -3.63E-04 +      +      +  A   +      +      +      +      +      +
3.200E+00 -3.63E-04 +      +      +  A   +      +      +      +      +      +
3.400E+00 -3.63E-04 +      +      +  A   +      +      +      +      +      +
3.600E+00 -3.63E-04 +      +      +  A   +      +      +      +      +      +
3.800E+00 -3.63E-04 +      +      +  A   +      +      +      +      +      +
4.000E+00 -3.63E-04-+------+------+--A---+------+------+------+------+------+-
4.200E+00 -3.63E-04 +      +      +  A   +      +      +      +      +      +
4.400E+00 -3.63E-04 +      +      +  A   +      +      +      +      +      +
4.600E+00 -3.63E-04 +      +      +  A   +      +      +      +      +      +
4.800E+00 -3.63E-04 +      +      +  A   +      +      +      +      +      +
5.000E+00 -3.63E-04 +      +      +  A   +      +      +      +      +      +
                   +            +            +            +            +

 ****  OPERATING POINT INFORMATION       TNOM=  27.000 TEMP=  27.000
   NODE      =VOLTAGE      NODE      =VOLTAGE      NODE      =VOLTAGE
+0:2         = 1.294E+00 0:3         = 6.473E-01 0:4         = 6.477E-01
+0:5         = 2.000E+00 0:100       = 5.000E+00

 **** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT  0:Q1       0:Q2       0:Q3       0:Q4
MODEL    0:NPN      0:NPN      0:NPN      0:NPN
 IB       1.834E-06  1.806E-06  1.825E-06  1.825E-06
 IC       3.669E-04  3.633E-04  3.651E-04  3.651E-04
 VBE      6.475E-01  6.471E-01  6.473E-01  6.473E-01
 VCE      6.475E-01  1.352E+00  6.477E-01  6.473E-01
 VBC       0.       -7.052E-01 -4.021E-04   0.
 VS      -1.294E+00 -2.000E+00 -6.477E-01 -6.473E-01
 POWER    2.387E-04  4.924E-04  2.376E-04  2.375E-04
 BETAD    2.000E+02  2.010E+02  2.000E+02  2.000E+02
 GM       1.418E-02  1.404E-02  1.411E-02  1.411E-02
 RPI      1.410E+04  1.431E+04  1.417E+04  1.417E+04
 RX       2.000E+02  2.000E+02  2.000E+02  2.000E+02
 RO       3.543E+05  3.598E+05  3.561E+05  3.561E+05
 BETAAC   1.999E+02  2.010E+02  1.999E+02  1.999E+02

 ****      SMALL-SIGNAL TRANSFER CHARACTERISTICS

      V(5)/VO                                       =  1.000E+00
      INPUT RESISTANCE AT          VO               =  3.622E+07
```

```
BJT CASCODE CURRENT MIRROR
* (BETA REDUCED BY 50 PERCENT)
VCC 100 0  5
R1      100 2  10K
Q1      2   2  3      NPN
Q2      5   2  4      NPN
Q3      4   3  0      NPN
Q4      3   3  0      NPN
VO      5   0  2
.MODEL NPN NPN IS=5E-15 BF=100 RB=200 VAF=130
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.DC VO 0 5 0.2
.PLOT I(VO)
.TF V(5) VO
.END

 ******  DC TRANSFER CURVES        TNOM=  27.000 TEMP=  27.000
   VOLT        I(VO)
(A      )     -1.000E-03    -5.000E-04       0.          5.000E-04    1.000E-03
                   +            +            +            +            +
  0.        4.26E-04-+------+------+------+------+------+---A-+------+------+-
2.000E-01  4.06E-04 +      +      +      +      +      +  A +      +      +
4.000E-01  3.61E-04 +      +      +      +      +      + A  +      +      +
6.000E-01 -1.95E-05 +      +      +      +     A+      +      +      +      +
8.000E-01 -3.54E-04 +      +      +  A   +      +      +      +      +      +
1.000E+00 -3.56E-04 +      +      +  A   +      +      +      +      +      +
1.200E+00 -3.56E-04 +      +      +  A   +      +      +      +      +      +
1.400E+00 -3.56E-04 +      +      +  A   +      +      +      +      +      +
1.600E+00 -3.56E-04 +      +      +  A   +      +      +      +      +      +
1.800E+00 -3.56E-04 +      +      +  A   +      +      +      +      +      +
2.000E+00 -3.56E-04-+------+------+--A---+------+------+------+------+------+-
2.200E+00 -3.56E-04 +      +      +  A   +      +      +      +      +      +
2.400E+00 -3.56E-04 +      +      +  A   +      +      +      +      +      +
2.600E+00 -3.56E-04 +      +      +  A   +      +      +      +      +      +
2.800E+00 -3.56E-04 +      +      +  A   +      +      +      +      +      +
3.000E+00 -3.56E-04 +      +      +  A   +      +      +      +      +      +
3.200E+00 -3.56E-04 +      +      +  A   +      +      +      +      +      +
3.400E+00 -3.56E-04 +      +      +  A   +      +      +      +      +      +
3.600E+00 -3.56E-04 +      +      +  A   +      +      +      +      +      +
3.800E+00 -3.56E-04 +      +      +  A   +      +      +      +      +      +
4.000E+00 -3.56E-04-+------+------+--A---+------+------+------+------+------+-
4.200E+00 -3.56E-04 +      +      +  A   +      +      +      +      +      +
4.400E+00 -3.56E-04 +      +      +  A   +      +      +      +      +      +
4.600E+00 -3.56E-04 +      +      +  A   +      +      +      +      +      +
4.800E+00 -3.56E-04 +      +      +  A   +      +      +      +      +      +
5.000E+00 -3.56E-04 +      +      +  A   +      +      +      +      +      +
                   +            +            +            +            +

 ****  OPERATING POINT INFORMATION       TNOM=  27.000 TEMP=  27.000
   NODE      =VOLTAGE      NODE      =VOLTAGE      NODE      =VOLTAGE
+0:2         = 1.294E+00 0:3         = 6.473E-01 0:4         = 6.480E-01
+0:5         = 2.000E+00 0:100       = 5.000E+00

 **** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT  0:Q1       0:Q2       0:Q3       0:Q4
MODEL    0:NPN      0:NPN      0:NPN      0:NPN
 IB       3.633E-06  3.543E-06  3.598E-06  3.598E-06
 IC       3.633E-04  3.562E-04  3.598E-04  3.598E-04
 VBE      6.476E-01  6.469E-01  6.473E-01  6.473E-01
 VCE      6.476E-01  1.352E+00  6.480E-01  6.473E-01
 VBC       0.       -7.051E-01 -6.686E-04   0.
 VS      -1.294E+00 -2.000E+00 -6.480E-01 -6.473E-01
 POWER    2.376E-04  4.839E-04  2.355E-04  2.352E-04
 BETAD    1.000E+02  1.005E+02  1.000E+02  1.000E+02
 GM       1.405E-02  1.377E-02  1.391E-02  1.391E-02
 RPI      7.118E+03  7.299E+03  7.189E+03  7.189E+03
 RX       2.000E+02  2.000E+02  2.000E+02  2.000E+02
 RO       3.578E+05  3.669E+05  3.613E+05  3.613E+05
 BETAAC   9.998E+01  1.005E+02  9.998E+01  9.998E+01

 ****      SMALL-SIGNAL TRANSFER CHARACTERISTICS

      V(5)/VO                                       =  1.000E+00
      INPUT RESISTANCE AT          VO               =  1.892E+07
```

4.5

$L_{eff} = 1\,\mu m - 2(0.09\,\mu m) = 0.82\,\mu m$

$r_o = \dfrac{1}{\lambda I_D}$ where $\lambda = \dfrac{dX_d}{dV_{DS}} \Big/ L_{eff}$

$\lambda = \dfrac{0.02}{0.82} = 0.024\ V^{-1}$

$r_o = \dfrac{1}{0.024(100\,\mu A)} = 417\ k\Omega$

$g_m = \sqrt{2 k' \dfrac{W}{L_{eff}} I_D} = \sqrt{2(194)\left(\dfrac{100}{0.82}\right)100}$

$= 2.18\ mA/V$

$R_o = r_{o2}\left[1 + (g_{m2} + g_{mb2})r_{o1}\right] + r_{o1}$

Here, $g_{mb2} = 0$ by assumption

$R_o \simeq r_{o2}(g_{m2} r_{o1}) = 417\,k(2.18\,m \cdot 417\,k)$

$= 379\ M\Omega$

```
CASCODE CURRENT MIRROR
VDD 100 0  3
IIN 100 3  100U
VO  5   0  3
M1  1   4  0   0 CMOSN W=100U L=1U
M2  5   3  1   1 CMOSN W=100U L=1U
M3  3   3  4   4 CMOSN W=100U L=1U
M4  4   4  0   0 CMOSN W=100U L=1U
* NOTE THAT CONNECTING THE BODY TO THE SOURCE ELIMINATES
* THE BODY EFFECT.
.MODEL CMOSN NMOS LEVEL=1 LAMBDA=0.024 VTO=0.6 KP=194U LD=0.09U
* NOTE THAT LAMBDA = (DXD/DVDS)/LEFF = 0.02/0.82=0.0244
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.DC VO 0 3 0.1
.PLOT DC I(VO)
.TF V(5) VO
.END
```

```
 ******  DC TRANSFER CURVES      TNOM=  27.000 TEMP=  27.000
   VOLT       I(VO)
(A         )   -1.500E-04   -1.000E-04   -5.000E-05      0.        5.000E-05
                  +             +             +             +             +
  0.         0.   -+------+------+------+------+------+------A------+------+-
1.000E-01 -9.86E-05 +      +      A      +      +      +      +      +      +
2.000E-01 -9.88E-05 +      +      A      +      +      +      +      +      +
3.000E-01 -9.91E-05 +      +      A      +      +      +      +      +      +
4.000E-01 -9.93E-05 +      +      A      +      +      +      +      +      +
5.000E-01 -9.95E-05 +      +      A      +      +      +      +      +      +
6.000E-01 -9.97E-05 +      +      A      +      +      +      +      +      +
7.000E-01 -9.99E-05 +      +      A      +      +      +      +      +      +
8.000E-01 -1.00E-04 +      +      A      +      +      +      +      +      +
9.000E-01 -1.00E-04 +      +      A      +      +      +      +      +      +
1.000E+00 -1.00E-04-+------+------A------+------+------+------+------+------+-
1.100E+00 -1.00E-04 +      +      A      +      +      +      +      +      +
1.200E+00 -1.00E-04 +      +      A      +      +      +      +      +      +
1.300E+00 -1.00E-04 +      +      A      +      +      +      +      +      +
1.400E+00 -1.00E-04 +      +      A      +      +      +      +      +      +
1.500E+00 -1.00E-04 +      +      A      +      +      +      +      +      +
1.600E+00 -1.00E-04 +      +      A      +      +      +      +      +      +
1.700E+00 -1.00E-04 +      +      A      +      +      +      +      +      +
1.800E+00 -1.00E-04 +      +      A      +      +      +      +      +      +
1.900E+00 -1.00E-04 +      +      A      +      +      +      +      +      +
2.000E+00 -1.00E-04-+------+------A------+------+------+------+------+------+-
2.100E+00 -1.00E-04 +      +      A      +      +      +      +      +      +
2.200E+00 -1.00E-04 +      +      A      +      +      +      +      +      +
2.300E+00 -1.00E-04 +      +      A      +      +      +      +      +      +
2.400E+00 -1.00E-04 +      +      A      +      +      +      +      +      +
2.500E+00 -1.00E-04 +      +      A      +      +      +      +      +      +
2.600E+00 -1.00E-04 +      +      A      +      +      +      +      +      +
2.700E+00 -1.00E-04 +      +      A      +      +      +      +      +      +
2.800E+00 -1.00E-04 +      +      A      +      +      +      +      +      +
2.900E+00 -1.00E-04 +      +      A      +      +      +      +      +      +
3.000E+00 -1.00E-04-+------+------A----- +------+------+------+------+------+-
                    +             +             +             +             +
 ****  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
   NODE     =VOLTAGE      NODE     =VOLTAGE      NODE     =VOLTAGE
+0:1       = 6.929E-01 0:3       = 1.382E+00 0:4       = 6.912E-01
+0:5       = 3.000E+00 0:100     = 3.000E+00

**** MOSFETS
SUBCKT
ELEMENT  0:M1       0:M2       0:M3       0:M4
MODEL    0:CMOSN    0:CMOSN    0:CMOSN    0:CMOSN
 ID       1.000E-04  1.000E-04  1.000E-04  1.000E-04
 IBS      0.         0.         0.         0.
 IBD     -6.929E-15 -2.307E-14 -6.912E-15 -6.912E-15
 VGS      6.912E-01  6.895E-01  6.912E-01  6.912E-01
 VDS      6.929E-01  2.307E+00  6.912E-01  6.912E-01
 VBS      0.         0.         0.         0.
 VTH      6.000E-01  6.000E-01  6.000E-01  6.000E-01
 VDSAT    9.119E-02  8.950E-02  9.119E-02  9.119E-02
 BETA     2.405E-02  2.497E-02  2.405E-02  2.405E-02
 GAM EFF  0.         0.         0.         0.
 GM       2.193E-03  2.235E-03  2.193E-03  2.193E-03
 GDS      2.361E-06  2.274E-06  2.361E-06  2.361E-06
 GMB      0.         0.         0.         0.

****      SMALL-SIGNAL TRANSFER CHARACTERISTICS

     V(5)/VO                                  =  1.000E+00
     INPUT RESISTANCE AT          VO          =  4.170E+08
```

4.6

Look at M2

$V_{DS_{M2}} = V_{OUT} - V_{DS_{M1}} = V_{OUT} - V_{GS_{M1}}$

$V_{GS_{M1}} = V_t + \sqrt{\frac{2I_D}{k' W/L_{eff}}}$

$= 0.6 + \sqrt{\frac{200\mu}{194\mu \; 100/0.82}}$

$= 0.692 \text{ V}$

$V_{DS_{ACT\,M2}} = V_{GS} - V_t$

$= 0.692 - 0.6 = 0.092 \text{ V}$

Assume no body effect on V_t

$V_{OUT} = 2\text{ V}$

$V_{DS} = 2 - 0.692 = 1.308 \text{ V}$

$V_{DS_{ACT}} = 0.092 \text{ V}$

$V_{DS} - V_{DS_{ACT}} = 1.216 \text{ V}$

From (1.261),

$I_{DB} = 5\,(1.216)(100\mu)\, e^{-30/1.216}$

$= 11.7 \text{ fA}$

From (1.262),

$g_{db} = 30 \frac{11.7 \text{ fA}}{(1.216)^2} = 0.238 \frac{\text{pA}}{\text{V}}$

$r_{db} = \frac{1}{g_{db}} = 4200 \text{ G}\Omega$

$R_o = 379 \text{ M}\Omega \parallel 4200 \text{ G}\Omega = 379 \text{ M}\Omega$

No change due to substrate leakage

$V_{OUT} = 3\text{V}$

$V_{DS} = 3 - 0.692 = 2.308 \text{ V}$

$V_{DS} - V_{DS_{ACT}} = 2.216 \text{ V}$

$I_{DB} = 2\,(2.216)(100\mu)\, e^{-30/2.216}$

$= 1.46 \text{ nA}$

$g_{db} = 29.7 \text{ nA/V}$

$r_{db} = 33.7 \text{ M}\Omega$

$R_o = 33.7 \text{ M}\Omega \parallel 379 \text{ M}\Omega = 30.9 \text{ M}\Omega$

Output resistance dominated by substrate leakage.

4.7

From condition (a), $V_{o\,min} = 0.2\,V$

This is split across M_1 and M_2

Therefore, $V_{ov} = V_{GS} - V_t = 0.1\,V$

From this and condition (b),

$$50\,\mu A = \frac{194\,\mu}{2}\left(\frac{W}{L_{eff}}\right)(0.1)^2$$

$$\Rightarrow \frac{W}{L_{eff}} = 51.5$$

$$r_o = \frac{1}{\lambda I_D} \quad \text{where } \lambda = \frac{dX_d}{dV_{DS}} \Big/ L_{eff}$$

$$\text{So, } r_o = \frac{L_{eff}}{50\,\mu\,(0.02\,\frac{\mu m}{V})} = \frac{L_{eff}}{1\times10^{-12}}$$

$$R_o = \frac{\Delta V_{OUT}}{\Delta I_{OUT}} = \frac{1V}{0.0002\,(I_D)} = \frac{1V}{0.0002\,(50\mu)}$$

$$= 100\,M\Omega$$

From (4.50), $R_o \cong r_{o2}\, g_{m2}\, r_{o1}$

$$\Rightarrow R_o \cong \left(\frac{L_{eff}}{10^{-12}}\right)^2 \sqrt{2(194)(51.5)(50)}$$

$$= \frac{L_{eff}^2}{10^{-21}} = 100\,M\Omega$$

Therefore, $L_{eff} = 0.32\,\mu m$

$$L_{drawn} = L_{eff} + 2L_d = 0.32 + 2(0.09)$$

$$= 0.5\,\mu m$$

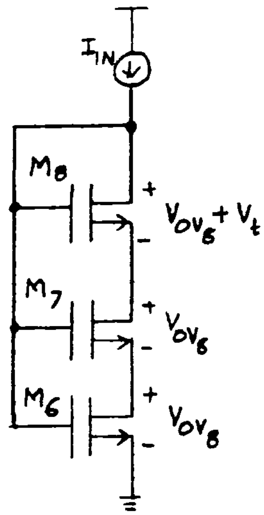
$$W = (51.5)(0.32) = 16.5\,\mu m$$

```
CASCODE CURRENT MIRROR WITH LEVEL SHIFT
******
VDD 100 0  3
VO  2   0  0.2
IR  100 4  51.84U
* NOTE THAT IR > 50 UA BECAUSE THIS CURRENT MIRROR HAS A
* NONZERO SYSTEMATIC GAIN ERROR.  IR = 51.9 UA IS CHOSEN
* BY TRIAL AND ERROR TO FORCE THE OUTPUT CURRENT TO BE 50 UA,
* AS GIVEN IN THE PROBLEM.

* IN THE HAND CALCULATION, THE REQUIRED WIDTH WAS CALCULATED
* TO BE 16.5 MICRONS; HOWEVER, TRIAL AND ERROR IN SPICE SHOWS
* THAT THE WIDTH HAS TO BE INCREASED TO 18 MICRONS TO OPERATE
* M1 AND M2 BARELY IN THE ACTIVE REGION.  THIS DIFFERENCE
* STEMS FROM THE OBSERVATION THAT ALL THE TRANSISTORS DO NOT
* OPERATE AT EQUAL CURRENTS.  TO OVERCOME THIS PROBLEM
* IN PRACTICE, THE W/L OF M4 WOULD BE REDUCED TO INCREASE
* THE DRAIN-SOURCE VOLTAGE ON M1.  THIS CHANGE WOULD ALSO BE
* USED TO MAKE SURE THAT M1 OPERATES SLIGHTLY BEYOND THE EDGE
* OF THE TRIODE REGION EVEN WHEN BODY EFFECT IS TAKEN
* INTO ACCOUNT.

M1  1   3  0  0  CMOSN W=18U L=0.5U
M2  2   6  1  1  CMOSN W=18U L=0.5U
M3  3   3  0  0  CMOSN W=18U L=0.5U
M4A 4   4  A3 A3 CMOSN W=18U L=0.5U
M4B A3  4  B3 B3 CMOSN W=18U L=0.5U
M4C B3  4  C3 C3 CMOSN W=18U L=0.5U
M4D C3  4  3  3  CMOSN W=18U L=0.5U
* NOTE THAT 4 TRANSISTORS ARE USED IN SERIES TO BUILD M4
* TO DESENSITIZE THE CIRCUIT TO VARIATIONS IN DELTA W
* AND DELTA L.  IN PRACTICE, 5 OR MORE TRANSISTORS WOULD BE
* USED TO PUSH M1 PAST THE EDGE OF SATURATION AND TO OVERCOME
* BODY-EFFECT MISMATCHES.
M5  100 4  6  6  CMOSN W=18U L=0.5U
M6  6   3  0  0  CMOSN W=18U L=0.5U
* NOTE THAT CONNECTING THE BODY TO THE SOURCE ELIMINATES
* THE BODY EFFECT.
.MODEL CMOSN NMOS LEVEL=1 LAMBDA=0.0625 VTO=0.6 KP=194U LD=0.09U
*NOTE THAT LAMBDA = (DXD/DVDS)/LEFF = 0.02/0.32
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.DC VO 0 3 0.1
.PLOT DC I(VO)
.TF V(2) VO
.END
```

```
 ******  DC TRANSFER CURVES      TNOM=  27.000 TEMP=  27.000
    VOLT       I(VO)
 (A        )   -6.000E-05    -4.000E-05    -2.000E-05      0.         2.000E-05
                  +             +             +             +             +

  0.         0.     -+------+------+------+------+------+------A------+------+-
 1.000E-01 -4.47E-05 +      +  A   +      +      +      +      +      +      +
 2.000E-01 -5.00E-05 +      A      +      +      +      +      +      +      +
 3.000E-01 -5.00E-05 +      A      +      +      +      +      +      +      +
 4.000E-01 -5.00E-05 +      A      +      +      +      +      +      +      +
 5.000E-01 -5.00E-05 +      A      +      +      +      +      +      +      +
 6.000E-01 -5.00E-05 +      A      +      +      +      +      +      +      +
 7.000E-01 -5.00E-05 +      A      +      +      +      +      +      +      +
 8.000E-01 -5.00E-05 +      A      +      +      +      +      +      +      +
 9.000E-01 -5.00E-05 +      A      +      +      +      +      +      +      +
 1.000E+00 -5.00E-05-+------A------+------+------+------+------+------+------+-
 1.100E+00 -5.00E-05 +      A      +      +      +      +      +      +      +
 1.200E+00 -5.00E-05 +      A      +      +      +      +      +      +      +
 1.300E+00 -5.00E-05 +      A      +      +      +      +      +      +      +
 1.400E+00 -5.00E-05 +      A      +      +      +      +      +      +      +
 1.500E+00 -5.00E-05 +      A      +      +      +      +      +      +      +
 1.600E+00 -5.00E-05 +      A      +      +      +      +      +      +      +
 1.`00E+00 -5.00E-05 +      A      +      +      +      +      +      +      +
 1.800E+00 -5.00E-05 +      A      +      +      +      +      +      +      +
 1.900E+00 -5.00E-05 +      A      +      +      +      +      +      +      +
 2.000E+00 -5.00E-05-+------A------+------+------+------+------+------+------+-
 2.100E+00 -5.00E-05 +      A      +      +      +      +      +      +      +
 2.200E+00 -5.00E-05 +      A      +      +      +      +      +      +      +
 2.300E+00 -5.00E-05 +      A      +      +      +      +      +      +      +
 2.400E+00 -5.00E-05 +      A      +      +      +      +      +      +      +
 2.500E+00 -5.00E-05 +      A      +      +      +      +      +      +      +
 2.600E+00 -5.00E-05 +      A      +      +      +      +      +      +      +
 2.700E+00 -5.00E-05 +      A      +      +      +      +      +      +      +
 2 900E+00 -5 00E-05 +      A      +      +      +      +      +      +      +
 2.900E+00 -5.00E-05 +      A      +      +      +      +      +      +      +
 3 000E+00 -5 00E-05-+------A------+------+------+------+------+------+------+-
                     +             +             +             +             +
```

```
****  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
  NODE      =VOLTAGE       NODE      =VOLTAGE       NODE      =VOLTAGE
+0:1        = 1.021E-01 0:2          = 2.000E-01 0:3          = 6.954E-01
+0:4        = 1.489E+00 0:6          = 7.975E-01 0:100        = 3.000E+00
+0:A3       = 7.938E-01 0:B3         = 7.529E-01 0:C3         = 7.217E-01

**** MOSFETS
SUBCKT
ELEMENT  0:M1       0:M2       0:M3       0:M4A      0:M4B
MODEL    0:CMOSN    0:CMOSN    0:CMOSN    0:CMOSN    0:CMOSN
 ID       5.000E-05  5.000E-05  5.184E-05  5.184E-05  5.184E-05
 IBS      0.         0.         0.         0.         0.
 IBD     -1.021E-15 -9.790E-16 -6.954E-15 -6.954E-15 -4.089E-16
 VGS      6.954E-01  6.954E-01  6.954E-01  6.954E-01  7.363E-01
 VDS      1.021E-01  9.790E-02  6.954E-01  6.954E-01  4.089E-02
 VBS      0.         0.         0.         0.         0.
 VTH      6.000E-01  6.000E-01  6.000E-01  6.000E-01  6.000E-01
 VDSAT    9.542E-02  9.543E-02  9.542E-02  9.542E-02  4.089E-02
 BETA     1.098E-02  1.098E-02  1.139E-02  1.139E-02  1.094E-02
 GAM EFF  0.         0.         0.         0.         0.
 GM       1.048E-03  1.048E-03  1.087E-03  1.087E-03  4.474E-04
 GDS      3.105E-06  3.106E-06  3.105E-06  3.105E-06  1.047E-03
 GMB      0.         0.         0.         0.         0.

SUBCKT
ELEMENT  0:M4C      0:M4D      0:M5       0:M6
MODEL    0:CMOSN    0:CMOSN    0:CMOSN    0:CMOSN
 ID       5.184E-05  5.184E-05  5.216E-05  5.216E-05
 IBS      0.         0.         0.         0.
 IBD     -3.121E-16 -2.625E-16 -2.202E-14 -7.975E-15
 VGS      7.675E-01  7.938E-01  6.917E-01  6.954E-01
 VDS      3.121E-02  2.625E-02  2.202E+00  7.975E-01
 VBS      0.         0.         0.         0.
 VTH      6.000E-01  6.000E-01  6.000E-01  6.000E-01
 VDSAT    3.121E-02  2.625E-02  9.167E-02  9.542E-02
 BETA     1.093E-02  1.093E-02  1.241E-02  1.146E-02
 GAM EFF  0.         0.         0.         0.
 GM       3.412E-04  2.870E-04  1.138E-03  1.093E-03
 GDS      1.494E-03  1.834E-03  2.865E-06  3.105E-06
 GMB      0.         0.         0.         0.

****      SMALL-SIGNAL TRANSFER CHARACTERISTICS

      V(2)/VO                                 =  1.000E+00
      INPUT RESISTANCE AT        VO           =  1.092E+08
```

4.8



M_8 operates in active region

M_6 and M_7 operate in triode region.

$$I = \frac{k'}{2}\left(\frac{W}{L}\right)_8 (V_{GS_8}-V_t)^2$$

$$I = \frac{k'}{2}\left(\frac{W}{L}\right)_7 \left[2(V_{GS_7}-V_t)V_{DS_7}-V_{DS_7}^2\right]$$

$$I = \frac{k'}{2}\left(\frac{W}{L}\right)_6 \left[2(V_{GS_6}-V_t)V_{DS_6}-V_{DS_6}^2\right]$$

$$\left(\frac{W}{L}\right)_8 (V_{OV_8})^2 = \left(\frac{W}{L}\right)_7 \left[2(2V_{OV_8})V_{OV_8}-V_{OV_8}^2\right]$$

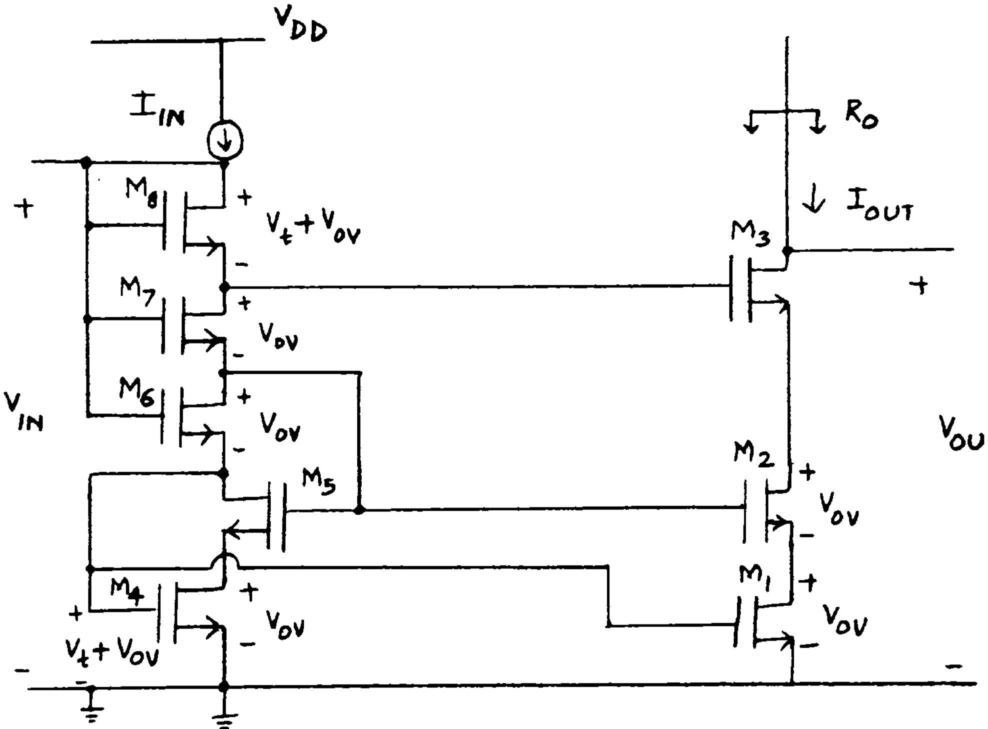
$$= \left(\frac{W}{L}\right)_6 \left[2(3V_{OV_8})V_{OV_8}-V_{OV_8}^2\right]$$

$$\left(\frac{W}{L}\right)_8 (V_{OV_8})^2 = \left(\frac{W}{L}\right)_7 (3V_{OV_8}^2) = \left(\frac{W}{L}\right)_6 (5V_{OV_8}^2)$$

$$\left(\frac{W}{L}\right)_7 = \frac{1}{3}\left(\frac{W}{L}\right)_8$$

$$\left(\frac{W}{L}\right)_6 = \frac{1}{5}\left(\frac{W}{L}\right)_8$$

In practice, $\left(\frac{W}{L}\right)_6$ and $\left(\frac{W}{L}\right)_7$ would be even smaller to increase V_{DS_6} and V_{DS_7} slightly so that all the transistors in the output branch of a current mirror using the circuit operate in the active region



$$V_{IN} = V_{GS_4} + V_{DS_6} + V_{DS_7} + V_{GS_8}$$
$$= V_t + V_{ov} + V_{ov} + V_{ov} + V_t + V_{ov}$$
$$= 2V_t + 4V_{ov}$$

and

$$r_o = r_{o1} = r_{o2} = r_{o3}$$

if $M_1 = M_2 = M_3$.

$$V_{OUT(min)} = V_{DS_1} + V_{DS_2} + V_{DS_3}(min)$$
$$= V_{ov} + V_{ov} + V_{ov}$$
$$= 3V_{ov}$$

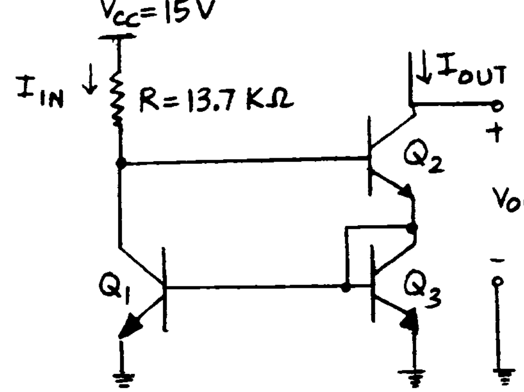
systematic gain error = 0
(because $V_{DS_4} = V_{DS_1} = V_{ov}$)

Assuming M_1-M_3 operate in the active region, the output resistance [ignoring the body effect as in (4.53)] is

$$R_o \cong r_o (g_m r_o)^2$$

where, $g_m = g_{m_1} = g_{m_2} = g_{m_3}$

4.9



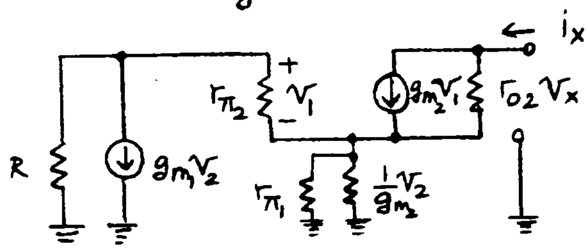
From (4·100)

$$I_{OUT} = I_{C_2} = I_{IN}\left[1 - \frac{2}{\beta^2+2\beta+2}\right]$$

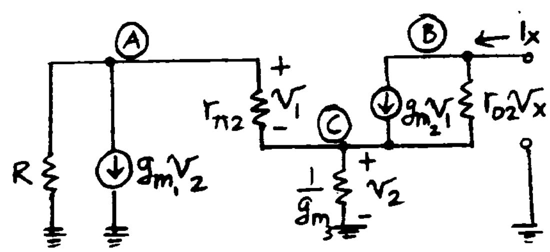
$$I_{IN} = \frac{15 - 2\times 0.7}{13.7K} = 0.993 \text{ mA} \simeq 1 \text{ mA}$$

$$\therefore I_{OUT} = 0.993\left[1 - \frac{2}{200^2+2\times 200+2}\right] \approx 0.993 \text{ mA} \approx 1 \text{ mA}$$

The small signal circuit is :



Each transistor has the same $I_C \simeq 1$ mA. ∴ same r_π, g_m and r_o. Neglect r_{π_1} compare to $1/g_{m_3}$ circuit becomes :



At (B) $i_x = g_m v_1 + \frac{v_x - v_2}{r_o}$ → (1)

At (A) $\frac{v_1 + v_2}{R} + g_m v_2 + \frac{v_1}{r_\pi} = 0$ → (2)

At (C) $\frac{v_1}{r_\pi} + g_m v_1 + \frac{v_x - v_2}{r_o} = g_m v_2$ → (3)

$\therefore v_1\left(\frac{1}{r_\pi} + g_m\right) + \frac{v_x}{r_o} = v_2\left(g_m + \frac{1}{r_o}\right)$ → (4)

From (2), $v_1\left(\frac{1}{R} + \frac{1}{r_\pi}\right) = -v_2\left(\frac{1}{R} + g_m\right)$

$\therefore v_1 = -v_2 \frac{1 + g_m R}{1 + \frac{R}{r_\pi}}$ → (5)

(5) in (4) :

$$-v_2 \frac{1+g_mR}{1+\frac{R}{r_\pi}}\left(\frac{1}{r_\pi} + g_m\right) + \frac{v_x}{r_o} = v_2\left(g_m + \frac{1}{r_o}\right)$$

$$\therefore v_x = v_2 r_o\left[g_m + \frac{1}{r_o} + \frac{\left(g_m + \frac{1}{r_\pi}\right)(1+g_mR)}{1+\frac{R}{r_\pi}}\right] \rightarrow (6)$$

(5) in (1) :

$$i_x = -g_m v_2 \frac{1+g_mR}{1+\frac{R}{r_\pi}} + \frac{v_x}{r_o} - \frac{v_2}{r_o} \rightarrow (7)$$

(6) in (7) :

$$\frac{i_x}{v_x} = \frac{1}{r_o} - \frac{\left[\frac{1}{r_o} + g_m\frac{1+g_mR}{1+R/r_\pi}\right]}{r_o\left[g_m + \frac{1}{r_o} + \frac{(g_m + 1/r_\pi)(1+g_mR)}{1+R/r_\pi}\right]}$$

$$= \frac{1}{r_o}\left[\frac{g_m(1+R/r_\pi) + 1/r_\pi\,(1+g_mR)}{\left(g_m+\frac{1}{r_o}\right)\left(1+\frac{R}{r_\pi}\right) + \left(g_m + \frac{1}{r_\pi}\right)(1+g_mR)}\right]$$

$$R_o = \frac{v_x}{i_x} = r_o\left[1 + \frac{\frac{1}{r_o} + \frac{1}{r_o}\frac{R}{r_\pi} + g_m(1+g_mR)}{g_m + 2\frac{g_mR}{r_\pi} + \frac{1}{r_\pi}\ (\simeq 0)}\right]$$

$$\cong r_o\left[1 + \frac{\frac{1}{r_o}\frac{r_\pi}{\beta_o} + \frac{1}{r_o}\frac{R}{\beta_o}\ (\simeq 0) + 1 + \frac{\beta_o R}{r_\pi}}{1 + 2R/r_\pi}\right]$$

$$\cong r_o\left[1 + \frac{1 + \frac{1}{g_m r_o} + g_m R}{1 + 2R/r_\pi}\right] \rightarrow (8)$$

$\left(\because g_m = \frac{\beta_o}{r_\pi} >> \frac{1}{r_\pi},\ g_m R = \frac{\beta_o R}{r_\pi} >> \frac{R}{r_o \beta_o} \right)$

In this problem $g_m = \frac{1\,mA}{26\,mV} = \frac{1}{26}\,\mho$

$r_\pi = \frac{\beta_o}{g_m} = 5.2\,k\Omega$, $R = 13.7\,k\Omega$

$r_o = \frac{130\,V}{1\,mA} = 130\,k\Omega$

$\therefore R_o = 130\,k\left[1 + \frac{528}{6.27}\right] = 11.1\,M\Omega$

(If $R \to \infty$ then $R_o = r_o\left[1 + \frac{\beta_o}{2}\right]$)

If V_{OUT} changes by 5V then,

I_{OUT} changes by

$$\Delta I_{OUT} = \frac{\Delta V_{OUT}}{R} = \frac{5}{11.1}\,\mu A = 0.45\,\mu A$$

The percentage change in I_{OUT} is

$$\frac{0.45 \times 10^{-6}}{10^{-3}} \times 100 = 0.045\%$$

```
WILSON CURRENT MIRROR
VCC 100 0  15
RBIAS  100 2  13.7K
Q1     2   3  0     NPN
Q2     4   2  3     NPN
Q3     3   3  0     NPN
VO     4   0  2
.MODEL NPN NPN IS=5E-15 BF=200 RB=200 VAF=130 RE=2
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.DC VO 0 15 0.5
.PRINT I(VO)
.PLOT I(VO)
.TF V(2) VO
* RESULTS (BETA = 200)
* WHEN VOUT = 10 VOLTS, IOUT = 992.2 MICROAMPS
* WHEN VOUT =  5 VOLTS, IOUT = 991.7 MICROAMPS
* SO IOUT CHANGES BY 0.5 MICROAMPS OR 0.05 PERCENT
* AS VOUT INCREASES FROM 5 VOLTS TO 10 VOLTS
* ALSO RO = 11.0 MEGAOHMS
.END
```

```
 ******  DC TRANSFER CURVES      TNOM=  27.000 TEMP=  27.000
   VOLT       I(VO)
(A        )   -1.000E-03      0.         1.000E-03    2.000E-03    3.000E-03
                  +           +             +            +            +
  0.       1.031E-03-+------+------+------+------A------+------+------+------+-
 5.00E-01  9.923E-04 +      +      +      +      A      +      +      +      +
 1.00E+00 -9.914E-04 A      +      +      +      +      +      +      +      +
 1.50E+00 -9.914E-04 A      +      +      +      +      +      +      +      +
 2.00E+00 -9.915E-04 A      +      +      +      +      +      +      +      +
 2.50E+00 -9.915E-04 A      +      +      +      +      +      +      +      +
 3.00E+00 -9.916E-04 A      +      +      +      +      +      +      +      +
 3.50E+00 -9.916E-04 A      +      +      +      +      +      +      +      +
 4.00E+00 -9.917E-04 A      +      +      +      +      +      +      +      +
 4.50E+00 -9.917E-04 A      +      +      +      +      +      +      +      +
 5.00E+00 -9.917E-04-A------+------+------+------+------+------+------+------+-
 5.50E+00 -9.918E-04 A      +      +      +      +      +      +      +      +
 6.00E+00 -9.918E-04 A      +      +      +      +      +      +      +      +
 6.50E+00 -9.919E-04 A      +      +      +      +      +      +      +      +
 7.00E+00 -9.919E-04 A      +      +      +      +      +      +      +      +
 7.50E+00 -9.920E-04 A      +      +      +      +      +      +      +      +
 8.00E+00 -9.920E-04 A      +      +      +      +      +      +      +      +
 8.50E+00 -9.920E-04 A      +      +      +      +      +      +      +      +
 9.00E+00 -9.921E-04 A      +      +      +      +      +      +      +      +
 9.50E+00 -9.921E-04 A      +      +      +      +      +      +      +      +
 1.00E+01 -9.922E-04-A------+------+------+------+------+------+------+------+-
 1.05E+01 -9.922E-04 A      +      +      +      +      +      +      +      +
 1.10E+01 -9.923E-04 A      +      +      +      +      +      +      +      +
 1.15E+01 -9.923E-04 A      +      +      +      +      +      +      +      +
 1.20E+01 -9.923E-04 A      +      +      +      +      +      +      +      +
 1.25E+01 -9.924E-04 A      +      +      +      +      +      +      +      +
 1.30E+01 -9.924E-04 A      +      +      +      +      +      +      +      +
 1.35E+01 -9.924E-04 A      +      +      +      +      +      +      +      +
 1.40E+01 -9.925E-04 A      +      +      +      +      +      +      +      +
 1.45E+01 -9.925E-04 A      +      +      +      +      +      +      +      +
 1.50E+01 -9.926E-04-A------+------+------+------+------+------+------+------+-
                  +           +             +            +            +
```

```
 ****  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
   NODE     =VOLTAGE      NODE     =VOLTAGE      NODE     =VOLTAGE
+0:2        = 1.351E+00 0:3        = 6.756E-01 0:4        = 2.000E+00
+0:100      = 1.500E+01

**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT  0:Q1        0:Q2        0:Q3
MODEL    0:NPN       0:NPN       0:NPN
 IB       4.931E-06   4.933E-06   4.933E-06
 IC       9.913E-04   9.915E-04   9.865E-04
 VBE      6.756E-01   6.757E-01   6.756E-01
 VCE      1.351E+00   1.324E+00   6.756E-01
 VBC     -6.757E-01  -6.487E-01    0.
 VS      -1.351E+00  -2.000E+00  -6.756E-01
 POWER    1.343E-03   1.316E-03   6.699E-04
 BETAD    2.010E+02   2.010E+02   2.000E+02
 GM       3.832E-02   3.833E-02   3.814E-02
 RPI      5.245E+03   5.243E+03   5.243E+03
 RX       2.000E+02   2.000E+02   2.000E+02
 RO       1.318E+05   1.317E+05   1.317E+05
 BETAAC   2.010E+02   2.009E+02   1.999E+02
```

```
****     SMALL-SIGNAL TRANSFER CHARACTERISTICS

     V(2)/VO                                        = -2.014E-04
     INPUT RESISTANCE AT          VO                =  1.098E+07
     OUTPUT RESISTANCE AT V(2)                      =  5.766E+01
```

```
WILSON CURRENT MIRROR (BETA REDUCED BY 50 PERCENT)
VCC 100 0  15
RBIAS  100 2  13.7K
Q1     2   3  0     NPN
Q2     4   2  3     NPN
Q3     3   3  0     NPN
VO     4   0  2
.MODEL NPN NPN IS=5E-15 BF=100 RB=200 VAF=130 RE=2
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.DC VO 0 15 0.5
.PRINT I(VO)
.PLOT I(VO)
.TF V(2) VO
* RESULTS (BETA = 100)
* WHEN VOUT = 10 VOLTS, IOUT = 992.5 MICROAMPS
* WHEN VOUT =  5 VOLTS, IOUT = 991.7 MICROAMPS
* SO IOUT CHANGES BY 0.8 MICROAMPS OR 0.08 PERCENT
* AS VOUT INCREASES FROM 5 VOLTS TO 10 VOLTS
* ALSO RO = 6.0 MEGAOHMS
.END
```

```
 ******  DC TRANSFER CURVES      TNOM=  27.000 TEMP=  27.000
   VOLT        I(VO)
(A         )   -1.000E-03       0.          1.000E-03    2.000E-03    3.000E-03
                   +            +            +            +            +

  0.       1.031E-03-+------+------+------+------A------+------+------+------+-
 5.00E-01  9.923E-04 +      +      +      +      A      +      +      +      +
 1.00E+00 -9.911E-04 A      +      +      +      +      +      +      +      +
 1.50E+00 -9.912E-04 A      +      +      +      +      +      +      +      +
 2.00E+00 -9.913E-04 A      +      +      +      +      +      +      +      +
 2.50E+00 -9.913E-04 A      +      +      +      +      +      +      +      +
 3.00E+00 -9.914E-04 A      +      +      +      +      +      +      +      +
 3.50E+00 -9.915E-04 A      +      +      +      +      +      +      +      +
 4.00E+00 -9.916E-04 A      +      +      +      +      +      +      +      +
 4.50E+00 -9.917E-04 A      +      +      +      +      +      +      +      +
 5.00E+00 -9.917E-04-A------+------+------+------+------+------+------+------+-
 5.50E+00 -9.918E-04 A      +      +      +      +      +      +      +      +
 6.00E+00 -9.919E-04 A      +      +      +      +      +      +      +      +
 6.50E+00 -9.920E-04 A      +      +      +      +      +      +      +      +
 7.00E+00 -9.920E-04 A      +      +      +      +      +      +      +      +
 7.50E+00 -9.921E-04 A      +      +      +      +      +      +      +      +
 8.00E+00 -9.922E-04 A      +      +      +      +      +      +      +      +
 8.50E+00 -9.923E-04 A      +      +      +      +      +      +      +      +
 9.00E+00 -9.924E-04 A      +      +      +      +      +      +      +      +
 9.50E+00 -9.924E-04 A      +      +      +      +      +      +      +      +
 1.00E+01 -9.925E-04-A------+------+------+------+------+------+------+------+-
 1.05E+01 -9.926E-04 A      +      +      +      +      +      +      +      +
 1.10E+01 -9.927E-04 A      +      +      +      +      +      +      +      +
 1.15E+01 -9.927E-04 A      +      +      +      +      +      +      +      +
 1.20E+01 -9.928E-04 A      +      +      +      +      +      +      +      +
 1.25E+01 -9.929E-04 A      +      +      +      +      +      +      +      +
 1.30E+01 -9.929E-04 A      +      +      +      +      +      +      +      +
 1.35E+01 -9.930E-04 A      +      +      +      +      +      +      +      +
 1.40E+01 -9.931E-04 A      +      +      +      +      +      +      +      +
 1.45E+01 -9.932E-04 A      +      +      +      +      +      +      +      +
 1.50E+01 -9.932E-04-A------+------+------+------+------+------+------+------+-
                   +            +            +            +            +
```

```
****  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
   NODE      =VOLTAGE      NODE      =VOLTAGE      NODE      =VOLTAGE
+0:2         = 1.353E+00 0:3         = 6.765E-01 0:4         = 2.000E+00
+0:100       = 1.500E+01

**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT  0:Q1       0:Q2       0:Q3
MODEL    0:NPN      0:NPN      0:NPN
 IB       9.811E-06  9.863E-06  9.815E-06
 IC       9.863E-04  9.913E-04  9.815E-04
 VBE      6.765E-01  6.766E-01  6.765E-01
 VCE      1.353E+00  1.323E+00  6.765E-01
 VBC     -6.766E-01 -6.469E-01   0.
 VS      -1.353E+00 -2.000E+00 -6.765E-01
 POWER    1.341E-03  1.319E-03  6.706E-04
 BETAD    1.005E+02  1.005E+02  1.000E+02
 GM       3.812E-02  3.832E-02  3.794E-02
 RPI      2.636E+03  2.622E+03  2.635E+03
 RX       2.000E+02  2.000E+02  2.000E+02
 RO       1.325E+05  1.318E+05  1.324E+05
 BETAAC   1.005E+02  1.004E+02  9.998E+01

****      SMALL-SIGNAL TRANSFER CHARACTERISTICS

     V(2)/VO                                        = -2.055E-04
     INPUT RESISTANCE AT          VO                =  6.039E+06
     OUTPUT RESISTANCE AT V(2)                      =  5.963E+01
```

4.10

$$g_{o1} = \frac{I_{REF}}{L_{eff}} \frac{dX_d}{dV_{DS}} = \frac{I_{REF}}{0.82}(0.02)$$

$$= 0.024\, I_{REF}$$

$$g_{o2} = \frac{I_{REF}}{0.82}(0.04) = 0.049\, I_{REF}$$

(a) In strong inversion,

$$g_{m1} = \sqrt{2k'\left(\frac{W}{L_{eff}}\right)_1 I_{REF}}$$

$$= \sqrt{2 \times 1.94 \times 10^{-4} \times \frac{100}{0.82} I_{REF}}$$

$$= 0.22\sqrt{I_{REF}}$$

$$A_v = \frac{-g_{m1}}{g_{o1}+g_{o2}} = \frac{-0.22\sqrt{I_{REF}}}{0.073\, I_{REF}}$$

$$= \frac{-3.0}{\sqrt{I_{REF}}}$$

I_{REF} (μA)	A_v (hand calc.)
1000	−95
100	−300
10	−950
1	−3000

(b) In the last two cases above, $(V_{GS}-V_t)_1$ calculated by $\sqrt{\frac{2I_{REF}}{k' W/L_{eff}}} < 78\text{mV}$

Therefore, M_1 operates in weak inversion for these cases

From (1.253), $g_{m1} = \frac{I_{REF}}{nV_T} = \frac{I_{REF}}{(1.5)(26\text{mV})}$

$$A_v = \frac{-g_{m1}}{g_{o1}+g_{o2}} = \frac{-I_{REF}}{(1.5)(26\text{mV})} \frac{1}{0.073\, I_{REF}}$$

$$= -350$$

I_{REF} (μA)	A_v (hand calc.)
1000	−95
100	−300
10	−350
1	−350

```
COMMON-SOURCE AMP WITH COMPLEMENTARY LOAD
* WITH IR = 1 MA AND WITHOUT WEAK INVERSION EFFECTS
VDD 100 0  3
VI  1   0  893.3M  AC 1
*THE DC INPUT IS ADJUSTED BY TRIAL AND ERROR SO THAT THE
*DC OUTPUT VOLTAGE IS ABOUT 1 VOLT.
M1  2   1  0   0   CMOSN W=100U L=1U
M2  2   3  100 100 CMOSP W=100U L=1U
M3  3   3  100 100 CMOSP W=100U L=1U
IR  3   0  1M
.MODEL CMOSN NMOS LEVEL=1 LAMBDA=0.024 VTO=0.6  KP=194U LD=0.09U
.MODEL CMOSP PMOS LEVEL=1 LAMBDA=0.049 VTO=-0.6 KP=65U  LD=0.09U
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.TF V(2) VI
.END

 ****  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
   NODE      =VOLTAGE      NODE      =VOLTAGE      NODE      =VOLTAGE
+0:1         = 8.933E-01 0:2         = 1.004E+00 0:3         = 1.910E+00
+0:100       = 3.000E+00

**** MOSFETS
SUBCKT
ELEMENT  0:M1        0:M2        0:M3
MODEL    0:CMOSN     0:CMOSP     0:CMOSP
 ID        1.042E-03 -1.042E-03 -1.000E-03
 IBS         0.          0.          0.
 IBD      -1.005E-14  1.995E-14  1.089E-14
 VGS       8.933E-01 -1.089E+00 -1.089E+00
 VDS       1.004E+00 -1.995E+00 -1.089E+00
 VBS         0.          0.          0.
 VTH       6.000E-01 -6.000E-01 -6.000E-01
 VDSAT     2.933E-01 -4.894E-01 -4.894E-01
 BETA      2.423E-02  8.702E-03  8.350E-03
 GAM EFF     0.          0.          0.
 GM        7.106E-03  4.259E-03  4.087E-03
 GDS       2.442E-05  4.652E-05  4.652E-05
 GMB         0.          0.          0.

****      SMALL-SIGNAL TRANSFER CHARACTERISTICS

     V(2)/VI                                        = -1.001E+02
     INPUT RESISTANCE AT              VI            =  1.000E+20
     OUTPUT RESISTANCE AT V(2)                      =  1.409E+04

COMMON-SOURCE AMP WITH COMPLEMENTARY LOAD
* WITH IR = 100 UA AND WITHOUT WEAK INVERSION EFFECTS
VDD 100 0  3
VI  1   0  693.4M  AC 1
*THE DC INPUT IS ADJUSTED BY TRIAL AND ERROR SO THAT THE
*DC OUTPUT VOLTAGE IS ABOUT 1 VOLT.
M1  2   1  0   0   CMOSN W=100U L=1U
M2  2   3  100 100 CMOSP W=100U L=1U
M3  3   3  100 100 CMOSP W=100U L=1U
IR  3   0  100U
.MODEL CMOSN NMOS LEVEL=1 LAMBDA=0.024 VTO=0.6  KP=194U LD=0.09U
.MODEL CMOSP PMOS LEVEL=1 LAMBDA=0.049 VTO=-0.6 KP=65U  LD=0.09U
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.TF V(2) VI
.END

 ****  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
   NODE      =VOLTAGE      NODE      =VOLTAGE      NODE      =VOLTAGE
+0:1         = 6.934E-01 0:2         = 1.028E+00 0:3         = 2.244E+00
+0:100       = 3.000E+00

**** MOSFETS
SUBCKT
ELEMENT  0:M1        0:M2        0:M3
MODEL    0:CMOSN     0:CMOSP     0:CMOSP
 ID        1.057E-04 -1.057E-04 -1.000E-04
 IBS         0.          0.          0.
 IBD      -1.029E-14  1.971E-14  7.560E-15
 VGS       6.934E-01 -7.560E-01 -7.560E-01
 VDS       1.028E+00 -1.971E+00 -7.560E-01
 VBS         0.          0.          0.
 VTH       6.000E-01 -6.000E-01 -6.000E-01
 VDSAT     9.340E-02 -1.560E-01 -1.560E-01
 BETA      2.424E-02  8.692E-03  8.220E-03
 GAM EFF     0.          0.          0.
 GM        2.264E-03  1.356E-03  1.282E-03
 GDS       2.477E-06  4.725E-06  4.725E-06
 GMB         0.          0.          0.

****      SMALL-SIGNAL TRANSFER CHARACTERISTICS

     V(2)/VI                                        = -3.144E+02
     INPUT RESISTANCE AT              VI            =  1.000E+20
     OUTPUT RESISTANCE AT V(2)                      =  1.388E+05

COMMON-SOURCE AMP WITH COMPLEMENTARY LOAD
* WITH IR = 10 UA AND WITHOUT WEAK INVERSION EFFECTS
VDD 100 0  3
VI  1   0  629.6M  AC 1
*THE DC INPUT IS ADJUSTED BY TRIAL AND ERROR SO THAT THE
*DC OUTPUT VOLTAGE IS ABOUT 1 VOLT.
M1  2   1  0   0   CMOSN W=100U L=1U
M2  2   3  100 100 CMOSP W=100U L=1U
M3  3   3  100 100 CMOSP W=100U L=1U
IR  3   0  10U
.MODEL CMOSN NMOS LEVEL=1 LAMBDA=0.024 VTO=0.6  KP=194U LD=0.09U
.MODEL CMOSP PMOS LEVEL=1 LAMBDA=0.049 VTO=-0.6 KP=65U  LD=0.09U
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.TF V(2) VI
.END

 ****  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
   NODE      =VOLTAGE      NODE      =VOLTAGE      NODE      =VOLTAGE
+0:1         = 6.296E-01 0:2         = 1.039E+00 0:3         = 2.350E+00
+0:100       = 3.000E+00

**** MOSFETS
SUBCKT
ELEMENT  0:M1        0:M2        0:M3
MODEL    0:CMOSN     0:CMOSP     0:CMOSP
 ID        1.062E-05 -1.062E-05 -1.000E-05
 IBS         0.          0.          0.
 IBD      -1.039E-14  1.961E-14  6.494E-15
 VGS       6.296E-01 -6.494E-01 -6.494E-01
 VDS       1.039E+00 -1.960E+00 -6.494E-01
 VBS         0.          0.          0.
 VTH       6.000E-01 -6.000E-01 -6.000E-01
 VDSAT     2.960E-02 -4.945E-02 -4.945E-02
 BETA      2.425E-02  8.688E-03  8.179E-03
 GAM EFF     0.          0.          0.
 GM        7.178E-04  4.296E-04  4.045E-04
 GDS       2.487E-07  4.749E-07  4.749E-07
 GMB         0.          0.          0.

****      SMALL-SIGNAL TRANSFER CHARACTERISTICS

     V(2)/VI                                        = -9.918E+02
     INPUT RESISTANCE AT              VI            =  1.000E+20
     OUTPUT RESISTANCE AT V(2)                      =  1.381E+06
```

```
COMMON-SOURCE AMP WITH COMPLEMENTARY LOAD
* WITH IR = 1 UA AND WITHOUT WEAK INVERSION EFFECTS
VDD 100 0  3
VI  1   0  609.38M AC 1
*THE DC INPUT IS ADJUSTED BY TRIAL AND ERROR SO THAT THE
*DC OUTPUT VOLTAGE IS ABOUT 1 VOLT.
M1  2   1  0   0   CMOSN W=100U L=1U
M2  2   3  100 100 CMOSP W=100U L=1U
M3  3   3  100 100 CMOSP W=100U L=1U
IR  3   0  1U
.MODEL CMOSN NMOS LEVEL=1 LAMBDA=0.024 VTO=0.6  KP=194U LD=0.09U
.MODEL CMOSP PMOS LEVEL=1 LAMBDA=0.049 VTO=-0.6 KP=65U  LD=0.09U
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.TF V(2) VI
.END

 ****  OPERATING POINT INFORMATION     TNOM=  27.000 TEMP=  27.000
   NODE      =VOLTAGE       NODE      =VOLTAGE       NODE      =VOLTAGE
+0:1        = 6.094E-01 0:2         = 1.001E+00 0:3         = 2.384E+00
+0:100      = 3.000E+00

**** MOSFETS
SUBCKT
ELEMENT  0:M1        0:M2        0:M3
MODEL    0:CMOSN     0:CMOSP     0:CMOSP
 ID       1.066E-06 -1.066E-06 -1.000E-06
 IBS       0.         0.         0.
 IBD      -1.001E-14  1.999E-14  6.156E-15
 VGS       6.094E-01 -6.156E-01 -6.156E-01
 VDS       1.001E+00 -1.998E+00 -6.156E-01
 VBS       0.         0.         0.
 VTH       6.000E-01 -6.000E-01 -6.000E-01
 VDSAT     9.380E-03 -1.565E-02 -1.565E-02
 BETA      2.423E-02  8.703E-03  8.166E-03
 GAM EFF   0.         0.         0.
 GM        2.272E-04  1.362E-04  1.278E-04
 GDS       2.498E-08  4.757E-08  4.757E-08
 GMB       0.         0.         0.

****      SMALL-SIGNAL TRANSFER CHARACTERISTICS

    V(2)/VI                                    = -3.132E+03
    INPUT RESISTANCE AT          VI            =  1.000E+20
    OUTPUT RESISTANCE AT V(2)                  =  1.378E+07

COMMON-SOURCE AMP WITH COMPLEMENTARY LOAD
* WITH IR = 1 MA AND WITH WEAK INVERSION EFFECTS
VDD 100 0  3
VI  1   0  901.0M  AC 1
*THE DC INPUT IS ADJUSTED BY TRIAL AND ERROR SO THAT THE
*DC OUTPUT VOLTAGE IS ABOUT 1 VOLT.
M1  2   1  0   0   CMOSN W=100U L=1U
M2  2   3  100 100 CMOSP W=100U L=1U
M3  3   3  100 100 CMOSP W=100U L=1U
IR  3   0  1M
* TO INCLUDE WEAK INVERSION EFFECTS, MUST CHANGE TO AT LEAST
* THE LEVEL 2 MODEL.
.MODEL CMOSN NMOS LEVEL=2 VTO=0.6 KP=194U LD=0.09U
+ TOX=8E-09 LAMBDA=0.024 NFS=1.35E12 NSUB=5E15
.MODEL CMOSP PMOS LEVEL=2 VTO=-0.6 KP=65U LD=0.09U
+ TOX=8E-09 LAMBDA=0.049 NFS=1.35E12 NSUB=4E16

* IN THE HSPICE MODEL, ID IS PROPORTIONAL TO EXP[(VGS - VT)/FAST]
* IN CHAPTER 1, ID IS PROPORTIONAL TO EXP[(VGS - VT)/(NVT)]
* THEREFORE, FAST MUST EQUAL NVT (WHICH IS N THERMAL VOLTAGES)
* FROM PAGE 7-19 OF THE HSPICE MANUAL,
* FAST IS ABOUT EQUAL TO VT(1 + Q NFS/COX)
* THEREFORE N = 1 + Q NFS/COX
* SOLVING FOR NFS GIVES NFS = (N-1)COX/Q
* COX SHOULD BE IN FARADS/CM^2 AND Q IS IN COULOMBS
* FOR EXAMPLE, IF N=1.5, COX = 4.32E-7 (FOR TOX=80 ANGSTROMS)
* NFS = 0.5*4.32E-7/1.6E-19 = 1.35E12

.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.TF V(2) VI
.END

****  OPERATING POINT INFORMATION     TNOM=  27.000 TEMP=  27.000
   NODE      =VOLTAGE       NODE      =VOLTAGE       NODE      =VOLTAGE
+0:1        = 9.010E-01 0:2         = 1.077E+00 0:3         = 1.878E+00
+0:100      = 3.000E+00

**** MOSFETS
SUBCKT
ELEMENT  0:M1        0:M2        0:M3
MODEL    0:CMOSN     0:CMOSP     0:CMOSP
 ID       1.043E-03 -1.043E-03 -1.000E-03
 IBS       0.         0.         0.
 IBD      -1.078E-14  1.922E-14  1.121E-14
 VGS       9.010E-01 -1.121E+00 -1.121E+00
 VDS       1.077E+00 -1.922E+00 -1.121E+00
 VBS       0.         0.         0.
 VTH       6.000E-01 -6.000E-01 -6.000E-01
 VDSAT     2.859E-01 -4.595E-01 -4.595E-01
 BETA      2.429E-02  8.751E-03  8.388E-03
 GAM EFF   9.438E-02  2.670E-01  2.670E-01
 GM        6.943E-03  4.021E-03  3.854E-03
 GDS       2.570E-05  5.644E-05  5.185E-05
 GMB       3.674E-04  5.414E-04  5.189E-04

****      SMALL-SIGNAL TRANSFER CHARACTERISTICS

    V(2)/VI                                    = -8.452E+01
    INPUT RESISTANCE AT          VI            =  1.000E+20
    OUTPUT RESISTANCE AT V(2)                  =  1.217E+04

COMMON-SOURCE AMP WITH COMPLEMENTARY LOAD
* WITH IR = 100 UA AND WITH WEAK INVERSION EFFECTS
VDD 100 0  3
VI  1   0  696.4M  AC 1
*THE DC INPUT IS ADJUSTED BY TRIAL AND ERROR SO THAT THE
*DC OUTPUT VOLTAGE IS ABOUT 1 VOLT.
M1  2   1  0   0   CMOSN W=100U L=1U
M2  2   3  100 100 CMOSP W=100U L=1U
M3  3   3  100 100 CMOSP W=100U L=1U
IR  3   0  100U
* TO INCLUDE WEAK INVERSION EFFECTS, MUST CHANGE TO AT LEAST
* THE LEVEL 2 MODEL.
.MODEL CMOSN NMOS LEVEL=2 VTO=0.6 KP=194U LD=0.09U
+ TOX=8E-09 LAMBDA=0.024 NFS=1.35E12 NSUB=5E15
.MODEL CMOSP PMOS LEVEL=2 VTO=-0.6 KP=65U LD=0.09U
+ TOX=8E-09 LAMBDA=0.049 NFS=1.35E12 NSUB=4E16

* IN THE HSPICE MODEL, ID IS PROPORTIONAL TO EXP[(VGS - VT)/FAST]
* IN CHAPTER 1, ID IS PROPORTIONAL TO EXP[(VGS - VT)/(NVT)]
* THEREFORE, FAST MUST EQUAL NVT (WHICH IS N THERMAL VOLTAGES)
* FROM PAGE 7-19 OF THE HSPICE MANUAL,
* FAST IS ABOUT EQUAL TO VT(1 + Q NFS/COX)
* THEREFORE N = 1 + Q NFS/COX
* SOLVING FOR NFS GIVES NFS = (N-1)COX/Q
* COX SHOULD BE IN FARADS/CM^2 AND Q IS IN COULOMBS
* FOR EXAMPLE, IF N=1.5, COX = 4.32E-7 (FOR TOX=80 ANGSTROMS)
* NFS = 0.5*4.32E-7/1.6E-19 = 1.35E12

.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.TF V(2) VI
.END

****  OPERATING POINT INFORMATION     TNOM=  27.000 TEMP=  27.000
   NODE      =VOLTAGE       NODE      =VOLTAGE       NODE      =VOLTAGE
+0:1        = 6.964E-01 0:2         = 1.014E+00 0:3         = 2.233E+00
+0:100      = 3.000E+00
```

```
**** MOSFETS
SUBCKT
ELEMENT  0:M1       0:M2       0:M3
MODEL    0:CMOSN    0:CMOSP    0:CMOSP
 ID       1.066E-04 -1.066E-04 -1.000E-04
 IBS       0.         0.         0.
 IBD      -1.015E-14  1.985E-14  7.670E-15
 VGS       6.964E-01 -7.670E-01 -7.670E-01
 VDS       1.014E+00 -1.985E+00 -7.670E-01
 VBS       0.         0.         0.
 VTH       6.000E-01 -6.000E-01 -6.000E-01
 VDSAT     9.127E-02 -1.457E-01 -1.457E-01
 BETA      2.425E-02  8.781E-03  8.236E-03
 GAM EFF   9.438E-02  2.670E-01  2.670E-01
 GM        2.213E-03  1.279E-03  1.200E-03
 GDS       2.623E-06  5.787E-06  5.091E-06
 GMB       1.245E-04  1.866E-04  1.750E-04

****      SMALL-SIGNAL TRANSFER CHARACTERISTICS

     V(2)/VI                                  = -2.631E+02
     INPUT RESISTANCE AT          VI          =  1.000E+20
     OUTPUT RESISTANCE AT V(2)                =  1.189E+05

COMMON-SOURCE AMP WITH COMPLEMENTARY LOAD
* WITH IR = 10 UA AND WITH WEAK INVERSION EFFECTS
VDD 100 0  3
VI  1   0  618.1M  AC 1
*THE DC INPUT IS ADJUSTED BY TRIAL AND ERROR SO THAT THE
*DC OUTPUT VOLTAGE IS ABOUT 1 VOLT.
M1  2   1  0   0   CMOSN W=100U L=1U
M2  2   3  100 100 CMOSP W=100U L=1U
M3  3   3  100 100 CMOSP W=100U L=1U
IR  3   0  10U
* TO INCLUDE WEAK INVERSION EFFECTS, MUST CHANGE TO AT LEAST
* THE LEVEL 2 MODEL.
.MODEL CMOSN NMOS LEVEL=2 VTO=0.6 KP=194U LD=0.09U
+ TOX=8E-09 LAMBDA=0.024 NFS=1.35E12 NSUB=5E15
.MODEL CMOSP PMOS LEVEL=2 VTO=-0.6 KP=65U LD=0.09U
+ TOX=8E-09 LAMBDA=0.049 NFS=1.35E12 NSUB=4E16

* IN THE HSPICE MODEL, ID IS PROPORTIONAL TO EXP[(VGS - VT)/FAST]
* IN CHAPTER 1, ID IS PROPORTIONAL TO EXP[(VGS - VT)/(NVT)]
* THEREFORE, FAST MUST EQUAL NVT (WHICH IS N THERMAL VOLTAGES)
* FROM PAGE 7-19 OF THE HSPICE MANUAL,
* FAST IS ABOUT EQUAL TO VT(1 + Q NFS/COX)
* THEREFORE N = 1 + Q NFS/COX
* SOLVING FOR NFS GIVES NFS = (N-1)COX/Q
* COX SHOULD BE IN FARADS/CM^2 AND Q IS IN COULOMBS
* FOR EXAMPLE, IF N=1.5, COX = 4.32E-7 (FOR TOX=80 ANGSTROMS)
* NFS = 0.5*4.32E-7/1.6E-19 = 1.35E12

.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.TF V(2) VI
.END

 ****  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
   NODE     =VOLTAGE       NODE      =VOLTAGE       NODE      =VOLTAGE
+0:1        = 6.181E-01 0:2          = 9.893E-01 0:3          = 2.347E+00
+0:100      = 3.000E+00

**** MOSFETS
SUBCKT
ELEMENT  0:M1       0:M2       0:M3
MODEL    0:CMOSN    0:CMOSP    0:CMOSP
 ID       1.074E-05 -1.074E-05 -1.000E-05
 IBS       0.         0.         0.
 IBD      -9.893E-15  2.011E-14  6.530E-15
 VGS       6.181E-01 -6.530E-01 -6.530E-01
 VDS       9.893E-01 -2.010E+00 -6.530E-01
 VBS       0.         0.         0.
 VTH       6.000E-01 -6.000E-01 -6.000E-01
 VDSAT     3.814E-02 -4.609E-02 -4.609E-02
 BETA      2.423E-02  8.793E-03  8.189E-03
 GAM EFF   9.438E-02  2.670E-01  2.670E-01
 GM        2.663E-04  4.053E-04  3.775E-04
 GDS       2.640E-07  5.837E-07  5.062E-07
 GMB       1.457E-05  6.089E-05  5.671E-05

****      SMALL-SIGNAL TRANSFER CHARACTERISTICS

     V(2)/VI                                  = -3.141E+02
     INPUT RESISTANCE AT          VI          =  9.999E+19
     OUTPUT RESISTANCE AT V(2)                =  1.179E+06

COMMON-SOURCE AMP WITH COMPLEMENTARY LOAD
* WITH IR = 1 UA AND WITH WEAK INVERSION EFFECTS
VDD 100 0  3
VI  1   0  525.4M  AC 1
*THE DC INPUT IS ADJUSTED BY TRIAL AND ERROR SO THAT THE
*DC OUTPUT VOLTAGE IS ABOUT 1 VOLT.
M1  2   1  0   0   CMOSN W=100U L=1U
M2  2   3  100 100 CMOSP W=100U L=1U
M3  3   3  100 100 CMOSP W=100U L=1U
IR  3   0  1U
* TO INCLUDE WEAK INVERSION EFFECTS, MUST CHANGE TO AT LEAST
* THE LEVEL 2 MODEL.
.MODEL CMOSN NMOS LEVEL=2 VTO=0.6 KP=194U LD=0.09U
+ TOX=8E-09 LAMBDA=0.024 NFS=1.35E12 NSUB=5E15
.MODEL CMOSP PMOS LEVEL=2 VTO=-0.6 KP=65U LD=0.09U
+ TOX=8E-09 LAMBDA=0.049 NFS=1.35E12 NSUB=4E16

* IN THE HSPICE MODEL, ID IS PROPORTIONAL TO EXP[(VGS - VT)/FAST]
* IN CHAPTER 1, ID IS PROPORTIONAL TO EXP[(VGS - VT)/(NVT)]
* THEREFORE, FAST MUST EQUAL NVT (WHICH IS N THERMAL VOLTAGES)
* FROM PAGE 7-19 OF THE HSPICE MANUAL,
* FAST IS ABOUT EQUAL TO VT(1 + Q NFS/COX)
* THEREFORE N = 1 + Q NFS/COX
* SOLVING FOR NFS GIVES NFS = (N-1)COX/Q
* COX SHOULD BE IN FARADS/CM^2 AND Q IS IN COULOMBS
* FOR EXAMPLE, IF N=1.5, COX = 4.32E-7 (FOR TOX=80 ANGSTROMS)
* NFS = 0.5*4.32E-7/1.6E-19 = 1.35E12

.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.TF V(2) VI
.END

 ****  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
   NODE     =VOLTAGE       NODE      =VOLTAGE       NODE      =VOLTAGE
+0:1        = 5.254E-01 0:2          = 9.969E-01 0:3          = 2.437E+00
+0:100      = 3.000E+00

**** MOSFETS
SUBCKT
ELEMENT  0:M1       0:M2       0:M3
MODEL    0:CMOSN    0:CMOSP    0:CMOSP
 ID       1.078E-06 -1.078E-06 -1.000E-06
 IBS       0.         0.         0.
 IBD      -9.969E-15  2.003E-14  5.629E-15
 VGS       5.254E-01 -5.629E-01 -5.629E-01
 VDS       9.969E-01 -2.003E+00 -5.629E-01
 VBS       0.         0.         0.
 VTH       6.000E-01 -6.000E-01 -6.000E-01
 VDSAT     3.814E-02 -3.717E-02 -3.717E-02
 BETA      2.424E-02  8.790E-03  8.152E-03
 GAM EFF   9.438E-02  2.670E-01  2.670E-01
 GM        2.674E-05  2.521E-05  2.338E-05
 GDS       2.651E-08  5.858E-08  5.039E-08
 GMB       1.393E-06  3.567E-06  3.308E-06

****      SMALL-SIGNAL TRANSFER CHARACTERISTICS

     V(2)/VI                                  = -3.141E+02
     INPUT RESISTANCE AT          VI          =  9.999E+19
     OUTPUT RESISTANCE AT V(2)                =  1.175E+07
```

4.11

From (1.140),

$$V_{t_2} = V_{t_{2,0}} + \gamma\left[\sqrt{2\phi_f + V_{SB_2}} - \sqrt{2\phi_f}\right]$$

$$C_{ox} = \frac{3.9 \times 8.86\times10^{-14}}{80\times10^{-8}} = 4.3\times10^{-7}\ \frac{F}{cm^2}$$

$$\gamma = \frac{1}{4.3\times10^{-7}}\sqrt{2(1.6\times10^{-19})(11.6)(8.86\times10^{-14})(5\times10^{15})}$$

$$= 0.094\ V^{1/2}$$

From (1.135),

$$2\phi_f = 2V_T \ln\frac{5\times10^{15}}{1.45\times10^{10}} = 663\ mV$$

so, $V_{t_2} = -1 + 0.094\left[\sqrt{1.663} - \sqrt{0.663}\right]$

$$= -0.955$$

$$I_{D_2} = \frac{k'}{2}\left(\frac{W}{L_{eff2}}\right)(V_{GS_2} - V_t)^2$$

$$= \frac{194}{2}\ \frac{10}{0.82}\ (0 + 0.955)^2 = 1.08\ mA$$

From (4.120),

$$\frac{v_o}{v_i} = -g_{m_1}\left(r_{o1} \| r_{o2} \| \frac{1}{g_{mb_2}}\right) = \frac{-g_{m_1}}{g_{o1} + g_{o2} + g_{mb_2}}$$

$$g_{m_1} = \sqrt{2(194)\frac{100}{0.82}(1080)} = 7.2\ mA/V$$

From (1.199),

$$g_{mb_2} = \frac{\gamma k'\left(\frac{W}{L_{eff}}\right)_2 (V_{GS_2} - V_{t_2})}{2\sqrt{2\phi_f + V_{SB_2}}} = \frac{0.094(194)\frac{10}{0.82}(0.955)}{2\sqrt{1.663}}$$

$$= 82.3\ \mu A/V$$

$$g_{o1} = g_{o2} = r_{o1}^{-1} = r_{o2}^{-1} = \frac{I_D}{L_{eff}}\ \frac{dX_d}{dV_{DS}} = \frac{1.08}{0.82}(0.02)$$

$$= 26.3\ \mu A/V$$

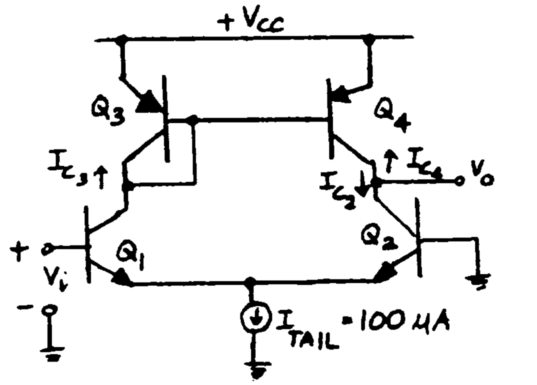
$$\frac{v_o}{v_i} = -\frac{7.2m}{2(26.3\mu) + 82.3} = -53$$

4.12

$V_{A_{pnp}} = 50V$ $\quad V_{A_{npn}} = 130V$

$\beta_{F_{pnp}} = 50$ $\quad \beta_{F_{npn}} = 200$

Assume no device mismatch



$$I_{c_1} \approx I_{c_2} = \frac{I_{EE}}{2} = 50\ \mu A = I_c$$

$$I_{c_3} \approx I_{c_4} = -50\ \mu A$$

$$\therefore g_m = \frac{I_c}{V_T} = \frac{50\ \mu A}{26\ mV} = \frac{1}{520}\ \mho$$

$$r_{o_{pnp}} = \frac{V_{A_{pnp}}}{I_c} = 1\ M\Omega$$

$$r_{o_{npn}} = \frac{V_{A_{npn}}}{I_c} = 2.6\ M\Omega$$

Since unloaded, the output resistance is

$$R_{OUT} = r_{o_{pnp}} \| r_{o_{npn}} = 722\ k\Omega$$

$$A_V = g_m R_{OUT} = \frac{1}{520} \times 722k$$

$$= 1388$$

```
BJT DIFFERENTIAL PAIR WITH CURRENT-MIRROR LOAD
******
VCC   100 0   2.5
VEE   200 0   -2.5
Q1    2   3   4     NPN
Q2    6   0   4     NPN
Q3    2   2   100   PNP
Q4    6   2   100   PNP
ITAIL 4   200 100U
RTAIL 4   200 1MEG
.MODEL NPN NPN RB=200 BF=200 VAF=130 IS=5E-15
.MODEL PNP PNP RB=300 BF=50  VAF=50  IS=2E-15

* A DC INPUT VOLTAGE OF ABOUT 1 MV FORCES THE COLLECTOR-EMITTER
* VOLTAGE OF Q2 ABOUT EQUAL TO THAT OF Q1.
VIDC  3   5   1M
VI    5   0
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.DC VI -0.01 0.01 0.002
.PLOT DC V(6)
.TF V(6) VI
.END

 ******  DC TRANSFER CURVES      TNOM=  27.000 TEMP=  27.000

    VOLT       V(6)
(A       )    -1.000E-00      0.          1.000E-00     2.000E+00    3.000E+00
                    +           +            +            +            +
-1.000E-02 -5.47E-01-+-----A+------+------+------+------+------+------+-
-8.000E-03 -5.39E-01 +     A+      +      +      +      +      +      +
-6.000E-03 -5.29E-01 +      A      +      +      +      +      +      +
-4.000E-03 -5.12E-01 +      A      +      +      +      +      +      +
-2.000E-03 -4.63E-01 +     +A      +      +      +      +      +      +
 0.         1.85E+00 +      +      +      +      +      +  A +      +      +
 2.000E-03  2.39E+00 +      +      +      +      +      +     A+      +
 4.000E-03  2.41E+00 +      +      +      +      +      +     A+      +
 6.000E-03  2.42E+00 +      +      +      +      +      +     A+      +
 8.000E-03  2.43E+00 +      +      +      +      +      +     A+      +
 1.000E-02  2.44E+00-+------+------+------+------+------+-----A+------+-
                    +           +            +            +            +
 ****  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
  NODE      =VOLTAGE       NODE      =VOLTAGE       NODE       =VOLTAGE
+0:2        = 1.880E+00 0:3          = 1.000E-03 0:4            =-5.951E-01
+0:5        =    0.     0:6          = 1.857E+00 0:100          = 2.500E+00
+0:200      =-2.500E+00

**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT   0:Q1         0:Q2         0:Q3         0:Q4
MODEL     0:NPN        0:NPN        0:PNP        0:PNP
 IB        2.547E-07    2.451E-07   -9.939E-07   -9.939E-07
 IC        5.168E-05    4.972E-05   -4.970E-05   -4.972E-05
 VBE       5.961E-01    5.951E-01   -6.194E-01   -6.194E-01
 VCE       2.475E+00    2.452E+00   -6.194E-01   -6.426E-01
 VBC      -1.879E+00   -1.857E+00    0.           2.318E-02
 VS       -1.880E+00   -1.857E+00   -1.880E+00   -1.880E+00
 POWER     1.281E-04    1.221E-04    3.140E-05    3.256E-05
 BETAD     2.028E+02    2.028E+02    5.000E+01    5.002E+01
 GM        1.998E-03    1.922E-03    1.920E-03    1.921E-03
 RPI       1.015E+05    1.055E+05    2.602E+04    2.602E+04
 RX        2.000E+02    2.000E+02    3.000E+02    3.000E+02
 RO        2.551E+06    2.652E+06    1.006E+06    1.006E+06
 BETAAC    2.028E+02    2.028E+02    4.997E+01    4.999E+01

 ****      SMALL-SIGNAL TRANSFER CHARACTERISTICS

     V(6)/VI                                          =  1.398E+03
     INPUT RESISTANCE AT          VI                  =  2.853E+05
     OUTPUT RESISTANCE AT V(6)                        =  7.294E+05
```

```
BJT DIFFERENTIAL PAIR WITH CURRENT-MIRROR LOAD
* (COMMON-MODE INPUT)
******
VCC   100 0   2.5
VEE   200 0   -2.5
Q1    2   3   4     NPN
Q2    6   5   4     NPN
* |CMRR| = 1398/0.0002561 = 5.46E6
Q3    2   2   100   PNP
Q4    6   2   100   PNP
ITAIL 4   200 100U
RTAIL 4   200 1MEG
.MODEL NPN NPN RB=200 BF=200 VAF=130 IS=5E-15
.MODEL PNP PNP RB=300 BF=50  VAF=50  IS=2E-15

* A DC INPUT VOLTAGE OF ABOUT 1 MV FORCES THE COLLECTOR-EMITTER
* VOLTAGE OF Q2 ABOUT EQUAL TO THAT OF Q1.
VIDC  3   5   1M
VI    5   0
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.DC VI -0.01 0.01 0.002
.PLOT DC V(6)
.TF V(6) VI
.END

 ******  DC TRANSFER CURVES      TNOM=  27.000 TEMP=  27.000
******

    VOLT       V(6)
(A       )     1.857E+00    1.857E+00    1.857E+00    1.857E+00    1.857E+00
                    +           +            +            +            +
-1.000E-02  1.85E+00-+------+------+------+------+------+------+--A---+------+-
-8.000E-03  1.85E+00 +      +      -      +      +      +     A+      +      +
-6.000E-03  1.85E+00 +      +      +      +      +      +  A   +      +      +
-4.000E-03  1.85E+00 +      +      -      +      +     A+      +      +      +
-2.000E-03  1.85E+00 +      +      +      +      + A    +      +      +      +
 0.         1.85E+00 +      +      +      +     A+      +      +      +      +
 2.000E-03  1.85E+00 +      +      +      + A    +      +      +      +      +
 4.000E-03  1.85E+00 +      +      +     A+      +      +      +      +      +
 6.000E-03  1.85E+00 +      +      + A    +      +      +      +      +      +
 8.000E-03  1.85E+00 +      +     A+      +      +      +      +      +      +
 1.000E-02  1.85E+00-+------+-A----+------+------+------+------+------+------+-
                    +           +            +            +            +
 ****  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
  NODE      =VOLTAGE       NODE      =VOLTAGE       NODE       =VOLTAGE
+0:2        = 1.880E+00 0:3          = 1.000E-03 0:4            =-5.951E-01
+0:5        =    0.     0:6          = 1.857E+00 0:100          = 2.500E+00
+0:200      =-2.500E+00

**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT   0:Q1         0:Q2         0:Q3         0:Q4
MODEL     0:NPN        0:NPN        0:PNP        0:PNP
 IB        2.547E-07    2.451E-07   -9.939E-07   -9.939E-07
 IC        5.168E-05    4.972E-05   -4.970E-05   -4.972E-05
 VBE       5.961E-01    5.951E-01   -6.194E-01   -6.194E-01
 VCE       2.475E+00    2.452E+00   -6.194E-01   -6.426E-01
 VBC      -1.879E+00   -1.857E+00    0.           2.318E-02
 VS       -1.880E+00   -1.857E+00   -1.880E+00   -1.880E+00
 POWER     1.281E-04    1.221E-04    3.140E-05    3.256E-05
 BETAD     2.028E+02    2.028E+02    5.000E+01    5.002E+01
 GM        1.998E-03    1.922E-03    1.920E-03    1.921E-03
 RPI       1.015E+05    1.055E+05    2.602E+04    2.602E+04
 RX        2.000E+02    2.000E+02    3.000E+02    3.000E+02
 RO        2.551E+06    2.652E+06    1.006E+06    1.006E+06
 BETAAC    2.028E+02    2.028E+02    4.997E+01    4.999E+01

 ****      SMALL-SIGNAL TRANSFER CHARACTERISTICS

     V(6)/VI                                          = -2.561E-04
     INPUT RESISTANCE AT          VI                  =  1.152E+08
     OUTPUT RESISTANCE AT V(6)                        =  7.294E+05
```

4.13

$$R_{o_{pnp}} = r_{o_{pnp}} \left(1 + g_m \left(R_E \| \left(r_\pi + R_e\right)\right)\right)$$

$$= 1M\left(1 + \frac{1}{520}\left(2k \| 50(520) + 2k\right)\right)$$

$$= 1M\left(1 + \frac{1867}{520}\right)$$

$$= 4.59\ M\Omega$$

$$R_{out} = 4.59\ M \| R_{o_{pnp}} = 4.59\ M \| 2.6\ M$$

$$= 1.66\ M\Omega$$

$$A_v = g_m R_{out} = \frac{1}{520}(1.66\ M) = 3192$$

```
BJT DIFFERENTIAL PAIR WITH EMITTER-DEGENERATED CURRENT-MIRROR LOAD
******
VCC   100 0   2.5
VEE   200 0   -2.5
Q1    2   3   4    NPN
Q2    6   0   4    NPN
Q3    2   2   8    PNP
Q4    6   2   9    PNP
RE3   100 8   2K
RE4   100 9   2K
ITAIL 4   200 100U
RTAIL 4   200 1MEG
.MODEL NPN NPN RB=200 BF=200 VAF=130 IS=5E-15
.MODEL PNP PNP RB=300 BF=50  VAF=50  IS=2E-15

* A DC INPUT VOLTAGE OF ABOUT 1 MV IS REQUIRED TO FORCE
* ALL THE TRANSISTORS TO OPERATE IN THE FORWARD-ACTIVE REGION.
VIDC  3   5   1M
VI    5   0
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.DC VI -0.01 0.01 0.001
.PLOT DC V(6)
.TF V(6) VI
.END

 ******  DC TRANSFER CURVES      TNOM=  27.000 TEMP=  27.000

   VOLT      V(6)
(A       )    -1.000E-00       0.          1.000E-00      2.000E+00     3.000E+00
                    +             +              +              +              +
-1.000E-02 -5.50E-01-+-----A+-----+------+------+------+------+------+------+-
-9.000E-03 -5.46E-01 +     A+     +      +      +      +      +      +      +
-8.000E-03 -5.43E-01 +     A+     +      +      +      +      +      +      +
-7.000E-03 -5.39E-01 +     A+     +      +      +      +      +      +      +
-6.000E-03 -5.34E-01 +      A     +      +      +      +      +      +      +
-5.000E-03 -5.28E-01 +      A     +      +      +      +      +      +      +
-4.000E-03 -5.21E-01 +      A     +      +      +      +      +      +      +
-3.000E-03 -5.11E-01 +      A     +      +      +      +      +      +      +
-2.000E-03 -4.96E-01 +      A     +      +      +      +      +      +      +
-1.000E-03 -4.58E-01 +      +A    +      +      +      +      +      +      +
 0.         1.72E+00-+------+-----+------+------+------+--A---+------+------+-
 1.000E-03  2.28E+00 +      +     +      +      +      +      +  A   +      +
 2.000E-03  2.30E+00 +      +     +      +      +      +      +  A   +      +
 3.000E-03  2.31E+00 +      +     +      +      +      +      +  A   +      +
 4.000E-03  2.32E+00 +      +     +      +      +      +      +   A  +      +
 5.000E-03  2.33E+00 +      +     +      +      +      +      +   A  +      +
 6.000E-03  2.33E+00 +      +     +      +      +      +      +   A  +      +
 7.000E-03  2.34E+00 +      +     +      +      +      +      +   A  +      +
 8.000E-03  2.34E+00 +      +     +      +      +      +      +   A  +      +
 9.000E-03  2.34E+00 +      +     +      +      +      +      +   A  +      +
 1.000E-02  2.35E+00-+------+-----+------+------+------+------+---A--+------+-
                    +             +              +              +              +
 ****  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
   NODE      =VOLTAGE      NODE      =VOLTAGE      NODE      =VOLTAGE
 +0:2        = 1.779E+00 0:3         = 1.000E-03 0:4         =-5.951E-01
 +0:5        =    0.     0:6         = 1.727E+00 0:8         = 2.398E+00
 +0:9        = 2.398E+00 0:100       = 2.500E+00 0:200       =-2.500E+00

 **** BIPOLAR JUNCTION TRANSISTORS
 SUBCKT
 ELEMENT  0:Q1        0:Q2        0:Q3        0:Q4
 MODEL    0:NPN       0:NPN       0:PNP       0:PNP
  IB       2.550E-07   2.453E-07  -9.941E-07  -9.932E-07
  IC       5.169E-05   4.971E-05  -4.970E-05  -4.971E-05
  VBE      5.961E-01   5.951E-01  -6.194E-01  -6.194E-01
  VCE      2.374E+00   2.322E+00  -6.194E-01  -6.713E-01
  VBC     -1.778E+00  -1.727E+00   0.          5.197E-02
  VS      -1.779E+00  -1.727E+00  -1.779E+00  -1.779E+00
  POWER    1.229E-04   1.156E-04   3.140E-05   3.399E-05
  BETAD    2.027E+02   2.026E+02   5.000E+01   5.005E+01
  GM       1.998E-03   1.922E-03   1.921E-03   1.921E-03
  RPI      1.014E+05   1.054E+05   2.601E+04   2.604E+04
  RX       2.000E+02   2.000E+02   3.000E+02   3.000E+02
  RO       2.549E+06   2.649E+06   1.006E+06   1.006E+06
  BETAAC   2.027E+02   2.026E+02   4.997E+01   5.002E+01

 ****      SMALL-SIGNAL TRANSFER CHARACTERISTICS

      V(6)/VI                                    =  3.136E+03
      INPUT RESISTANCE AT          VI            =  5.358E+05
      OUTPUT RESISTANCE AT V(6)                  =  1.636E+06
```

```
BJT DIFFERENTIAL PAIR WITH EMITTER-DEGENERATED CURRENT-MIRROR LOAD
* (COMMON-MODE INPUT)
******
VCC   100 0   2.5
VEE   200 0   -2.5
Q1    2   3   4    NPN
Q2    6   5   4    NPN
* |CMRR| = 3136/0.00124 = 2.53E6
Q3    2   2   8    PNP
Q4    6   2   9    PNP
RE3   100 8   2K
RE4   100 9   2K
ITAIL 4   200 100U
RTAIL 4   200 1MEG
.MODEL NPN NPN RB=200 BF=200 VAF=130 IS=5E-15
.MODEL PNP PNP RB=300 BF=50  VAF=50  IS=2E-15

* A DC INPUT VOLTAGE OF ABOUT 1 MV IS REQUIRED TO FORCE
* ALL THE TRANSISTORS TO OPERATE IN THE FORWARD-ACTIVE REGION.
VIDC  3   5   1M
VI    5   0
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.DC VI -0.01 0.01 0.001
.PLOT DC V(6)
.TF V(6) VI
.END

 ******  DC TRANSFER CURVES      TNOM=  27.000 TEMP=  27.000

   VOLT      V(6)
(A       )    1.727E+00      1.727E+00      1.727E+00      1.727E+00     1.727E+00
                    +             +              +              +              +
-1.000E-02  1.72E+00-+------+-----+------+------+------+------+---A--+------+-
-9.000E-03  1.72E+00 +      +     +      +      +      +      +  A   +      +
-8.000E-03  1.72E+00 +      +     +      +      +      +      + A    +      +
-7.000E-03  1.72E+00 +      +     +      +      +      +      A      +      +
-6.000E-03  1.72E+00 +      +     +      +      +      +    A +      +      +
-5.000E-03  1.72E+00 +      +     +      +      +      +  A   +      +      +
-4.000E-03  1.72E+00 +      +     +      +      +      + A    +      +      +
-3.000E-03  1.72E+00 +      +     +      +      +      A      +      +      +
-2.000E-03  1.72E+00 +      +     +      +      +    A +      +      +      +
-1.000E-03  1.72E+00 +      +     +      +      +   A  +      +      +      +
 0.         1.72E+00-+------+-----+------+------+-A----+------+------+------+-
 1.000E-03  1.72E+00 +      +     +      +      A      +      +      +      +
 2.000E-03  1.72E+00 +      +     +      +    A +      +      +      +      +
 3.000E-03  1.72E+00 +      +     +      +   A  +      +      +      +      +
 4.000E-03  1.72E+00 +      +     +      + A    +      +      +      +      +
 5.000E-03  1.72E+00 +      +     +      A      +      +      +      +      +
 6.000E-03  1.72E+00 +      +     +     A+      +      +      +      +      +
 7.000E-03  1.72E+00 +      +     +  A   +      +      +      +      +      +
 8.000E-03  1.72E+00 +      +     + A    +      +      +      +      +      +
 9.000E-03  1.72E+00 +      +     A      +      +      +      +      +      +
 1.000E-02  1.72E+00-+------+-----A+-----+------+------+------+------+------+-
                    +             +              +              +              +
 **** BIPOLAR JUNCTION TRANSISTORS
 SUBCKT
 ELEMENT  0:Q1        0:Q2        0:Q3        0:Q4
 MODEL    0:NPN       0:NPN       0:PNP       0:PNP
  IB       2.550E-07   2.453E-07  -9.941E-07  -9.932E-07
  IC       5.169E-05   4.971E-05  -4.970E-05  -4.971E-05
  VBE      5.961E-01   5.951E-01  -6.194E-01  -6.194E-01
  VCE      2.374E+00   2.322E+00  -6.194E-01  -6.713E-01
  VBC     -1.778E+00  -1.727E+00   0.          5.197E-02
  VS      -1.779E+00  -1.727E+00  -1.779E+00  -1.779E+00
  POWER    1.229E-04   1.156E-04   3.140E-05   3.399E-05
  BETAD    2.027E+02   2.026E+02   5.000E+01   5.005E+01
  GM       1.998E-03   1.922E-03   1.921E-03   1.921E-03
  RPI      1.014E+05   1.054E+05   2.601E+04   2.604E+04
  RX       2.000E+02   2.000E+02   3.000E+02   3.000E+02
  RO       2.549E+06   2.649E+06   1.006E+06   1.006E+06
  BETAAC   2.027E+02   2.026E+02   4.997E+01   5.002E+01

 ****      SMALL-SIGNAL TRANSFER CHARACTERISTICS

      V(6)/VI                                    = -1.240E-03
      INPUT RESISTANCE AT          VI            =  1.150E+08
      OUTPUT RESISTANCE AT V(6)                  =  1.636E+06
```

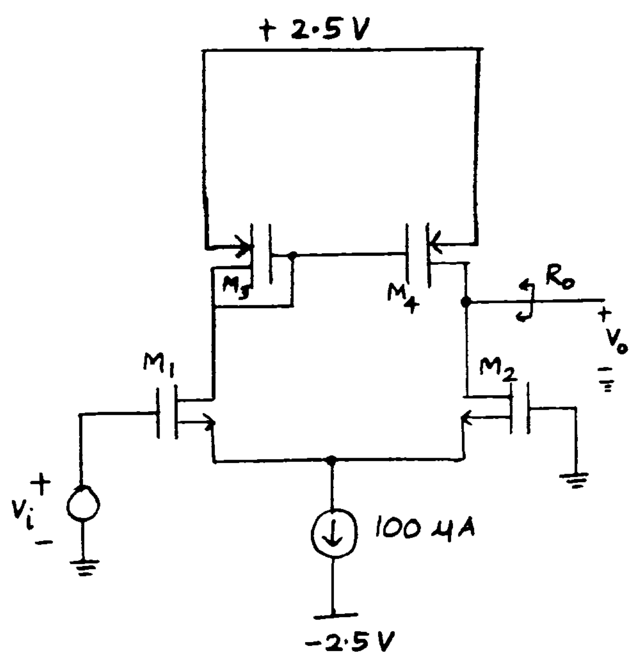
4.14

In the figure below,

$I_1 = I_2 = I_3 = I_4 = 50\ \mu A$

and

$R_o = r_{o2} \parallel r_{o4}$



From (1.163),

$$V_{An} = L_{eff} \Big/ \frac{dX_d}{dV_{DS}}$$

$$\Rightarrow V_{An} = \frac{1-2(0.12)}{0.08} =$$

$$|V_{Ap}| = \frac{1-2(0.18)}{0.04} = 16\,V$$

$$r_{o2} = \frac{9.5\,V}{50\,\mu A} = 190\,k\Omega$$

$$r_{o4} = \frac{16\,V}{50\,\mu A} = 320\,k\Omega$$

$$C_{ox} = \frac{3.9 \times 8.854 \times 10^{-14}}{150 \times 10^{-8}\,cm} = 2.3 \times 10^{-7}\,\frac{F}{cm^2}$$

$$K_p' = 2.3 \times 10^{-7}(250) = 58\,\frac{\mu A}{V^2}$$

$$K_n' = 2.3 \times 10^{-7}(550) = 127\,\frac{\mu A}{V^2}$$

$$g_{m1} = \sqrt{2 K_n' \left(\frac{W}{L}\right)_1 I_1}$$

$$= \sqrt{2(127)\frac{50}{[1-2(0.12)]}\,50}$$

$$= 914\,\frac{\mu A}{V} = G_m$$

$$R_o = r_{o2} \parallel r_{o4} = 190\,k\Omega \parallel 320\,k\Omega$$

$$= 119\,k\Omega$$

$$\frac{V_o}{V_i} = +G_m R_o = 0.914\,m\,(119\,K)$$

$$= 109$$

From SPICE (inserted at the end),

$$\frac{V_o}{V_i} = 142 \quad \text{and} \quad R_o = 138\,k\Omega$$

The difference between the hand calculations and SPICE in this case stems from the fact that early voltages are small. As a result, the expressions for transconductance and output resistance should be changed.

$$r_{o2} = \frac{V_{An} + V_{DS_2}}{I_{D_2}}$$

$$V_{DS_2} = 0 - V_{t_2} - V_{ov_2}$$

$V_{t_2} = 0.7\,V$ (ignoring body effect)

$$V_{ov_2} = \sqrt{\frac{2(50)}{127\,(50)/[1-2(0.12)]}} = 109\text{ mV}$$

$$V_{S_2} \cong -0.7 - 0.1 = -0.8\,V$$

If $M_1 = M_2$ and $M_3 = M_4$,

$$V_{D_2} = V_{D_3} = 2.5 - |V_{tp}| - |V_{ov_3}|$$

$$V_{tp} = -0.7\,V$$

$$|V_{ov_3}| = \sqrt{\frac{2(50)}{58\,(100)/1-2(0.18)}} = 105\text{ mV}$$

$$V_{D_2} \cong 2.5 - 0.7 - 0.1 = 1.7\,V$$

$$V_{DS_2} = 1.7 + 0.8 = 2.5\,V$$

$$r_{o2} = \frac{9.5 + 2.5}{50\,\mu A} = 240\,k\Omega$$

Similarly,

$$r_{o4} = \frac{|V_{Ap}| + |V_{DS_4}|}{I_{D_4}}$$

$$V_{DS_4} = V_{DS_3} = V_{GS_3} \simeq -0.7 - 0.1 = -0.8\,V$$

$$r_{o4} = \frac{(16 + 0.8)\,V}{50\,\mu A} = 336\,k\Omega$$

From (1.179),

$$g_m = k'\frac{W}{L}(V_{GS} - V_t)(1 + \lambda V_{DS})$$

From (1.165)

$$I_D = \frac{k'}{2}\frac{W}{L}(V_{GS} - V_t)^2(1 + \lambda V_{DS})$$

So,
$$V_{GS} - V_t = \sqrt{\frac{2I_D}{k'\frac{W}{L}(1 + \lambda V_{DS})}}$$

Then,
$$g_m = k'\frac{W}{L}\sqrt{\frac{2I_D}{k'\frac{W}{L}(1 + \lambda V_{DS})}}\,(1 + \lambda V_{DS})$$

$$g_m = \sqrt{2k'\frac{W}{L}I_D(1 + \lambda V_{DS})}$$

$$= \sqrt{2(127)\frac{50}{1-2(0.12)}(50)\left(1 + \frac{2.5}{9.5}\right)}$$

$$= 1027.32\,\mu A/V$$

$$\frac{V_o}{V_i} = \left(1.03\,\frac{mA}{V}\right)(240\,k\Omega \,||\, 336\,k\Omega)$$

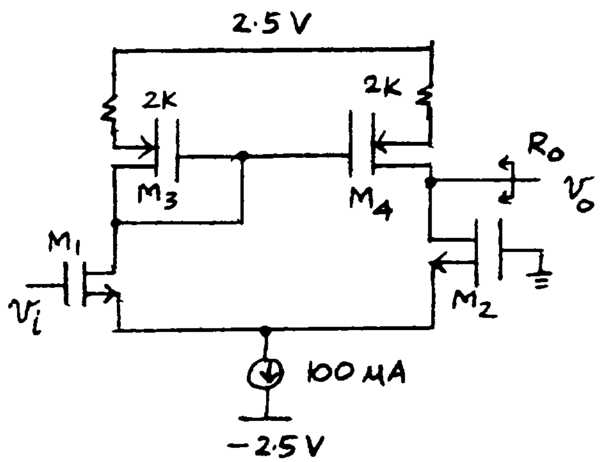
$$= 144.2$$

Although these final hand calculations are more accurate than the original hand calculations, hand calculations usually use the original formulae for simplicity.

```
MOS DIFFERENTIAL PAIR WITH CURRENT-MIRROR LOAD
******
VDD   100 0   2.5
VSS   200 0   -2.5
M1    2   3   4    200 NMOS  W=50U  L=1U
M2    6   0   4    200 NMOS  W=50U  L=1U
M3    2   2   100  100 PMOS  W=100U L=1U
M4    6   2   100  100 PMOS  W=100U L=1U
ITAIL 4   200 100U
RTAIL 4   200 1MEG
*FOR N-CHAN, KP = UN*COX = 550*1.38E-7 = 127 UA/V**2
*FOR P-CHAN, KP = UP*COX = 250*1.38E-7 =  58 UA/V**2
.MODEL NMOS NMOS LEVEL=1 LAMBDA=0.105263 VTO=0.7  KP=127U LD=0.12U
.MODEL PMOS PMOS LEVEL=1 LAMBDA=0.0625   VTO=-0.7 KP= 58U LD=0.18U

VIDC  3   5   0M
VI    5   0
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.DC VI -0.01 0.01 0.002
.PLOT DC V(6)
.TF V(6) VI
.END

******  DC TRANSFER CURVES     TNOM=  27.000 TEMP=  27.000

    VOLT       V(6)
(A       )     0.          1.000E-00   2.000E+00   3.000E+00   4.000E+00
                    +           +           +           +           +
-1.000E-02  3.41E-01-+----A-+-----+-----+-----+-----+-----+-----+-----+-
-8.000E-03  6.01E-01 +     +A     +     +     +     +     +     +     +
-6.000E-03  8.67E-01 +     +   A  +     +     +     +     +     +     +
-4.000E-03  1.13E+00 +     +      + A   +     +     +     +     +     +
-2.000E-03  1.41E+00 +     +      +    A+     +     +     +     +     +
 0.         1.69E+00 +     +      +     +  A  +     +     +     +     +
 2.000E-03  1.98E+00 +     +      +     +     A     +     +     +     +
 4.000E-03  2.27E+00 +     +      +     +     +  A  +     +     +     +
 6.000E-03  2.41E+00 +     +      +     +     +    A+     +     +     +
 8.000E-03  2.42E+00 +     +      +     +     +    A+     +     +     +
 1.000E-02  2.42E+00-+-----+------+-----+-----+----A+-----+-----+-----+-
                    +           +           +           +           +
****  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
  NODE      =VOLTAGE       NODE      =VOLTAGE        NODE      =VOLTAGE
+0:2        = 1.696E+00 0:3          =    0.        0:4         =-7.982E-01
+0:5        =    0.     0:6          = 1.696E+00 0:100          = 2.500E+00
+0:200      =-2.500E+00

**** MOSFETS
SUBCKT
ELEMENT  0:M1        0:M2        0:M3        0:M4
MODEL    0:NMOS      0:NMOS      0:PMOS      0:PMOS
 ID        5.085E-05   5.085E-05  -5.085E-05  -5.085E-05
 IBS      -1.702E-14  -1.702E-14   0.          0.
 IBD      -4.197E-14  -4.197E-14   8.034E-15   8.034E-15
 VGS       7.982E-01   7.982E-01  -8.034E-01  -8.034E-01
 VDS       2.494E+00   2.494E+00  -8.034E-01  -8.034E-01
 VBS      -1.701E+00  -1.701E+00   0.          0.
 VTH       7.000E-01   7.000E-01  -7.000E-01  -7.000E-01
 VDSAT     9.819E-02   9.819E-02  -1.034E-01  -1.034E-01
 BETA      1.055E-02   1.055E-02   9.518E-03   9.518E-03
 GAM EFF   0.          0.          0.          0.
 GM        1.036E-03   1.036E-03   9.838E-04   9.838E-04
 GDS       4.239E-06   4.239E-06   3.026E-06   3.026E-06
 GMB       0.          0.          0.          0.

****      SMALL-SIGNAL TRANSFER CHARACTERISTICS

      V(6)/VI                                      =  1.423E+02
      INPUT RESISTANCE AT          VI              =  1.000E+20
      OUTPUT RESISTANCE AT V(6)                    =  1.379E+05
```

```
MOS DIFFERENTIAL PAIR WITH CURRENT-MIRROR LOAD
* (COMMON-MODE INPUT)
******
VDD   100 0   2.5
VSS   200 0   -2.5
M1    2   3   4    200 NMOS  W=50U  L=1U
M2    6   5   4    200 NMOS  W=50U  L=1U
*|CMRR| = 142.3/0.0005043 = 2.82E5
M3    2   2   100  100 PMOS  W=100U L=1U
M4    6   2   100  100 PMOS  W=100U L=1U
ITAIL 4   200 100U
RTAIL 4   200 1MEG
*FOR N-CHAN, KP = UN*COX = 550*1.38E-7 = 127 UA/V**2
*FOR P-CHAN, KP = UP*COX = 250*1.38E-7 =  58 UA/V**2
.MODEL NMOS NMOS LEVEL=1 LAMBDA=0.105263 VTO=0.7  KP=127U LD=0.12U
.MODEL PMOS PMOS LEVEL=1 LAMBDA=0.0625   VTO=-0.7 KP= 58U LD=0.18U

VIDC  3   5   0M
VI    5   0
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.DC VI -0.01 0.01 0.002
.PLOT DC V(6)
.TF V(6) VI
.END

******  DC TRANSFER CURVES     TNOM=  27.000 TEMP=  27.000

    VOLT       V(6)
(A       )     1.696E+00   1.696E+00   1.696E+00   1.696E+00   1.696E+00
                    +           +           +           +           +
-1.000E-02  1.69E+00-+-----+-----+-----+-----+----+-A---+-----+-----+-
-8.000E-03  1.69E+00 +     +     +     +     +   A+     +     +     +
-6.000E-03  1.69E+00 +     +     +     +     + A   +    +     +     +
-4.000E-03  1.69E+00 +     +     +     +     +A    +    +     +     +
-2.000E-03  1.69E+00 +     +     +     +   A +     +    +     +     +
 0.         1.69E+00 +     +     +     + A   +     +    +     +     +
 2.000E-03  1.69E+00 +     +     +    A+     +     +    +     +     +
 4.000E-03  1.69E+00 +     +     + A   +     +     +    +     +     +
 6.000E-03  1.69E+00 +     +     A     +     +     +    +     +     +
 8.000E-03  1.69E+00 +     +   A +     +     +     +    +     +     +
 1.000E-02  1.69E+00-+-----+-A---+-----+-----+-----+----+-----+-----+-
                    +           +           +           +           +
****  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
  NODE      =VOLTAGE       NODE      =VOLTAGE        NODE      =VOLTAGE
+0:2        = 1.696E+00 0:3          =    0.        0:4         =-7.982E-01
+0:5        =    0.     0:6          = 1.696E+00 0:100          = 2.500E+00
+0:200      =-2.500E+00

**** MOSFETS
SUBCKT
ELEMENT  0:M1        0:M2        0:M3        0:M4
MODEL    0:NMOS      0:NMOS      0:PMOS      0:PMOS
 ID        5.085E-05   5.085E-05  -5.085E-05  -5.085E-05
 IBS      -1.702E-14  -1.702E-14   0.          0.
 IBD      -4.197E-14  -4.197E-14   8.034E-15   8.034E-15
 VGS       7.982E-01   7.982E-01  -8.034E-01  -8.034E-01
 VDS       2.494E+00   2.494E+00  -8.034E-01  -8.034E-01
 VBS      -1.701E+00  -1.701E+00   0.          0.
 VTH       7.000E-01   7.000E-01  -7.000E-01  -7.000E-01
 VDSAT     9.819E-02   9.819E-02  -1.034E-01  -1.034E-01
 BETA      1.055E-02   1.055E-02   9.518E-03   9.518E-03
 GAM EFF   0.          0.          0.          0.
 GM        1.036E-03   1.036E-03   9.838E-04   9.838E-04
 GDS       4.239E-06   4.239E-06   3.026E-06   3.026E-06
 GMB       0.          0.          0.          0.

****      SMALL-SIGNAL TRANSFER CHARACTERISTICS

      V(6)/VI                                      = -5.043E-04
      INPUT RESISTANCE AT          VI              =  1.000E+20
      OUTPUT RESISTANCE AT V(6)                    =  1.379E+05
```

4.15



$$K_p' = 2.3 \times 10^{-7}(250) = 58 \frac{\mu A}{V^2}$$

$$R_o = r_{o2} \| r_{o4}(1 + g_{m4}(2K))$$

$$g_{m4} = \sqrt{2(58)\frac{100}{1-2(0.18)}(50)}$$

$$= 952 \ \mu A/V$$

$$R_o = 190K \| [320K + (1 + (0.952)(2))]$$

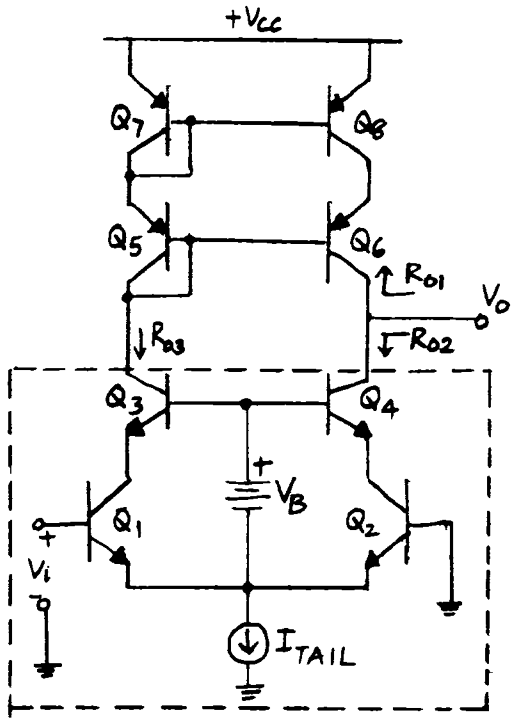
$$= 158 \ K\Omega$$

$$\frac{v_o}{v_i} = G_m R_o = 0.914\ (158) = 144$$

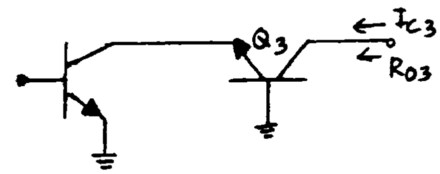
```
MOS DIFFERENTIAL PAIR WITH SOURCE-DEGENERATED CURRENT-MIRROR LOAD
******
VDD  100 0   2.5
VSS  200 0   -2.5
M1   2  3  4   4  NMOS  W=50U  L=1U
M2   6  0  4   4  NMOS  W=50U  L=1U
* NOTE THAT CONNECTING THE BODY TO THE SOURCE ELIMINATES
* THE BODY EFFECT.
M3   2  2  8    100 PMOS  W=100U L=1U
M4   6  2  9    100 PMOS  W=100U L=1U
RS3  100 8   2K
RS4  100 9   2K
ITAIL 4   200 100U
RTAIL 4   200 1MEG
*FOR N-CHAN, KP = UN*COX = 550*1.38E-7 = 127 UA/V**2
*FOR P-CHAN, KP = UP*COX = 250*1.38E-7 =  58 UA/V**2
.MODEL NMOS NMOS LEVEL=1 LAMBDA=0.105263 VTO=0.7  KP=127U LD=0.12U
.MODEL PMOS PMOS LEVEL=1 LAMBDA=0.0625   VTO=-0.7 KP= 58U LD=0.18U

VIDC  3   5   0M
VI    5   0
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.DC VI -0.01 0.01 0.002
.PLOT DC V(6)
.TF V(6) VI
.END

 ******  DC TRANSFER CURVES     TNOM=  27.000 TEMP=  27.000

    VOLT      V(6)
(A       )   -1.000E-00      0.          1.000E-00     2.000E+00    3.000E+00
                 +             +             +             +            +
-1.000E-02 -1.79E-01-+-------+---A--+-------+-------+-------+-------+-------+-
-8.000E-03  1.49E-01 +       +      + A     +       +       +       +       +
-6.000E-03  4.90E-01 +       +      +       A       +       +       +       +
-4.000E-03  8.45E-01 +       +      +       +     A +       +       +       +
-2.000E-03  1.21E+00 +       +      +       +       + A     +       +       +
 0.         1.59E+00 +       +      +       +       +       +A      +       +
 2.000E-03  1.99E+00 +       +      +       +       +       +       A       +
 4.000E-03  2.31E+00 +       +      +       +       +       +       + A  +  +
 6.000E-03  2.33E+00 +       +      +       +       +       +       +  A +  +
 8.000E-03  2.34E+00 +       +      +       +       +       +       +  A +  +
 1.000E-02  2.35E+00-+-------+------+-------+-------+-------+-------+--A-+----+-
                 +             +             +             +            +
 ****  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
   NODE      =VOLTAGE      NODE      =VOLTAGE      NODE      =VOLTAGE


 +0:2       = 1.594E+00 0:3       =   0.       0:4        =-7.986E-01
 +0:5       =   0.      0:6       = 1.594E+00 0:8        = 2.398E+00
 +0:9       = 2.398E+00 0:100     = 2.500E+00 0:200      =-2.500E+00

 **** MOSFETS
 SUBCKT
 ELEMENT  0:M1       0:M2       0:M3       0:M4
 MODEL    0:NMOS     0:NMOS     0:PMOS     0:PMOS
  ID       5.085E-05  5.085E-05 -5.085E-05 -5.085E-05
  IBS      0.         0.         1.017E-15  1.017E-15
  IBD     -2.394E-14 -2.394E-14  9.051E-15  9.051E-15
  VGS      7.986E-01  7.986E-01 -8.034E-01 -8.034E-01
  VDS      2.393E+00  2.393E+00 -8.034E-01 -8.034E-01
  VBS      0.         0.         1.017E-01  1.017E-01
  VTH      7.000E-01  7.000E-01 -7.000E-01 -7.000E-01
  VDSAT    9.860E-02  9.860E-02 -1.034E-01 -1.034E-01
  BETA     1.046E-02  1.046E-02  9.518E-03  9.518E-03
  GAM EFF  0.         0.         0.         0.
  GM       1.031E-03  1.031E-03  9.838E-04  9.838E-04
  GDS      4.275E-06  4.275E-06  3.026E-06  3.026E-06
  GMB      0.         0.         0.         0.

 ****      SMALL-SIGNAL TRANSFER CHARACTERISTICS

      V(6)/VI                                    =  1.945E+02
      INPUT RESISTANCE AT         VI             =  1.000E+20
      OUTPUT RESISTANCE AT V(6)                  =  1.901E+05
```

```
MOS DIFFERENTIAL PAIR WITH SOURCE-DEGENERATED CURRENT-MIRROR LOAD
* (COMMON-MODE INPUT)
******
VDD  100 0   2.5
VSS  200 0   -2.5
M1   2  3  4   4  NMOS  W=50U  L=1U
M2   6  5  4   4  NMOS  W=50U  L=1U
*|CMRR| = 194.5/0.0015 = 1.30E5
* NOTE THAT CONNECTING THE BODY TO THE SOURCE ELIMINATES
* THE BODY EFFECT.
M3   2  2  8    100 PMOS  W=100U L=1U
M4   6  2  9    100 PMOS  W=100U L=1U
RS3  100 8   2K
RS4  100 9   2K
ITAIL 4   200 100U
RTAIL 4   200 1MEG
*FOR N-CHAN, KP = UN*COX = 550*1.38E-7 = 127 UA/V**2
*FOR P-CHAN, KP = UP*COX = 250*1.38E-7 =  58 UA/V**2
.MODEL NMOS NMOS LEVEL=1 LAMBDA=0.105263 VTO=0.7  KP=127U LD=0.12U
.MODEL PMOS PMOS LEVEL=1 LAMBDA=0.0625   VTO=-0.7 KP= 58U LD=0.18U

VIDC  3   5   0M
VI    5   0
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.DC VI -0.01 0.01 0.002
.PLOT DC V(6)
.TF V(6) VI
.END

 ******  DC TRANSFER CURVES     TNOM=  27.000 TEMP=  27.000

    VOLT      V(6)
(A       )    1.594E+00    1.594E+00    1.594E+00    1.594E+00    1.594E+00
                 +             +             +             +            +
-1.000E-02  1.59E+00-+-------+------+-------+-------+-------+-------+--A---+------+-
-8.000E-03  1.59E+00 +       +      +       +       +       +     A+      +       +
-6.000E-03  1.59E+00 +       +      +       +       +       +A      +      +       +
-4.000E-03  1.59E+00 +       +      -       +       +   A   +       +      +       +
-2.000E-03  1.59E+00 +       +      +       -       A       +       +      +       +
 0.         1.59E+00 +       +      +       +  A    +       +       +      +       +
 2.000E-03  1.59E+00 +       +      +      A+       +       +       +      +       +
 4.000E-03  1.59E+00 +       +      +A      +       +       +       +      +       +
 6.000E-03  1.59E+00 +       +   A  +       +       +       +       +      +       +
 8.000E-03  1.59E+00 +       A      +       +       +       +       +      +       +
 1.000E-02  1.59E+00-+--A----+------+-------+-------+-------+-------+------+-------+-
                 +             +             +             +            +
 ****  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
   NODE      =VOLTAGE      NODE      =VOLTAGE      NODE      =VOLTAGE
 +0:2       = 1.594E+00 0:3       =   0.       0:4        =-7.986E-01
 +0:5       =   0.      0:6       = 1.594E+00 0:8        = 2.398E+00
 +0:9       = 2.398E+00 0:100     = 2.500E+00 0:200      =-2.500E+00

 **** MOSFETS
 SUBCKT
 ELEMENT  0:M1       0:M2       0:M3       0:M4
 MODEL    0:NMOS     0:NMOS     0:PMOS     0:PMOS
  ID       5.085E-05  5.085E-05 -5.085E-05 -5.085E-05
  IBS      0.         0.         1.017E-15  1.017E-15
  IBD     -2.394E-14 -2.394E-14  9.051E-15  9.051E-15
  VGS      7.986E-01  7.986E-01 -8.034E-01 -8.034E-01
  VDS      2.393E+00  2.393E+00 -8.034E-01 -8.034E-01
  VBS      0.         0.         1.017E-01  1.017E-01
  VTH      7.000E-01  7.000E-01 -7.000E-01 -7.000E-01
  VDSAT    9.860E-02  9.860E-02 -1.034E-01 -1.034E-01
  BETA     1.046E-02  1.046E-02  9.518E-03  9.518E-03
  GAM EFF  0.         0.         0.         0.
  GM       1.031E-03  1.031E-03  9.838E-04  9.838E-04
  GDS      4.275E-06  4.275E-06  3.026E-06  3.026E-06
  GMB      0.         0.         0.         0.

 ****      SMALL-SIGNAL TRANSFER CHARACTERISTICS

      V(6)/VI                                    = -1.500E-03
      INPUT RESISTANCE AT         VI             =  9.999E+19
      OUTPUT RESISTANCE AT V(6)                  =  1.901E+05
```

4.16

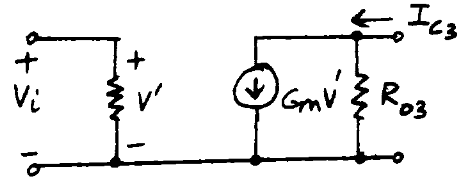


Half circuit of the dotted box :



is the CE-CB configuration.

∴ the equivalent circuit is



Where $R_i = r_{\pi_1}$, $G_m = g_{m_1}$

$R_{o3} = \beta_3 r_{o3} = \beta_4 r_{o4} = R_{o2}$

$R_{OUT} = R_{o1} \parallel R_{o2}$

$R_{o1} \approx \dfrac{\beta_6 r_{o6}}{2}$

$I_{c_1} \approx I_{c_2} \approx I_{c_3} = I_{c_4} = -I_{c_5} \approx -I_{c_6}$
$\approx -I_{c_7} = -I_{c_8} \approx I_{EE}/2$

$\therefore g_{m_1} = g_{m_2} = g_{m_3} = g_{m_4} = g_{m_5}$
$= g_{m_6} = g_{m_7} = g_{m_8} = g_m$

$\beta_4 = \beta_{npn} = 200$, $\beta_6 = \beta_{pnp} = 50$

$\therefore r_{o6} = \dfrac{1}{g_m \eta_{pnp}}$, $r_{o4} = \dfrac{1}{g_m \eta_{npn}}$

$R_{OUT} = R_{o1} \parallel R_{o2}$

$$= \frac{1}{\dfrac{2 g_m \eta_{pnp}}{\beta_6} + \dfrac{g_m \eta_{npn}}{\beta_4}}$$

$$A_V = g_m R_{OUT} = \frac{1}{\dfrac{2\eta_{pnp}}{\beta_6} + \dfrac{\eta_{npn}}{\beta_4}}$$

$$A_V = \left[1 \Big/ \left(2 \times \frac{5\times10^{-4}}{50} + \frac{2\times10^{-4}}{200} \right) \right] = 4.8\times10^{4}$$

```
BJT CASCODED DIFFERENTIAL PAIR WITH CASCODED CURRENT-MIRROR LOAD
VCC    100 0    2.5
VEE    200 0    -2.5
VBIAS 9    2    1.3
Q1     3    1    2    NPN
Q2     4    0    2    NPN
Q3     5    9    3    NPN
Q4     6    9    4    NPN
Q5     5    5    7    PNP
Q6     6    5    8    PNP
Q7     7    7    100  PNP
Q8     8    7    100  PNP
ITAIL 2     200 100U
RTAIL 2     200 1MEG
.MODEL NPN NPN RB=200 BF=200 VAF=130 IS=5E-15
.MODEL PNP PNP RB=300 BF=50  VAF=50  IS=2E-15

* A DC INPUT VOLTAGE OF ABOUT 2 MV FORCES THE VOLTAGE FROM
* THE OUTPUT TO GROUND TO BE ABOUT EQUAL TO THE VOLTAGE
* FROM NODE 5 (THE CASCODE CURRENT MIRROR INPUT) TO GROUND.
VIDC  1    10   2M
VI    10   0
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.DC VIDC -0.01 0.01 0.001
.PLOT DC V(6)
.TF V(6) VI
.END
```

```
******  DC TRANSFER CURVES      TNOM=  27.000 TEMP=  27.000
   VOLT        V(6)
(A       )      0.          5.000E-01    1.000E-00    1.500E+00    2.000E+00
                   +            +            -            +            +
-1.000E-02  1.06E-01-+--A---+------+------+------+------+------+------+------+-
-9.000E-03  1.11E-01 +  A   +      +      +      +      +      +      +      +
-8.000E-03  1.15E-01 +  A   +      +      +      +      +      +      +      +
-7.000E-03  1.20E-01 +  A   +      +      +      +      +      +      +      +
-6.000E-03  1.25E-01 +   A  +      +      +      +      +      +      +      +
-5.000E-03  1.31E-01 +   A  +      +      +      +      +      +      +      +
-4.000E-03  1.36E-01 +   A  +      +      +      +      +      +      +      +
-3.000E-03  1.43E-01 +   A  +      +      +      +      +      +      +      +
-2.000E-03  1.51E-01 +   A  +      +      +      +      +      +      +      +
-1.000E-03  1.60E-01 +   A  +      +      +      +      +      +      +      +
  0.        1.73E-01-+----A-+------+------+------+------+------+------+------+-
 1.000E-03  1.93E-01 +    A +      +      +      +      +      +      +      +
 2.000E-03  5.86E-01 +      +      + A    +      +      +      +      +      +
 3.000E-03  1.77E+00 +      +      +      +      +      +      +      +A     +
 4.000E-03  1.79E+00 +      +      +      +      +      +      +      +A     +
 5.000E-03  1.80E+00 +      +      +      +      +      +      +      + A    +
 6.000E-03  1.81E+00 +      +      +      +      +      +      +      + A    +
 7.000E-03  1.82E+00 +      +      +      +      +      +      +      + A    +
 8.000E-03  1.82E+00 +      +      +      +      +      +      +      + A    +
 9.000E-03  1.83E+00 +      +      +      +      +      +      +      + A    +
 1.000E-02  1.83E+00-+------+------+------+------+------+------+------+-A----+-
                   +            +            +            +            +
```

**** OPERATING POINT INFORMATION   TNOM= 27.000 TEMP= 27.000

NODE	=VOLTAGE	NODE	=VOLTAGE	NODE	=VOLTAGE
+0:1	= 2.000E-03	0:2	=-5.950E-01	0:3	= 1.081E-01
+0:4	= 1.100E-01	0:5	= 1.260E+00	0:6	= 5.857E-01
+0:7	= 1.880E+00	0:8	= 1.879E+00	0:9	= 7.050E-01
+0:10	= 0.	0:100	= 2.500E+00	0:200	=-2.500E+00

**** BIPOLAR JUNCTION TRANSISTORS

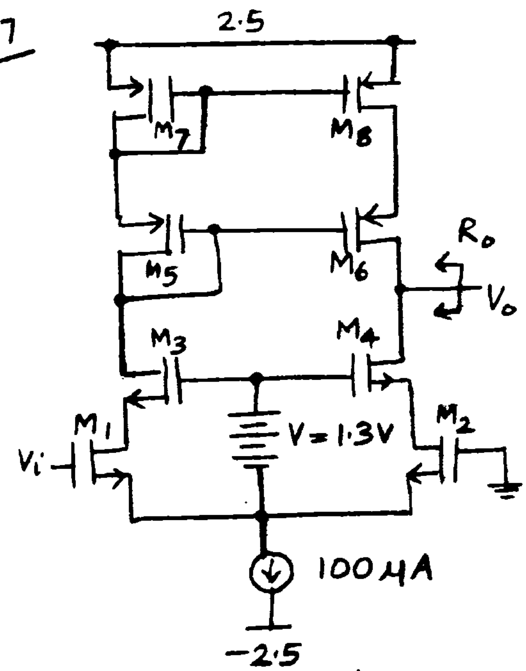
SUBCKT				
ELEMENT	0:Q1	0:Q2	0:Q3	0:Q4
MODEL	0:NPN	0:NPN	0:NPN	0:NPN
IB	2.644E-07	2.447E-07	2.621E-07	2.439E-07
IC	5.292E-05	4.899E-05	5.265E-05	4.874E-05
VBE	5.970E-01	5.950E-01	5.968E-01	5.950E-01
VCE	7.032E-01	7.050E-01	1.152E+00	4.757E-01
VBC	-1.061E-01	-1.100E-01	-5.558E-01	1.192E-01
VS	-1.081E-01	-1.100E-01	-1.260E+00	-5.857E-01
POWER	3.737E-05	3.468E-05	6.084E-05	2.333E-05
BETAD	2.001E+02	2.001E+02	2.008E+02	1.998E+02
GM	2.045E-03	1.894E-03	2.035E-03	1.884E-03
RPI	9.783E+04	1.056E+05	9.866E+04	1.060E+05
RX	2.000E+02	2.000E+02	2.000E+02	2.000E+02
RO	2.458E+06	2.656E+06	2.479E+06	2.664E+06
BETAAC	2.001E+02	2.001E+02	2.008E+02	1.997E+02

SUBCKT				
ELEMENT	0:Q5	0:Q6	0:Q7	0:Q8
MODEL	0:PNP	0:PNP	0:PNP	0:PNP
IB	-1.014E-06	-9.619E-07	-9.941E-07	-9.941E-07
IC	-5.068E-05	-4.874E-05	-4.970E-05	-4.970E-05
VBE	-6.199E-01	-6.185E-01	-6.194E-01	-6.194E-01
VCE	-6.199E-01	-1.293E+00	-6.194E-01	-6.208E-01
VBC	0.	6.750E-01	0.	1.369E-03
VS	-1.261E+00	-1.261E+00	-1.880E+00	-1.880E+00
POWER	3.204E-05	6.364E-05	3.140E-05	3.147E-05
BETAD	5.000E+01	5.067E+01	5.000E+01	5.000E+01
GM	1.958E-03	1.884E-03	1.921E-03	1.921E-03
RPI	2.551E+04	2.689E+04	2.601E+04	2.601E+04
RX	3.000E+02	3.000E+02	3.000E+02	3.000E+02
RO	9.866E+05	1.039E+06	1.006E+06	1.006E+06
BETAAC	4.997E+01	5.064E+01	4.997E+01	4.997E+01

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

```
V(6)/VI                               =  4.909E+04
INPUT RESISTANCE AT        VI         =  2.148E+05
OUTPUT RESISTANCE AT V(6)             =  2.611E+07
```

4.17



$$R_o = (g_{m6} r_{o6} r_{o8}) \parallel (g_{m4} r_{o4} r_{o2})$$

$$g_{m6} = \sqrt{2(58)\frac{100}{0.64}(50)} = 0.952 \ \frac{mA}{V}$$

$$g_{m4} = \sqrt{2(127)\frac{50}{0.76}(50)} = 0.914 \ \frac{mA}{V}$$

$$r_{o6} = r_{o8} = \frac{16}{50\mu} = 320 \ k\Omega$$

$$r_{o4} = r_{o2} = \frac{9.5}{50\mu} = 190 \ k\Omega$$

$$R_o = \left[(0.952)(320)^2\right] \parallel \left[(0.914)(190)^2\right]$$

$$= 24.7 \ M\Omega$$

$$\frac{V_o}{V_i} = G_m R_o = g_{m1} R_o$$

$$= 0.914 \ (24.7 \times 10^3) = 22{,}600$$

[In the figure, in practice V would be adjusted so that M_1 and M_2 barely operate in the active region]

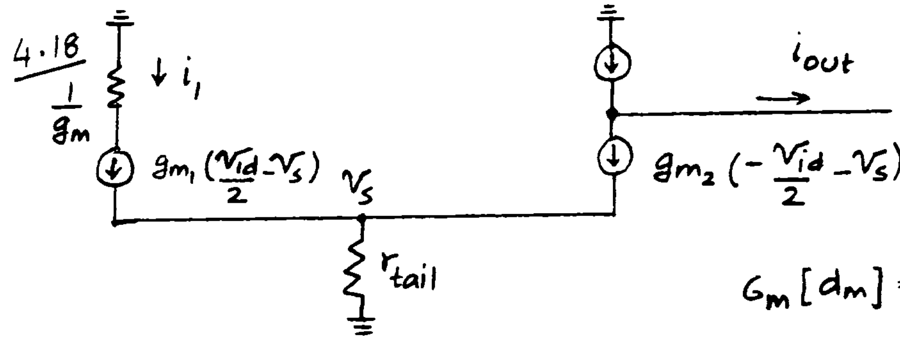
```
MOS CASCODED DIFFERENTIAL PAIR WITH CASCODED CURRENT-MIRROR LOAD
******
VDD   100 0 2.5
VSS   200 0 -2.5
VBIAS 9   2   1.3
M1    3   1   2   2   CMOSN W=50U L=1U
M2    4   0   2   2   CMOSN W=50U L=1U
M3    5   9   3   3   CMOSN W=50U L=1U
M4    6   9   4   4   CMOSN W=50U L=1U
M5    5   5   7   7   CMOSP W=100U L=1U
M6    6   5   8   8   CMOSP W=100U L=1U
M7    7   7   100 100 CMOSP W=100U L=1U
M8    8   7   100 100 CMOSP W=100U L=1U
ITAIL 2   200 100U
RTAIL 2   200 1MEG
*FOR N-CHAN, KP = UN*COX = 550*1.38E-7 = 127 UA/V**2
*FOR P-CHAN, KP = UP*COX = 250*1.38E-7 =  58 UA/V**2
.MODEL CMOSN NMOS LEVEL=1 LAMBDA=0.105263 VTO=0.7  KP=127U LD=0.12U
.MODEL CMOSP PMOS LEVEL=1 LAMBDA=0.0625   VTO=-0.7 KP= 58U LD=0.18U
VIDC  1   10  0M
VI    10  0
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.DC VIDC -0.01 0.01 0.001
.PLOT DC V(6)
.TF V(6) VI
.END
```

```
 ******  DC TRANSFER CURVES     TNOM=  27.000 TEMP=  27.000

    VOLT        V(6)
(A        )   -1.000E-00      0.          1.000E-00     2.000E+00     3.000E+00
                   +              +             +             +             +
-1.000E-02 -7.30E-01-+---A--+------+------+------+------+------+------+------+-
-9.000E-03 -7.27E-01 +   A  +      +      +      +      +      +      +      +
-8.000E-03 -7.24E-01 +   A  +      +      +      +      +      +      +      +
-7.000E-03 -7.21E-01 +   A  +      +      +      +      +      +      +      +
-6.000E-03 -7.17E-01 +   A  +      +      +      +      +      +      +      +
-5.000E-03 -7.13E-01 +   A  +      +      +      +      +      +      +      +
-4.000E-03 -7.08E-01 +   A  +      +      +      +      +      +      +      +
-3.000E-03 -7.01E-01 +   A  +      +      +      +      +      +      +      +
-2.000E-03 -6 59E-01 +    A +      +      +      +      +      +      +      +
-1.000E-03 -4.71E-01 +      A      +      +      +      +      +      +      +
  0.        8.93E-01-+------+------+------+-----A+------+------+------+------+-
 1.000E-03  1.98E+00 +      +      +      +      +      +      A      +      +
 2.000E-03  2.28E+00 +      +      +      +      +      +      +   A  +      +
 3.000E-03  2.40E+00 +      +      +      +      +      +      +     A+      +
 4.000E-03  2.40E+00 +      +      +      +      +      +      +     A+      +
 5.000E-03  2.41E+00 +      +      +      +      +      +      +     A+      +
 6.000E-03  2.41E+00 +      +      +      +      +      +      +     A+      +
 7.000E-03  2.41E+00 +      +      +      +      +      +      +     A+      +
 8.000E-03  2.42E+00 +      +      +      +      +      +      +     A+      +
 9.000E-03  2.42E+00 +      +      +      +      +      +      +     A+      +
 1.000E-02  2.42E+00-+------+------+------+------+------+------+-----A+------+-
                   +              +             +             +             +
```

```
 ****  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
   NODE      =VOLTAGE      NODE      =VOLTAGE      NODE      =VOLTAGE
+0:1         =   0.        0:2       =-8.076E-01  0:3       =-3.115E-01
+0:4         =-3.115E-01   0:5       = 8.933E-01  0:6       = 8.933E-01
+0:7         = 1.696E+00   0:8       = 1.696E+00  0:9       = 4.924E-01
+0:10        =   0.        0:100     = 2.500E+00  0:200     =-2.500E+00
```

```
SUBCKT
ELEMENT  0:M1        0:M2        0:M3        0:M4
MODEL    0:CMOSN     0:CMOSN     0:CMOSN     0:CMOSN
 ID       5.085E-05   5.085E-05   5.085E-05   5.085E-05
 IBS       0.          0.          0.          0.
 IBD     -4.961E-15  -4.961E-15  -1.205E-14  -1.205E-14
 VGS      8.076E-01   8.076E-01   8.039E-01   8.039E-01
 VDS      4.961E-01   4.961E-01   1.204E+00   1.204E+00
 VBS       0.          0.          0.          0.
 VTH      7.000E-01   7.000E-01   7.000E-01   7.000E-01
 VDSAT    1.076E-01   1.076E-01   1.039E-01   1.039E-01
 BETA     8.792E-03   8.792E-03   9.415E-03   9.415E-03
 GAM EFF   0.          0.          0.          0.
 GM       9.455E-04   9.455E-04   9.785E-04   9.785E-04
 GDS      5.087E-06   5.087E-06   4.750E-06   4.750E-06
 GMB       0.          0.          0.          0.

SUBCKT
ELEMENT  0:M5        0:M6        0:M7        0:M8
MODEL    0:CMOSP     0:CMOSP     0:CMOSP     0:CMOSP
 ID      -5.085E-05  -5.085E-05  -5.085E-05  -5.085E-05
 IBS       0.          0.          0.          0.
 IBD      8.034E-15   8.034E-15   8.034E-15   8.034E-15
 VGS     -8.034E-01  -8.034E-01  -8.034E-01  -8.034E-01
 VDS     -8.034E-01  -8.034E-01  -8.034E-01  -8.034E-01
 VBS       0.          0.          0.          0.
 VTH     -7.000E-01  -7.000E-01  -7.000E-01  -7.000E-01
 VDSAT   -1.034E-01  -1.034E-01  -1.034E-01  -1.034E-01
 BETA     9.518E-03   9.518E-03   9.518E-03   9.518E-03
 GAM EFF   0.          0.          0.          0.
 GM       9.838E-04   9.838E-04   9.838E-04   9.838E-04
 GDS      3.026E-06   3.026E-06   3.026E-06   3.026E-06
 GMB       0.          0.          0.          0.

****     SMALL-SIGNAL TRANSFER CHARACTERISTICS

      V(6)/VI                                  =  2.791E+04
      INPUT RESISTANCE AT          VI          =  1.000E+20
      OUTPUT RESISTANCE AT V(6)                =  2.967E+07
```

4.18



$$i_1 = g_{m1}\left(\frac{v_{id}}{2} - v_s\right)$$

$$i_2 = g_{m2}\left(-\frac{v_{id}}{2} - v_s\right)$$

$$v_s = (i_1 + i_2)\, r_{tail}$$

$$= \left[g_{m1}\left(\frac{v_{id}}{2} - v_s\right) + g_{m2}\left(-\frac{v_{id}}{2} - v_s\right)\right] r_{tail}$$

$$= \left[(g_{m1} - g_{m2})\frac{v_{id}}{2} - (g_{m1}+g_{m2})v_s\right] r_{tail}$$

① $$v_s\left[1 + (g_{m1} + g_{m2})\, r_{tail}\right] = (g_{m1} - g_{m2})\, r_{tail}\frac{v_{id}}{2}$$

$$i_{out} = \frac{g_{m4}}{g_{m3}}(i_1) - i_2$$

$$= \frac{g_{m4}}{g_{m3}}\, g_{m1}\left(\frac{v_{id}}{2} - v_s\right) - g_{m2}\left(-\frac{v_{id}}{2} - v_s\right)$$

② $$i_{out} = \frac{v_{id}}{2}\left[\frac{g_{m4}}{g_{m3}} g_{m1} + g_{m2}\right] - v_s\left[\frac{g_{m4}}{g_{m3}} g_{m1} - g_{m2}\right]$$

Plug ① into ②,

$$i_{out} = \frac{v_{id}}{2}\left[\frac{g_{m4}}{g_{m3}} g_{m1} + g_{m2}\right] - \frac{(g_{m1} - g_{m2})\, r_{tail}\frac{v_{id}}{2}}{1 + (g_{m1} + g_{m2})\, r_{tail}}\left[\frac{g_{m4}}{g_{m3}} g_{m1} - g_{m2}\right]$$

$$\Rightarrow i_{out} = \frac{v_{id}}{2}\left\{\frac{g_{m4}}{g_{m3}} g_{m1}\left[1 - \frac{(g_{m1} - g_{m2})\, r_{tail}}{1 + (g_{m1} + g_{m2})\, r_{tail}}\right] + g_{m2}\left[1 + \frac{(g_{m1} - g_{m2})\, r_{tail}}{1 + (g_{m1} + g_{m2})\, r_{tail}}\right]\right.$$

$$G_m[dm] = \frac{i_{out}}{v_{id}}$$

$$= \frac{1}{2}\left\{\frac{g_{m4}}{g_{m3}} g_{m1}\left[1 - \frac{(g_{m1} - g_{m2})\, r_{tail}}{1 + (g_{m1} + g_{m2})\, r_{tail}}\right] + g_{m2}\left[1 + \frac{(g_{m1} - g_{m2})\, r_{tail}}{1 + (g_{m1} + g_{m2})\, r_{tail}}\right]\right\}$$

$$\frac{(g_{m1} - g_{m2})\, r_{tail}}{1 + (g_{m1} + g_{m2})\, r_{tail}} \approx \frac{(g_{m1} - g_{m2})}{g_{m1} + g_{m2}}$$

$$= \frac{\Delta g_{m1,2}}{2 g_{m1,2}}$$

where, $g_{m1} = g_{m1,2} + \frac{\Delta g_{m1,2}}{2}$

$g_{m2} = g_{m1,2} - \frac{\Delta g_{m1,2}}{2}$

Also, $g_{m3} = g_{m3,4} + \frac{\Delta g_{m3,4}}{2}$

$g_{m4} = g_{m3,4} - \frac{\Delta g_{m3,4}}{2}$

$G_m[dm] =$

$$\frac{1}{2}\left\{\frac{1 - \frac{\Delta g_{m3,4}}{2 g_{m3,4}}}{1 + \frac{\Delta g_{m3,4}}{2 g_{m3,4}}}\, g_{m1,2}\left(1 + \frac{\Delta g_{m1,2}}{2 g_{m1,2}}\right)\left(1 - \frac{\Delta g_{m1,2}}{2 g_{m1,2}}\right) + g_{m1,2}\left(1 - \frac{\Delta g_{m1,2}}{2 g_{m1,2}}\right)\left(1 + \frac{\Delta g_{m1,2}}{2 g_{m1,2}}\right)\right\}$$

$$G_m[dm] = \frac{1}{2} g_{m_{1,2}} \left(1 - \frac{\Delta g_{m_{1,2}}}{2g_{m_{1,2}}}\right)\left(1 + \frac{\Delta g_{m_{1,2}}}{2g_{m_{1,2}}}\right) \cdot \left[\frac{1 - \frac{\Delta g_{m_{3,4}}}{2g_{m_{3,4}}}}{1 + \frac{\Delta g_{m_{3,4}}}{2g_{m_{3,4}}}} + 1\right]$$

$$\approx \frac{1}{2} g_{m_{1,2}} \left[1 - \left(\frac{\Delta g_{m_{1,2}}}{2g_{m_{1,2}}}\right)^2\right]\left(\frac{2}{1 + \frac{\Delta g_{m_{3,4}}}{2g_{m_{3,4}}}}\right)$$

$$\approx g_{m_{1,2}} \left[\frac{1 - \left(\frac{\Delta g_{m_{1,2}}}{2g_{m_{1,2}}}\right)^2}{1 + \frac{\Delta g_{m_{3,4}}}{2g_{m_{3,4}}}}\right]$$

(Exact if $r_{tail} \to \infty$)

```
DIFFERENTIAL PAIR WITH ACTIVE LOAD WITH MISMATCH
* FIND GM[DM]
GM1   3    5    1    5    1.05M
RO1   3    5    0.95MEG
GM2   4    5    0    5    0.95M
RO2   4    5    1.05MEG
GM3   3    0    3    0    1.1M
RO3   3    0    1MEG
GM4   4    0    3    0    0.9M
RO4   4    0    1MEG
RTAIL 5    0    0.5MEG
* SHORT THE OUTPUT TO FIND THE TRANSCONDUCTANCE
VOUT  4    0    0
VI    1    0    0 AC 1
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.TF I(VOUT) VI
.END

****      SMALL-SIGNAL TRANSFER CHARACTERISTICS

I(VOUT)/VI                              =  9.060E-04
INPUT RESISTANCE AT          VI         =  1.000E+20
OUTPUT RESISTANCE AT I(VOUT)            =  5.240E+05
```

Numerical values:

$$g_{m_{1,2}} = \frac{1.05 + 0.95}{2} = 1 \text{ mA/V}$$

$$\Delta g_{m_{1,2}} = 1.05 - 0.95 = 0.1 \text{ mA/V}$$

$$g_{m_{3,4}} = \frac{1.1 + 0.9}{2} = 1 \text{ mA/V}$$

$$\Delta g_{m_{3,4}} = 1.1 - 0.9 = 0.2 \text{ mA/V}$$

$$G_m[dm] = \frac{1}{1.1}\left[1 - (0.05)^2\right]$$

$$\approx 0.9068 \text{ mA/V}$$

Without mismatch

$$G_m[dm] = g_{m_{1,2}} = 1 \text{ mA/V}$$

4.19

(a) $i_2 = g_{m2}(v_{ic} - v_1) - \dfrac{v_1}{r_{o2}}$

$v_1 = (i_1 + i_2)\, r_{tail}$

$$i_2 = g_{m2}\left[v_{ic} - (i_2 + i_1) r_{tail}\right] - \frac{(i_1 + i_2) r_{tail}}{r_{o2}}$$

$i_1 = i_2(1 - \varepsilon d)$

$$i_2 = g_{m2}\left[v_{ic} - (i_2 - i_2\varepsilon d + i_2) r_{tail}\right] - \frac{(i_2 - i_2\varepsilon d + i_1)\, r_{tail}}{r_{o2}}$$

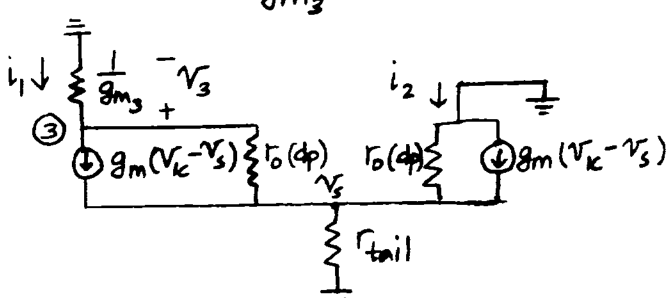
$$i_2\left[1 + g_{m2} r_{tail}(2 - \varepsilon d) + (2 - \varepsilon d)\frac{r_{tail}}{r_{o2}}\right] = g_{m2} v_{ic}$$

$$\frac{i_2}{v_{ic}} = \frac{g_{m2}}{1 + g_{m2} r_{tail}(2 - \varepsilon d) + (2 - \varepsilon d)\dfrac{r_{tail}}{r_{o2}}}$$

$$\approx \frac{g_{m2}}{1 + g_{m2} r_{tail}(2 - \varepsilon d) + 2\dfrac{r_{tail}}{r_{o2}}}$$

$$\approx \frac{g_{m2}}{2 g_{m2} r_{tail}} = \frac{1}{2 r_{tail}}$$

(b) First suppose mismatch = 0. Find εd from $\dfrac{1}{g_{m3}} \neq 0$ alone.



$$i_1 = g_m(v_{ic} - v_s) + \frac{v_3 - v_s}{r_o(dp)}$$

$$i_1 = g_m(v_{ic} - v_s) - \frac{v_s}{r_o(dp)} - \frac{i_1}{g_{m3} r_o(dp)}$$

$$i_1\left(1 + \frac{1}{g_{m3} r_o(dp)}\right) = g_m(v_{ic} - v_s) - \frac{v_s}{r_o} = i_2$$

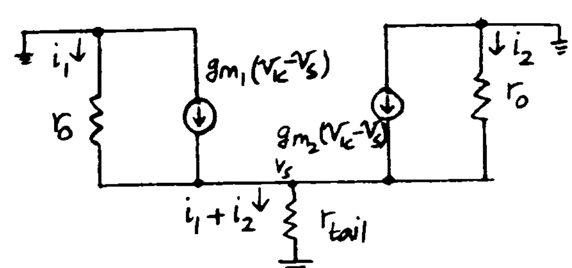
$$\frac{i_1}{i_2} = \frac{1}{1 + \dfrac{1}{g_{m3} r_o(dp)}}$$

$$\varepsilon d = 1 - \frac{i_1}{i_2} = \frac{1 + \dfrac{1}{g_{m3} r_o(dp)} - 1}{1 + \dfrac{1}{g_{m3} r_o(dp)}}$$

$$\approx \frac{1}{g_{m3} r_o(dp)}$$

This result is consistent with (4.173)

(c) Next, assume $\dfrac{1}{g_{m3}} = 0$ and $r_{o1} = r_{o2}$. Find εd from $g_{m1} \neq g_{m2}$ alone.



$$i_1 = g_{m1}(v_{ic} - v_s) - \frac{v_s}{r_o} \quad \rightarrow ①$$

$$i_2 = g_{m2}(v_{ic} - v_s) - \frac{v_s}{r_o}$$

$$= g_{m2}\left(i_1 + \frac{v_s}{r_o}\right)\frac{1}{g_{m1}} - \frac{v_s}{r_o} \quad \text{(from ①)}$$

$$= \frac{g_{m2}}{g_{m1}} i_1 + \frac{v_s}{r_o}\left(\frac{g_{m2}}{g_{m1}} - 1\right)$$

$$v_s = (i_1 + i_2)\, r_{tail}$$

$$i_2 = \frac{g_{m2}}{g_{m1}}\, i_1 + \frac{(i_1+i_2)\, r_{tail}}{r_o}\left(\frac{g_{m2}}{g_{m1}} - 1\right)$$

$$i_2 = i_1\left[\frac{g_{m2}}{g_{m1}} + \frac{r_{tail}}{r_o}\left(\frac{g_{m2}}{g_{m1}} - 1\right)\right] + i_2\, \frac{r_{tail}}{r_o}\left(\frac{g_{m2}}{g_{m1}} - 1\right)$$

$$i_2\left[1 + \frac{r_{tail}}{r_o}\left(1 - \frac{g_{m2}}{g_{m1}}\right)\right] = i_1\left[\frac{g_{m2}}{g_{m1}} + \frac{r_{tail}}{r_o}\left(\frac{g_{m2}}{g_{m1}} - 1\right)\right]$$

$$\frac{i_1}{i_2} = \frac{1 + \frac{r_{tail}}{r_o}\left(1 - \frac{g_{m2}}{g_{m1}}\right)}{\frac{g_{m2}}{g_{m1}} + \frac{r_{tail}}{r_o}\left(\frac{g_{m2}}{g_{m1}} - 1\right)} = \frac{1 + \frac{r_{tail}}{r_o}\left(1 - \frac{g_{m2}}{g_{m1}}\right)}{\frac{g_{m2}}{g_{m1}}\left(1 + \frac{r_{tail}}{r_o}\right) - \frac{r_{tail}}{r_o}}$$

$$\varepsilon_d = 1 - \frac{i_1}{i_2}$$

$$= \frac{\frac{g_{m2}}{g_{m1}} + \frac{r_{tail}}{r_o}\left(\frac{g_{m2}}{g_{m1}} - 1\right) - 1 - \frac{r_{tail}}{r_o}\left(1 - \frac{g_{m2}}{g_{m1}}\right)}{\frac{g_{m2}}{g_{m1}}\left(1 + \frac{r_{tail}}{r_o}\right) - \frac{r_{tail}}{r_o}}$$

$$\cong \frac{\frac{g_{m2}}{g_{m1}} - 1 + 2\frac{r_{tail}}{r_o}\left(\frac{g_{m2}}{g_{m1}} - 1\right)}{\frac{g_{m2}}{g_{m1}}}$$

$$\approx \frac{\left(\frac{g_{m2}}{g_{m1}} - 1\right)\left(1 + \frac{2 r_{tail}}{r_o}\right)}{\frac{g_{m2}}{g_{m1}}}$$

$$\approx \left(1 - \frac{g_{m1}}{g_{m2}}\right)\left[1 + \frac{2 r_{tail}}{r_o}\right]$$

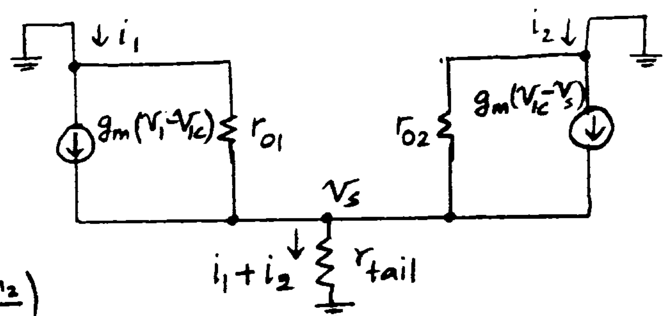
$$= \frac{g_{m2} - g_{m1}}{g_{m2}}\left[1 + \frac{2 r_{tail}}{r_o}\right]$$

$$\approx \frac{-\Delta g_m}{g_m - \frac{\Delta g_m}{2}}\left[1 + \frac{2 r_{tail}}{r_o}\right]$$

$$\approx \frac{-\Delta g_m}{g_m}\left(1 + \frac{\Delta g_m}{2 g_m}\right)\left[1 + \frac{2 r_{tail}}{r_o}\right]$$

$$\approx \frac{-\Delta g_m}{g_m}\left[1 + \frac{2 r_{tail}}{r_o}\right]$$

(d) Next assume $\frac{1}{g_{m3}} = 0$. Find ε_d from $r_{o1} \neq r_{o2}$ alone.



$$i_1 = g_m(v_{1c} - v_s) - \frac{v_s}{r_{o1}}$$

$$i_2 = g_m(v_{1c} - v_s) - \frac{v_s}{r_{o2}}$$

$$= \underbrace{g_m(v_{1c} - v_s) - \frac{v_s}{r_{o1}}}_{i_1} + \frac{v_s}{r_{o1}} - \frac{v_s}{r_{o2}}$$

$$i_2 = i_1 + (i_1 + i_2)\, r_{tail}\left(\frac{1}{r_{o1}} - \frac{1}{r_{o2}}\right)$$

$$i_2\left[1 - r_{tail}\left(\frac{1}{r_{o1}} - \frac{1}{r_{o2}}\right)\right] = i_1\left[1 + r_{tail}\left(\frac{1}{r_{o1}} - \frac{1}{r_{o2}}\right)\right]$$

$$\frac{i_1}{i_2} = \frac{1 - r_{tail}\left(\frac{1}{r_{o1}} - \frac{1}{r_{o2}}\right)}{1 + r_{tail}\left(\frac{1}{r_{o1}} - \frac{1}{r_{o2}}\right)}$$

$$\varepsilon_d = 1 - \frac{i_1}{i_2} = \frac{1 + r_{tail}\left(\frac{1}{r_{o1}} - \frac{1}{r_{o2}}\right) - 1 + r_{tail}\left(\frac{1}{r_{o1}} - \frac{1}{r_{o2}}\right)}{1 + r_{tail}\left(\frac{1}{r_{o1}} - \frac{1}{r_{o2}}\right)}$$

$$= \frac{2 r_{tail}\left(\frac{1}{r_{o1}} - \frac{1}{r_{o2}}\right)}{1 + r_{tail}\left(\frac{1}{r_{o1}} - \frac{1}{r_{o2}}\right)} \approx 2 r_{tail}\left(\frac{1}{r_{o1}} - \frac{1}{r_{o2}}\right)$$

$$r_{o1} = r_o(dp) + \Delta r_o(dp)/2$$

$$r_{o2} = r_o(dp) - \Delta r_o(dp)/2$$

$$\frac{1}{r_{o1}} - \frac{1}{r_{o2}} = \frac{1}{r_o(dp) + \frac{\Delta r_o(dp)}{2}} - \frac{1}{r_o(dp) - \frac{\Delta r_o(dp)}{2}}$$

$$= \frac{-\Delta r_o(dp)}{r_o^2(dp) - \underbrace{\frac{\Delta r_o^2(dp)}{4}}_{\text{ignore}}}$$

$$\approx \frac{-\Delta r_o(dp)}{r_o^2(dp)}$$

$$\varepsilon_d \cong -2\,\frac{r_{tail}}{r_o(dp)}\,\frac{\Delta r_o(dp)}{r_o(dp)}$$

(e) Total $\varepsilon_d \approx \dfrac{1}{g_{m3} r_o(dp)} - \dfrac{2 r_{tail}}{r_o(dp)}\dfrac{\Delta r_o(dp)}{r_o(dp)} - \dfrac{\Delta g_m(dp)}{g_m(dp)}\left[1 + \dfrac{2 r_{tail}}{r_o(dp)}\right]$

(same as 4·186)

(f)
$$\varepsilon_m = \frac{1}{1 + g_{m3} r_{o3}} + \frac{(g_{m3} - g_{m4}) r_{o3}}{1 + g_{m3} r_{o3}}$$

$$\approx \frac{1}{g_{m3} r_{o3}} + \frac{g_{m3} - g_{m4}}{g_{m3}}$$

$$\approx \frac{1}{g_{m3} r_{o3}} + \frac{\Delta g_{m3,4}}{g_{m3,4} + \frac{\Delta g_{m3,4}}{2}}$$

$$\approx \frac{1}{g_{m3} r_{o3}} + \frac{\Delta g_{m3,4}}{g_{m3,4}\left(1 + \frac{\Delta g_{m3,4}}{2 g_{m3,4}}\right)}$$

$$\approx \frac{1}{g_{m3} r_{o3}} + \frac{\Delta g_{m3,4}}{g_{m3,4}}\left(1 - \frac{\Delta g_{m3,4}}{2 g_{m3,4}}\right)$$

$$\approx \frac{1}{g_{m3} r_{o3}} + \frac{\Delta g_{m3,4}}{g_{m3,4}}$$

(same as 4·187)

(g)
$$G_m[CM] \approx -\frac{\varepsilon_d + \varepsilon_m}{2 r_{tail}}$$

Numerical values:

$$\varepsilon_d = \frac{1}{1.1m(1000)} - \frac{0.1}{1}\left[1 + 2\,\frac{0.5}{1}\right]$$

$$\cong -0.0991$$

$$\varepsilon_m \cong \frac{1}{1.1m(1000)} + \frac{0.2}{1} = 0.2009$$

$$G_m[CM] \approx \frac{-0.0991 + 0.2009}{2(0.5\,M)}$$

$$= -1.02 \times 10^{-7}\ A/V$$

$$CMRR = \frac{G_m[dm]}{G_m[CM]} \cong 8880$$

```
DIFFERENTIAL PAIR WITH ACTIVE LOAD WITH MISMATCH
* FIND GM[CM]
GM1   3    5   1   5   1.05M
RO1   3    5   0.95MEG
GM2   4    5   1   5   0.95M
RO2   4    5   1.05MEG
GM3   3    0   3   0   1.1M
RO3   3    0   1MEG
GM4   4    0   3   0   0.9M
RO4   4    0   1MEG
RTAIL 5    0   0.5MEG
* SHORT THE OUTPUT TO FIND THE TRANSCONDUCTANCE
VOUT  4    0   0
VI    1    0   0 AC 1
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.TF I(VOUT) VI
.END

****      SMALL-SIGNAL TRANSFER CHARACTERISTICS

I(VOUT)/VI                              = -9.237E-08
INPUT RESISTANCE AT         VI          =  1.000E+20
OUTPUT RESISTANCE AT I(VOUT)            =  5.240E+05
```

From SPICE,

$$CMRR = \left|\frac{0.906\times10^{-3}}{-9.237\times10^{-8}}\right| = 9810$$

Without mismatch

From (4.186),

$$\varepsilon_d \simeq \frac{1}{g_{m3} r_o(dp)} = \frac{1}{1m(1\,Meg)} = \frac{1}{1000}$$

From (4.187),

$$\varepsilon_m \simeq \frac{1}{g_{m3} r_{o3}} = \frac{1}{1m(1\,Meg)} = \frac{1}{1000}$$

From (4.185),

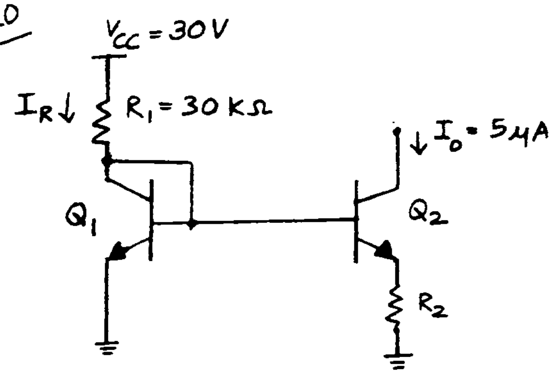
$$G_m[cm] \simeq -\frac{\varepsilon_d+\varepsilon_m}{2r_{tail}} \simeq -\frac{\frac{2}{1000}}{2(0.5\,Meg)} = -2\times10^{-9}\ A/V$$

CMRR (without mismatch)

$$= \frac{1\ mA/V}{2\times10^{-9}\ A/V} = 500{,}000$$

So, mismatch reduces CMRR

4.20



$$I_R = \frac{V_{CC}-V_{BE(on)}}{R_1} = \frac{30-0.7}{30k} = 0.977\,mA$$

$$V_{BE_1} = V_{BE_2} + I_o R_2$$

$$\therefore I_o R_2 = V_T \ln\frac{I_{C1}}{I_o} \simeq V_T \ln\frac{I_R}{I_o}$$

$$\therefore R_2 = \frac{V_T}{I_o}\ln\frac{I_R}{I_o} = \frac{26\,mV}{5\,\mu A}\ln\frac{0.977\,mA}{5\,\mu A}$$

$$= 27.4\,k\Omega$$

$$R_o = r_{o2}\left(1+\frac{g_{m2}R_2}{1+\frac{g_{m2}R_2}{\beta_o}}\right)$$

$$r_{o2} = \frac{130V}{5\,\mu A} = 26\,M\Omega$$

$$R_2 = 27.4\,k\Omega$$

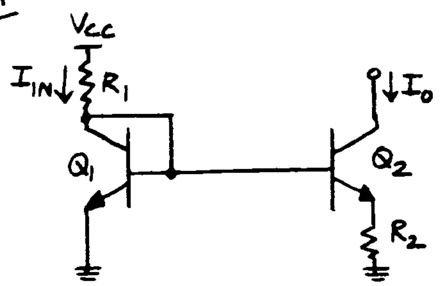
$$g_{m2} = \frac{1}{26}\,\frac{5}{1000} = 1.9\times10^{-4}\ A/V$$

$$\beta_o = 200$$

$$R_o = 26\left(1+\frac{1.9\times10^{-4}\times27.4\times10^{3}}{1+\frac{1.9\times10^{-4}\times27.4\times10^{3}}{200}}\right)$$

$$= 158\ M\Omega$$

4.21



$$I_{IN} = \frac{V_{cc} - V_{BE(on)}}{R_1} = \frac{V'}{R_1}$$

where $V' = V_{cc} - V_{BE(on)}$

$$I_o R_2 = V_T \ln \frac{I_{IN}}{I_o}$$

$$\therefore I_o R_2 = V_T \ln \frac{V'}{I_o R_1}$$

$$\therefore R_2 = \frac{V_T}{I_o} \ln \frac{V'}{I_o R_1}$$

Let $f = R_1 + R_2 = R_1 + \frac{V_T}{I_o} \ln \frac{V'}{I_o R_1}$

$$\frac{df}{dR_1} = 1 + \frac{V_T}{I_o} \frac{I_o R_1}{V'} \left(-\frac{V'}{I_o R_1^2} \right)$$

$$= 1 - \frac{V_T}{I_o} \frac{1}{R_1} = 0$$

$\therefore R_1 = \frac{V_T}{I_o}$ and

$$R_2 = \frac{V_T}{I_o} \ln \left(\frac{V'}{I_o} \frac{I_o}{V_T} \right)$$

These give minimum total resistance for given V_{cc} and I_o

For Problem (4.20), $V_{cc} = 30V$ and $I_o = 5\mu A$.

$$\therefore R_1 = \frac{26 \text{ mV}}{5 \mu A} = 5.2 \text{ k}\Omega$$

$$R_2 = \frac{26 \text{ mV}}{5 \mu A} \ln \frac{29.3}{0.026} = 36.5 \text{ k}\Omega$$

This value of R_1 is too small in practice as the current drawn from the supply is about

$$\frac{30 - 0.7}{5.2 \text{ K}} = 5.6 \text{ mA}$$ which is quite high

4.22

Circuit as shown in fig (4.31a) with $V_{cc} = 15V$, $R_1 = 20 \text{ k}\Omega$, $R_2 = 10 \text{ k}\Omega$

$$I_{IN} = \frac{15 - 0.7}{20 \text{ k}\Omega} = 0.72 \text{ mA}$$

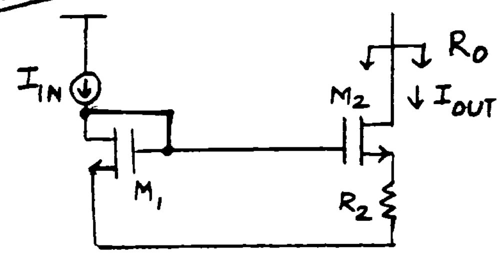
$$I_{OUT} R_2 = V_T \ln \frac{I_{C1}}{I_{OUT}} \approx V_T \ln \frac{I_{IN}}{I_{OUT}}$$

$$I_{OUT} = \frac{V_T}{R_2} \ln \frac{I_{IN}}{I_{OUT}} = 2.6 \times 10^{-6} \ln \frac{0.72 \text{ mA}}{I_{OUT}}$$

By trial and error we find out,

$I_{OUT} \doteq 10.9 \mu A$

4.23



Ignore BE. $X_d = L_d = 0$

$$V_{ov_1} = \sqrt{\frac{2I_{IN}}{k'(W/L)_1}}$$

$$\left(\frac{W}{L}\right)_1 = \frac{2I_{IN}}{k'(V_{ov_1})^2} = \frac{200}{194\,(0.2)^2} = 25.8$$

$$\sqrt{I_{OUT}} = \frac{-\sqrt{\frac{2}{k'(W/L)_2}} + \sqrt{\frac{2}{k'(W/L)_2} + 4R_2V_{ov_1}}}{2R_2} \times \frac{\sqrt{2k'(W/L)_2}}{\sqrt{2k'(W/L)_2}}$$

$$g_{m_2}R_2 = -1 + \sqrt{1 + 2R_2V_{ov_1}k'(W/L)_2} \longrightarrow (1)$$

$$R_o = r_{o2}(1 + g_{m_2}R_2)$$

$$g_{m_2}R_2 = \frac{R_o}{r_{o2}} - 1$$

$$V_A = \frac{L}{dX_d/dV_{DS}} = \frac{1}{0.02} = 50$$

$$r_{o2} = \frac{50}{10\mu} = 5\,M\Omega$$

$$\therefore R_o = 50\,M\Omega$$

$$g_{m_2}R_2 = 10 - 1 = 9 \longrightarrow (2)$$

Putting (2) in (1),

$$1 + 2R_2V_{ov_1}k'\left(\frac{W}{L}\right)_2 = 100$$

$$2R_2V_{ov_1}k'\left(\frac{W}{L}\right)_2 = 99 \longrightarrow (3)$$

$$\text{swing} = I_{OUT}R_2 + V_{ov_2}$$

$$R_2 = \frac{\text{swing} - V_{ov_2}}{I_{OUT}}$$

$$I_{OUT}R_2 = \text{swing} - \sqrt{\frac{2I_{OUT}}{k'(W/L)_2}}$$

where from (3), we can put

$$\left(\frac{W}{L}\right)_2 = 99/2R_2V_{ov_1}k'$$

$$I_{OUT}R_2 = \text{swing} - \sqrt{\frac{2I_{OUT}}{k'}\,\frac{2R_2V_{ov_1}k'}{99}}$$

$$I_{OUT}R_2 + \sqrt{\frac{4}{99}V_{ov_1}I_{OUT}}\,\sqrt{R_2} - \text{swing} = 0$$

which gives

$$\sqrt{R_2} = \frac{-\sqrt{\frac{4}{99}V_{ov_1}I_{OUT}}}{2I_{OUT}} \pm \frac{\sqrt{\frac{4}{99}V_{ov_1}I_{OUT} + 4I_{OUT}\,\text{swing}}}{2I_{OUT}}$$

$\sqrt{R_2}$ must be greater than zero,

$$\therefore \sqrt{R_2} = \frac{-\sqrt{\frac{4}{99}(0.2)\,10^{-5}}}{2\times10^{-5}} + \frac{\sqrt{\frac{4}{99}(0.2)\,10^{-5} + 4\times10^{-5}(0.2)}}{2\times10^{-5}}$$

$$= \frac{2.5584\times10^{-3}}{2\times10^{-5}} = 128$$

$$R_2 = 16.36\,k\Omega$$

$$\left(\frac{W}{L}\right)_2 = \frac{99}{2(16.36k)(0.2)(196\,\frac{\mu A}{V})} = 77.2$$

4.24

(a) $I_{OUT} = 0.1\,\mu A$ when $I_{IN} = 1\,\mu A$

$$I_{OUT} = I_{IN} \exp\left[-\frac{I_{IN}R}{nV_T}\right] \quad (4.206)$$

$$\Rightarrow R = \frac{nV_T}{I_{IN}} \ln \frac{I_{IN}}{I_{OUT}}$$

$$R = \frac{(1.5)(26\text{ mV})}{(1\,\mu A)} \ln 10 = 90\text{ k}\Omega$$

To keep transistor in weak inversion $V_{GS} - V_t < 0$. Input transistor conducts more current,

$$I_{IN} = \frac{W}{L} I_t \exp\left[\frac{V_{GS_1} - V_t}{nV_T}\right]$$

$$nV_T \ln \frac{I_{IN}}{\frac{W}{L} I_t} = V_{GS_1} - V_t < 0$$

$$\therefore I_{IN} < \frac{W}{L} I_t$$

$$\frac{W}{L} > \frac{I_{IN}}{I_t} = \frac{1\,\mu A}{0.1\,\mu A} = 10$$

(b) $I_{OUT} = 0.1\,\mu A$ when $R = 10\text{ k}\Omega$

$$\ln \frac{I_{IN}}{I_{OUT}} = \frac{I_{IN}R}{nV_T}$$

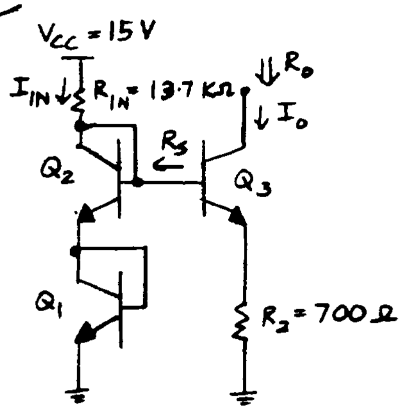
Trial & Error :

I_{IN}	$\ln \frac{I_{IN}}{I_{OUT}}$	$\frac{I_{IN}R}{nV_T}$
$1\,\mu A$	2.3	0.256
$10\,\mu A$	4.6	2.56
$20\,\mu A$	5.29	5.12
$21\,\mu A$	5.35	5.38

So, $I_{IN} \simeq 21\,\mu A$

$$\frac{W}{L} > \frac{I_{IN}}{I_t} = \frac{21\,\mu}{0.1} = 210$$

4.25



Assume :

$I_S = 5 \times 10^{-15}$ A

$\beta_o = 200$

$$V_{BE_1} + V_{BE_2} = V_{BE_3} + I_o R_2$$

$$I_{C_1} \simeq I_{C_2} = I_{IN} \ ; \ I_o = I_{E_3}$$

$$I_{IN} = \frac{15 - 2 \times 0.7}{13.7\text{ k}} = 0.993\text{ mA}$$

$$V_T \ln \frac{I_{C_1}}{I_S} + V_T \ln \frac{I_{C_2}}{I_S} = V_T \ln \frac{I_o}{I_S} + I_o R_2$$

$$\therefore I_o = \frac{V_T}{R_2} \ln \frac{I_{IN}^2}{I_o I_S} = \frac{26\text{mV}}{700\,\Omega} \ln \frac{(0.993 \times 10^{-3})^2}{(5 \times 10^{-15} I_o)}$$

By trial and error, $I_o \simeq 0.97$ mA

R_S is the equivalent resistance looking into the base of Q_2

$$R_S \simeq \frac{2}{g_m} = 2\frac{V_T}{I_{IN}} = 52\,\Omega << r_{\pi_3}$$

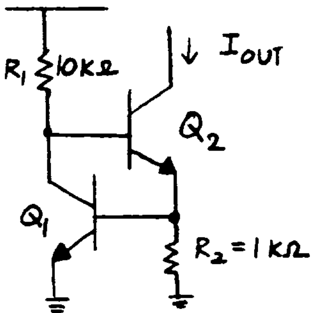
where $r_{\pi_3} \simeq 2.6\text{ k}\Omega \ \therefore \ g_{m_3} = \frac{1}{26}$ ℧

$$R_o = r_{o3}\left(1 + \frac{g_{m_3} R_2}{1 + \frac{g_{m_3} R_2}{\beta_o}}\right) = 3.2\text{ M}\Omega$$

where, $r_{o3} = \frac{V_A}{I_o} \simeq 130\text{ k}\Omega$

4.26

$V_{CC} = 15V$



$$S = \frac{V_{CC}}{I_{OUT}} \frac{\partial I_{OUT}}{\partial V_{CC}}$$

For this circuit

$$I_{OUT} \approx \frac{V_{BE_1}}{R_2}$$

$$I_{C_1} = \frac{V_{CC} - V_{BE_1} - V_{BE_2}}{R_1} \quad \text{and}$$

$$V_{BE_1} = V_T \ln \frac{I_{C_1}}{I_S}$$

$$\therefore I_{OUT} = \frac{V_T}{R_2} \ln \frac{V_{CC} - V_{BE_1} - V_{BE_2}}{I_S R_1}$$

If $V_{BE(on)} << V_{CC}$ then,

$$\frac{\partial I_{OUT}}{\partial V_{CC}} \approx \frac{V_T}{R_2} \frac{1}{V_{CC} - V_{BE_1} - V_{BE_2}}$$

$$\text{and } S = \frac{V_{CC}}{I_{OUT}} \frac{V_T}{R_2} \frac{1}{V_{CC} - V_{BE_1} - V_{BE_2}}$$

$$I_{C_1} \approx \frac{15 - 0.7 - 0.7}{10} = 1.36 \text{ mA}$$

$$\therefore V_{BE_1} \cong 26 \ln \frac{1.36 \times 10^{-3}}{5 \times 10^{-5}} \text{ mV}$$

$$= 0.685 \text{ V}$$

$$\therefore I_{OUT} = \frac{0.685}{1} = 0.685 \text{ mA}$$

$$\therefore S = \frac{15}{0.685 \times 10^{-3}} \frac{26 \times 10^{-3}}{1000} \frac{1}{13.6} = 0.04$$

4.27

From (4.245),

$$V_{BE(on)} = V_T \ln I_1 T^{-\gamma} E e^{V_{G0}/V_T}$$

Put $I_1 = I_0 [1 - K_1 (T - T_0)]$

where $K_1 = 1500 \times 10^{-6}$

$$\therefore V_{BE(on)} = V_T \left[\ln \{ I_0 [1 - K_1 (T - T_0)] \} - \gamma \ln T + \ln E + \frac{V_{G0}}{V_T} \right]$$

$$= V_{G0} - V_T \left[\gamma \ln T - \ln E - \ln I_0 - \ln \{ 1 - K_1 (T - T_0) \} \right]$$

$$\simeq V_{G0} - V_T [\gamma \ln T - \ln E I_0] - V_T K_1 (T - T_0)$$

Using $\ln(1 + x) \approx x$,

Now, $V_{OUT} = V_{BE(on)} + K V_T$

$$\therefore V_{OUT} = V_{G0} - V_T \gamma \ln T + V_T (K + \ln E I_0) - V_T K_1 (T - T_0) \longrightarrow ①$$

$$\left. \frac{d V_{OUT}}{dT} \right|_{T = T_0} = 0, \text{ then}$$

$$\frac{V_{T_0}}{T_0} (K + \ln E I_0) - \frac{V_{T_0}}{T_0} \gamma \ln T_0 - \frac{V_{T_0}}{T_0} \gamma - V_{T_0} K_1 = 0$$

$$\therefore K + \ln E I_0 = \gamma \ln T_0 + \gamma + K_1 T_0 \rightarrow ②$$

② → ① gives,

$$V_{OUT} = V_{G0} + V_T \gamma \ln \frac{T_0}{T} + V_T \gamma - V_T K_1 (T - 2T_0)$$

At $T = T_0$, $V_{OUT} = V_{G0} + V_{T0} \gamma + V_{T0} K_1 T_0$

If $T_0 = 298°K$, $K_1 = 1500 \times 10^{-6}$

$V_{T0} = 26$ mV, $V_{G0} = 1.205$ V

$$\therefore V_{OUT} = 1.205 + 3.2 \times 26 \times 10^{-3} + 26 \times 10^{-3} \times 1500 \times 10^{-6} \times 298$$

$$= 1.2996 \text{ V}$$

4.28

For zero TC_F of V_{OUT} at 25°C

we require $V_{OUT} = 1.262\,V$

$$V_{OUT} = V_{BE_1} + \frac{R_2}{R_3}(V_{BE_1} - V_{BE_2})$$

$$= V_{BE_1} + 0.1\frac{R_2}{R_3}$$

If $I_1 = 200\,\mu A$, then

$$V_{BE_1} = V_T \ln \frac{200\times10^{-6}}{5\times10^{-15}} = 0.635\,V$$

$$\therefore 1.262 = 0.635 + 0.1\frac{R_2}{R_3}$$

$$\therefore \frac{R_2}{R_3} = 6.27 \longrightarrow (1)$$

Also, $R_1 = \frac{V_{OUT} - V_{BE_1}}{I_1} = \frac{1.262 - 0.635}{200\times10^{-6}}$

$$= 3.135\,k\Omega$$

Now, $V_{BE_2} = V_{BE_1} - 0.1 = 0.535\,V$

$$\therefore I_2 = I_S e^{V_{BE_2}/V_T} = 5\times10^{-15} e^{535/26}$$

$$= 4.32\,\mu A$$

$$\therefore R_2 + R_3 = \frac{1.262 - 0.535}{4.32\times10^{-6}} = 168.3\,k\Omega$$

From (1), $R_2 = 6.23 R_3$

$$\therefore 6.23 R_3 + R_3 = 168.3\,k\Omega$$

$$\therefore R_3 = 23.1\,k\Omega,\ R_2 = 145.2\,k\Omega$$

4.29

$$V_{EB_2} = V_T \ln \frac{I_{C_2}}{I_{S_2}} = V_T \ln \frac{I_{E_2}}{I_{S_2}}$$

(because base current is ignored)

$$I_{E_2} = \frac{\Delta V_{EB}}{R_3}$$

Now double I_{S_1} and I_{S_2}. ΔV_{EB} is constant. see (4.272). Therefore, I_{E_2} and I_{C_2} are constant. So, V_{EB_2} changes by $V_T \ln \frac{1}{2} = -18\,mV$

From (4.248),

$$V_{EB_2} = V_{G0} - V_T\left[(\gamma-\alpha)\ln T - \ln(EG)\right]$$

$$\frac{dV_{EB_2}}{dT} = -\frac{V_T(\gamma-\alpha)}{T} - (\gamma-\alpha)\ln T\frac{V_T}{T} + \frac{V_T}{T}\ln(EG)$$

$$= \frac{-V_T(\gamma-\alpha) - V_T\left[(\gamma-\alpha)\ln T - \ln(EG)\right] + V_{G0} - V_{G0}}{T}$$

$$= \frac{V_{EB_2} - V_{G0} - V_T(\gamma-\alpha)}{T}$$

Under nominal conditions, the slope of the V_{EB_2} term and the slope of the ΔV_{EB} term at the output are set equal in magnitude and opposite in polarity at 25°C to set $TC_F = 0$. However, under the specified conditions, V_{EB_2} has fallen by 18 mV, and its slope has fallen by $\frac{18\,mV}{25+273}$

$$= \frac{18}{298} = 60\,\mu V/K = 60\,\mu V/°C$$

since V_{EB_2} contributes directly to the output (see 4.266), the output slope changes by the same amount.

Therefore, $\left.\frac{dV_{OUT}}{dT}\right|_{T=25°C} = -60\,\mu V/°C$

4.30

With I_{S_1} and I_{S_2} adjusted from the nominal value but the gain equal to the nominal value, SPICE gives

$$\left.\frac{dV_{OUT}}{dT}\right|_{T=25^\circ C} = -60\ \mu V/^\circ C$$

With the gain readjusted so that V_{OUT} = target at 25°C,

$$\left.\frac{dV_{OUT}}{dT}\right|_{T=25^\circ C} = 0$$

Therefore, the case of $I_S \neq$ nominal can be corrected by trimming the gain to set the output equal to the target.

```
BAND-GAP REFERENCE (CASE 1)
******
* CASE 1:  Q1 AND Q2 NORMAL;
*          R3 ADJUSTED FOR TC=0 AT 25 DEG C
*
* IN CASE 1, D(VOUT)/DT = 0 AT T = 25 DEGREES C:
*      VOUT (AT T =  0 DEGREES C) = 1.1606 VOLTS
*      VOUT (AT T = 25 DEGREES C) = 1.1608 VOLTS
*      VOUT (AT T = 50 DEGREES C) = 1.1606 VOLTS

Q1     0  0   1      MOD1
Q2     0  0   2      MOD2
R1     4  1   1K
R2     4  3   8K
R3     3  2   2.39K
E1     4   0  1     3 10K

.MODEL MOD1 PNP IS=1.25E-17
.MODEL MOD2 PNP IS=1E-16

.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.TEMP 0 25 50
.END

 **** OPERATING POINT INFORMATION     TNOM= 27  TEMP=  0
   NODE=VOLTAGE        NODE=VOLTAGE        NODE=VOLTAGE
+0:1   = 8.3348E-01 0:2   = 7.3560E-01 0:3   = 8.3336E-01
+0:4   = 1.1606E+00

**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT   0:Q1         0:Q2
MODEL     0:MOD1       0:MOD2
 IB      -3.2389E-06 -4.0501E-07
 IC      -3.2389E-04 -4.0501E-05
 VBE     -8.3348E-01 -7.3560E-01
 VCE     -8.3348E-01 -7.3560E-01
 VBC        0.           0.
 VS         0.           0.
 POWER    2.7266E-04  3.0090E-05
 BETAD    1.0000E+02  1.0000E+02
 GM       1.3761E-02  1.7207E-03
 RPI      7.2670E+03  5.8115E+04
 RX         0.           0.
 RO       1.7378E+17  2.1722E+16
 BETAAC   9.9999E+01  9.9999E+01
```

```
**** OPERATING POINT INFORMATION       TNOM=  27 TEMP= 25
   NODE=VOLTAGE        NODE=VOLTAGE        NODE=VOLTAGE
+0:1   = 8.0368E-01 0:2   = 6.9683E-01 0:3   = 8.0356E-01
+0:4   = 1.1608E+00

**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT   0:Q1         0:Q2
MODEL     0:MOD1       0:MOD2
 IB      -3.5359E-06 -4.4213E-07
 IC      -3.5359E-04 -4.4213E-05
 VBE     -8.0368E-01 -6.9683E-01
 VCE     -8.0368E-01 -6.9683E-01
 VBC        0.           0.
 VS         0.           0.
 POWER    2.8701E-04  3.1117E-05
 BETAD    1.0000E+02  1.0000E+02
 GM       1.3763E-02  1.7209E-03
 RPI      7.2660E+03  5.8109E+04
 RX         0.           0.
 RO       2.7965E+15  3.4956E+14
 BETAAC   9.9999E+01  9.9999E+01

 **** OPERATING POINT INFORMATION      TNOM=  27 TEMP= 50
   NODE=VOLTAGE        NODE=VOLTAGE        NODE=VOLTAGE
+0:1   = 7.7351E-01 0:2   = 6.5771E-01 0:3   = 7.7339E-01
+0:4   = 1.1606E+00

**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT   0:Q1         0:Q2
MODEL     0:MOD1       0:MOD2
 IB      -3.8328E-06 -4.7924E-07
 IC      -3.8328E-04 -4.7924E-05
 VBE     -7.7351E-01 -6.5771E-01
 VCE     -7.7351E-01 -6.5771E-01
 VBC        0.           0.
 VS         0.           0.
 POWER    2.9943E-04  3.1835E-05
 BETAD    9.9999E+01  1.0000E+02
 GM       1.3764E-02  1.7210E-03
 RPI      7.2652E+03  5.8104E+04
 RX         0.           0.
 RO       8.4155E+13  1.0519E+13
 BETAAC   9.9999E+01  9.9999E+01
```

```
BAND-GAP REFERENCE (CASE 2)
* CASE 2: ISAT IN Q1 AND Q2 DOUBLED;
*         R3 SAME AS IN CASE 1
*
* IN CASE 2,
* D(VOUT)/DT = (1.1443 VOLTS - 1.1413 VOLTS)/(50 DEGREES C)
*            = -60 MICROVOLTS/(DEGREE C) AT T = 25 DEG C:
*       VOUT (AT T =  0 DEGREES C) = 1.1443 VOLTS
*       VOUT (AT T = 25 DEGREES C) = 1.1430 VOLTS
*       VOUT (AT T = 50 DEGREES C) = 1.1413 VOLTS

Q1    0  0  1    MOD1
Q2    0  0  2    MOD2
R1    4  1  1K
R2    4  3  8K
R3    3  2  2.39K
E1    4   0  1    3 10K

* THE SATURATION CURRENTS HERE ARE DOUBLED FROM CASE 1
.MODEL MOD1 PNP IS=2.5E-17
.MODEL MOD2 PNP IS=2E-16
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.TEMP 0 25 50
.END

 ****  OPERATING POINT INFORMATION     TNOM=  27 TEMP=  0
   NODE=VOLTAGE        NODE=VOLTAGE        NODE=VOLTAGE
+0:1    = 8.1717E-01 0:2    = 7.1928E-01 0:3    = 8.1705E-01
+0:4    = 1.1443E+00

**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT   0:Q1         0:Q2
MODEL     0:MOD1       0:MOD2
 IB      -3.2390E-06 -4.0502E-07
 IC      -3.2390E-04 -4.0502E-05
 VBE     -8.1717E-01 -7.1928E-01
 VCE     -8.1717E-01 -7.1928E-01
 VBC        0.          0.
 VS         0.          0.
 POWER    2.6733E-04  2.9424E-05
 BETAD    1.0000E+02  1.0000E+02
 GM       1.3761E-02  1.7207E-03
 RPI      7.2669E+03  5.8114E+04
 RX         0.          0.
 RO       8.6891E+16  1.0861E+16
 BETAAC   9.9999E+01  9.9999E+01

****  OPERATING POINT INFORMATION     TNOM=  27 TEMP= 25
   NODE=VOLTAGE        NODE=VOLTAGE        NODE=VOLTAGE
+0:1    = 7.8587E-01 0:2    = 6.7903E-01 0:3    = 7.8575E-01
+0:4    = 1.1430E+00

**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT   0:Q1         0:Q2
MODEL     0:MOD1       0:MOD2
 IB      -3.5359E-06 -4.4213E-07
 IC      -3.5359E-04 -4.4213E-05
 VBE     -7.8587E-01 -6.7903E-01
 VCE     -7.8587E-01 -6.7903E-01
 VBC        0.          0.
 VS         0.          0.
 POWER    2.8066E-04  3.0322E-05
 BETAD    1.0000E+02  1.0000E+02
 GM       1.3763E-02  1.7209E-03
 RPI      7.2659E+03  5.8108E+04
 RX         0.          0.
 RO       1.3982E+15  1.7478E+14
 BETAAC   9.9999E+01  9.9999E+01

 ****  OPERATING POINT INFORMATION     TNOM=  27 TEMP= 50
   NODE=VOLTAGE        NODE=VOLTAGE        NODE=VOLTAGE
+0:1    = 7.5421E-01 0:2    = 6.3841E-01 0:3    = 7.5409E-01
+0:4    = 1.1413E+00

**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT   0:Q1         0:Q2
MODEL     0:MOD1       0:MOD2
 IB      -3.8329E-06 -4.7925E-07
 IC      -3.8329E-04 -4.7925E-05
 VBE     -7.5421E-01 -6.3841E-01
 VCE     -7.5421E-01 -6.3841E-01
 VBC        0.          0.
 VS         0.          0.
 POWER    2.9197E-04  3.0902E-05
 BETAD    1.0000E+02  1.0000E+02
 GM       1.3764E-02  1.7211E-03
 RPI      7.2650E+03  5.8103E+04
 RX         0.          0.
 RO       4.2077E+13  5.2597E+12
 BETAAC   9.9999E+01  9.9999E+01
```

```
BAND-GAP REFERENCE (CASE 3)
* CASE 3: ISAT IN Q1 AND Q2 DOUBLED;
*         R3 ADJUSTED TO MAKE VOUT = TARGET IN CASE 1
*
* IN CASE 3,
* R3 IS ADJUSTED UNTIL VOUT (AT T = 25 DEGREES C)
* IS EQUAL TO 1.1608 V (THE TARGET FROM CASE 1)
* UNDER THIS CONDITION,
* THE RESULTING D(VOUT)/DT = 0 AT T = 25 DEGREES C:
*       VOUT (AT T =  0 DEGREES C) = 1.1606 VOLTS
*       VOUT (AT T = 25 DEGREES C) = 1.1608 VOLTS
*       VOUT (AT T = 50 DEGREES C) = 1.1606 VOLTS

Q1     0  0   1      MOD1
Q2     0  0   2      MOD2
R1     4  1   1K
R2     4  3   8K
* R3 IS ADJUSTED TO MAKE VOUT = TARGET IN CASE 1
R3     3  2   2.2835K
E1     4   0  1     3 10K

* THE SATURATION CURRENTS HERE ARE DOUBLED FROM CASE 1
.MODEL MOD1 PNP IS=2.5E-17
.MODEL MOD2 PNP IS=2E-16

.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.TEMP 0 25 50
.END

 ****  OPERATING POINT INFORMATION      TNOM=  27 TEMP=  0
   NODE=VOLTAGE        NODE=VOLTAGE        NODE=VOLTAGE
+0:1    = 8.1824E-01 0:2    = 7.2036E-01 0:3    = 8.1812E-01
+0:4    = 1.1606E+00

**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT   0:Q1        0:Q2
MODEL     0:MOD1      0:MOD2
 IB       -3.3901E-06 -4.2390E-07
 IC       -3.3901E-04 -4.2390E-05
 VBE      -8.1824E-01 -7.2036E-01
 VCE      -8.1824E-01 -7.2036E-01
 VBC        0.          0.
 VS         0.          0.
 POWER     2.8016E-04  3.0841E-05
 BETAD     1.0000E+02  1.0000E+02
 GM        1.4403E-02  1.8010E-03
 RPI       6.9431E+03  5.5526E+04
 RX         0.          0.
 RO        8.6891E+16  1.0861E+16
 BETAAC    9.9999E+01  9.9999E+01

****  OPERATING POINT INFORMATION      TNOM=  27 TEMP= 25
   NODE=VOLTAGE        NODE=VOLTAGE        NODE=VOLTAGE
+0:1    = 7.8704E-01 0:2    = 6.8020E-01 0:3    = 7.8692E-01
+0:4    = 1.1608E+00

**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT   0:Q1        0:Q2
MODEL     0:MOD1      0:MOD2
 IB       -3.7008E-06 -4.6275E-07
 IC       -3.7008E-04 -4.6275E-05
 VBE      -7.8704E-01 -6.8020E-01
 VCE      -7.8704E-01 -6.8020E-01
 VBC        0.          0.
 VS         0.          0.
 POWER     2.9418E-04  3.1791E-05
 BETAD     1.0000E+02  1.0000E+02
 GM        1.4405E-02  1.8011E-03
 RPI       6.9421E+03  5.5520E+04
 RX         0.          0.
 RO        1.3982E+15  1.7478E+14
 BETAAC    9.9999E+01  9.9999E+01

 ****  OPERATING POINT INFORMATION      TNOM=  27 TEMP= 50
   NODE=VOLTAGE        NODE=VOLTAGE        NODE=VOLTAGE
+0:1    = 7.5548E-01 0:2    = 6.3968E-01 0:3    = 7.5536E-01
+0:4    = 1.1606E+00

**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT   0:Q1        0:Q2
MODEL     0:MOD1      0:MOD2
 IB       -4.0116E-06 -5.0160E-07
 IC       -4.0116E-04 -5.0160E-05
 VBE      -7.5548E-01 -6.3968E-01
 VCE      -7.5548E-01 -6.3968E-01
 VBC        0.          0.
 VS         0.          0.
 POWER     3.0610E-04  3.2407E-05
 BETAD     1.0000E+02  1.0000E+02
 GM        1.4406E-02  1.8013E-03
 RPI       6.9413E+03  5.5515E+04
 RX         0.          0.
 RO        4.2077E+13  5.2597E+12
 BETAAC    9.9999E+01  9.9999E+01
```

4.31 With $V_{OS} = 0$

From (4.266),

$$V_{OUT} = V_{EB_2} + V_{R_3} + V_{R_2}$$

From (4.264),

$$V_{R_3} = V_{EB_1} - V_{EB_2}$$

Therefore,

$$V_{OUT} = V_{EB_2} + V_{EB_1} - V_{EB_2} + V_{R_2}$$

$$V_{OUT} = V_{EB_1} + V_{R_2}$$

From (4.265),

$$V_{OUT} = V_{EB_1} + \frac{R_2}{R_3} \Delta V_{EB}$$

since $\Delta V_{EB} \propto V_T$,

$$V_{OUT} = V_{EB_1} + K V_T \quad \text{where } K \propto \frac{R_2}{R_3}$$

Therefore, if R_3 is 1% low, then K is 1% high.

Thus,

$$V_{OUT} = V_{OUT}\Big|_{nom} + 0.01\, K V_T$$

since $\left.\frac{dV_{OUT}|_{nom}}{dT}\right|_{T=T_0} = 0$

$$\left.\frac{dV_{OUT}}{dT}\right|_{T=T_0} = 0.01\, K \frac{V_{T_0}}{T_0}$$

Now, $K V_{T_0} = V_{OUT}\Big|_{T=T_0} - V_{EB_1}\Big|_{T=T_0}$

$$\cong 1.26 - 0.6 \cong 0.66\ V$$

$$\therefore \left.\frac{dV_{OUT}}{dT}\right|_{T=T_0} = 0.01 \frac{0.66}{298^\circ K}$$

$$= 22\ \mu V/^\circ C$$

4.32

(a) $I_{C_2} = \frac{V_{BE_1} - V_{BE_2}}{R_3}$

Negative feed back forces

$V_{C_2} = V_{BE_1} - V_{os}$

$V_{OUT} = V_{BE_1} - V_{os} + (V_{BE_1} - V_{BE_2})\frac{R_2}{R_3}$

Therefore, the output-referred offset is equal to $-V_{os}$ here

From (4.271),

$$\left.\frac{dV_{OUT}}{dT}\right|_{T=T_0} = -\frac{V_{os(OUT)}}{T_0}$$

$$\left.\frac{dV_{OUT}}{dT}\right|_{T=298^\circ K} = \frac{30\text{ mV}}{298} = 101\ \mu V/^\circ C$$

(b) $V_{os} > 0$ reduces V_{OUT} so pick R_2 too big. This magnifies the ΔV_{BE} term, $\therefore \frac{dV_{OUT}}{dT} > 0$

4.33

$V_{GS} = V_t + V_{ov}$

$$V_{GS} = V_t(T=298^\circ K) - M\Delta T + \sqrt{\frac{2I}{k'(T=298^\circ K)\left(\frac{T}{298}\right)^{-n}\frac{W}{L}}}$$

$$V_{GS} = V_t(T=298^\circ K) - M\Delta T + V_{ov}(T=298^\circ K)\left(\frac{T}{298}\right)^{n/2}$$

$$\frac{dV_{GS}}{dT} = -M + V_{ov}(T=298^\circ K)\frac{n}{2}\left(\frac{T}{298}\right)^{\frac{n}{2}-1}\frac{1}{298} = 0$$

$$\sqrt{\frac{2I}{k'(T=298^\circ K)\frac{W}{L}}}\ \frac{n}{2}\left(\frac{T}{298}\right)^{\frac{n}{2}-1}\frac{1}{298} = m$$

$$\sqrt{\frac{W}{L}} = \sqrt{\frac{2I}{k'(T=298^\circ K)}}\left(\frac{n}{2m\,298}\right)\left(\frac{T}{298}\right)^{\frac{n}{2}-1}$$

$$\frac{W}{L} = \frac{2I}{k'(T=298^\circ K)}\left[\frac{n}{2m(298)}\right]^2\left(\frac{T}{298}\right)^{2\left(\frac{n}{2}-1\right)}$$

Make $\frac{dV_{GS}}{dT} = 0$ at $T = 298^\circ K$

$$\frac{W}{L} = \frac{2I}{k'(T=298^\circ K)}\left[\frac{n}{2m(298)}\right]^2$$

$$= \frac{2(200)}{194}\left[\frac{1.5}{2(0.002)(298)}\right]^2$$

$$= 3.265$$

4.34

Since $M_3 = M_4$, $|I_{D_3}| = |I_{D_4}| = I_{D_1} = I_{D_2} = I_{BIAS}$

$$I_{BIAS}R = V_{GS_1} - V_{GS_2}$$

$$I_{BIAS} = \frac{1}{R}\left(V_{t_1} - \sqrt{\frac{I_{BIAS}}{\frac{\mu_n C_{ox}}{2}\left(\frac{W}{L}\right)_1}} - V_{t_2} - \sqrt{\frac{I_{BIAS}}{\frac{\mu_n C_{ox}}{2}\left(\frac{W}{L}\right)_2}}\right.$$

Ignoring body effect,

$$V_{t_1} = V_{t_2}$$

$$I_{BIAS} = \frac{1}{R}\sqrt{\frac{2I_{BIAS}}{\mu_n C_{ox}}}\left(\sqrt{\left(\frac{L}{W}\right)_1} - \sqrt{\left(\frac{L}{W}\right)_2}\right)$$

$$\therefore I_{BIAS} = \frac{2}{R^2 \mu_n C_{ox}}\left(\sqrt{\left(\frac{L}{W}\right)_1} - \sqrt{\left(\frac{L}{W}\right)_2}\right)^2$$

$$\frac{1}{I_{BIAS}}\frac{dI_{BIAS}}{dT} = -\frac{1}{\mu_n}\frac{d\mu_n}{dT} - \frac{2}{R}\frac{dR}{dT}$$

(4.243), $\mu_n \propto T^{-n}$

$$\therefore -\frac{1}{\mu_n}\frac{d\mu_n}{dT} > 0$$

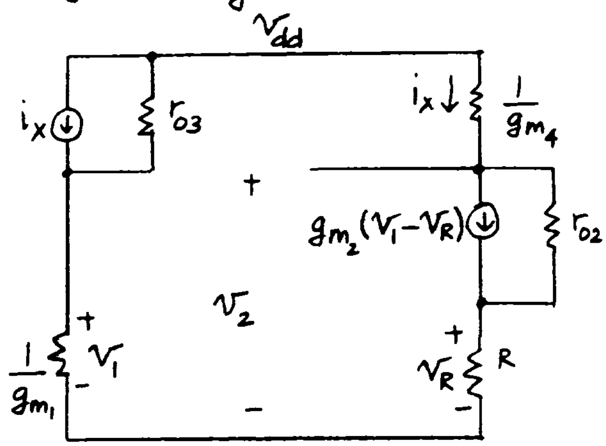
(2.11), $R \propto \mu_x^{-1} \propto T^n$

$$\therefore \frac{2}{R}\frac{dR}{dT} > 0$$

Here μ_x is the mobility of the specific doping material used for the resistor. The above two terms tend to cancel each other.

4.35

small-signal model



$$\text{KCL:}\quad i_x = \frac{v_1 - v_{dd}}{r_{o3}} + v_1 g_{m_1}$$

$$\rightarrow v_1\left(\frac{1}{r_{o3}} + g_{m_1}\right) = i_x + \frac{v_{dd}}{r_{o3}}$$

$$v_2 = v_{dd} - \frac{i_x}{g_{m_4}} = v_R + v_{r_{o2}}$$

$$= i_x R + [i_x - g_{m_2}(v_1 - v_R)]\, r_{o2}$$

so,

$$v_{dd} - \frac{i_x}{g_{m_4}} = i_x R + i_x r_{o2} - g_{m_2} r_{o2} v_1 + g_{m_2} r_{o2} i_x R$$

$$v_{dd} = i_x\left(R + r_{o2} + g_{m_2} r_{o2} R + \frac{1}{g_{m_4}}\right) - \frac{g_{m_2} r_{o2}\left(i_x + v_{dd}/r_{o3}\right)}{g_{m_1} + 1/r_{o3}}$$

$$v_{dd}\overbrace{\left(1 + \frac{g_{m_2} r_{o2}}{1 + g_{m_1} r_{o3}}\right)}^{\simeq 1 + g_{m_2}/g_{m_1}} = i_x\Big(\cancel{R} + \cancel{r_{o2}} + g_{m_2} r_{o2} R + \cancel{\frac{1}{g_{m_4}}} - \underbrace{\frac{g_{m_2} r_{o2}}{1 + g_{m_1} r_{o3}}\cdot r_{o3}}_{\simeq -\frac{g_{m_2} r_{o2}}{g_{m_1}}}\Big)$$

Assume $r_{o2} \doteq r_{o3}$,

$$\frac{i_{bias}}{v_{dd}} = \frac{i_x}{v_{dd}} \simeq \frac{1 + g_{m_2}/g_{m_1}}{g_{m_2} r_{o2}\left(R - \frac{1}{g_{m_1}}\right)}$$

$$\simeq \frac{1 + g_{m_2}/g_{m_1}}{g_{m_2} r_{o2} R}$$

4.36

$\left(\frac{W}{L}\right)_1 = \frac{100\ \mu m}{1\ \mu m} \quad \left(\frac{W}{L}\right)_2 = \frac{50\ \mu m}{1\ \mu m}$

Ignore channel length modulation

for top mosfet current mirror.

Then $|I_{D_3}| = |I_{D_4}|$ and $I_{D_1} = I_{D_2}$

Also ignore base currents $|I_{c_1}| = |I_{c_2}|$

$$V_{GS_1} + V_T \ln \frac{|I_{c_1}|}{I_{S_1}} = V_{GS_2} + V_T \ln \frac{|I_{c_2}|}{I_{S_2}}$$

$$V_{GS_2} - V_{GS_1} = V_T \ln \frac{I_{c_1}}{I_{c_2}} \frac{I_{S_2}}{I_{S_1}} = V_T \ln 10$$

Neglect body effect, $V_{t_1} \approx V_{t_2}$

$$\therefore \sqrt{\frac{2 I_{C_{1,2}}}{\mu_n C_{ox}}} \left(\sqrt{\left(\frac{L}{W}\right)_2} - \sqrt{\left(\frac{L}{W}\right)_1} \right) = V_T \ln 10$$

$$I_{C_{1,2}} = \left(\frac{V_T \ln 10}{\sqrt{\left(\frac{L}{W}\right)_2} - \sqrt{\left(\frac{L}{W}\right)_1}} \right)^2 \frac{\mu_n C_{ox}}{2} = 203\ \mu A$$

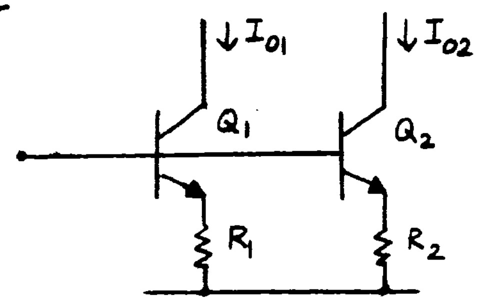
$V_T^2 \propto T^2, \quad \mu_n \propto T^{-n}$

$\therefore I_{C_{1,2}} \propto T^{2-n}$

```
BIAS CIRCUIT
* IDEAL CASE: LAMBDA=0 AND IGNORE BODY EFFECT
* ALSO USE INFINITE BETA AND EARLY VOLTAGE
* AND RB = 0 IN THE BIPOLAR TRANSISTORS
******
VCC    100 0  3   AC  1
M1     3   3  2   2   CMOSN W=100U L=1U
M2     5   3  1   1   CMOSN W=50U  L=1U
M3     3   4  100 100 CMOSP W=50U  L=1U
M4     4   4  100 100 CMOSP W=50U  L=1U
Q1     0   0  1   PNP 10
Q2     0   0  2   PNP
* THE FOLLOWING ELEMENT IS INSERTED TO MEASURE IBIAS
VIBIAS 4 5  0
.MODEL PNP   PNP  IS=2E-15 BF=1E8 VAF=1E8
.MODEL CMOSN NMOS LEVEL=1 VTO=0.6  KP=194U
.MODEL CMOSP PMOS LEVEL=1 VTO=-0.8 KP=65U
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.TF    I(VIBIAS) VCC
.END

 ****  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
   NODE      =VOLTAGE      NODE      =VOLTAGE      NODE      =VOLTAGE
+0:1        = 5.956E-01 0:2        = 6.552E-01 0:3        = 1.398E+00
+0:4        = 1.848E+00 0:5        = 1.848E+00 0:100      = 3.000E+00

SUBCKT
ELEMENT  0:Q1       0:Q2
MODEL    0:PNP      0:PNP
 IB     -2.005E-12 -2.005E-12
 IC     -2.005E-04 -2.005E-04
 VBE    -5.956E-01 -6.552E-01
 VCE    -5.956E-01 -6.552E-01
 VBC       0.         0.
 VS        0.         0.
 POWER   1.194E-04  1.314E-04
 BETAD   1.000E+08  1.000E+08
 GM      7.753E-03  7.753E-03
 RPI     1.289E+10  1.289E+10
 RX        0.         0.
 RO      3.599E+11  4.801E+11
 BETAAC  9.999E+07  9.999E+07

**** MOSFETS
SUBCKT
ELEMENT  0:M1       0:M2       0:M3       0:M4
MODEL    0:CMOSN    0:CMOSN    0:CMOSP    0:CMOSP
 ID      2.005E-04  2.005E-04 -2.005E-04 -2.005E-04
 IBS       0.         0.         0.         0.
 IBD    -7.438E-15 -1.253E-14  1.601E-14  1.151E-14
 VGS     7.438E-01  8.033E-01 -1.151E+00 -1.151E+00
 VDS     7.438E-01  1.253E+00 -1.601E+00 -1.151E+00
 VBS       0.         0.         0.         0.
 VTH     6.000E-01  6.000E-01 -8.000E-01 -8.000E-01
 VDSAT   1.438E-01  2.033E-01 -3.513E-01 -3.513E-01
 BETA    1.940E-02  9.700E-03  3.250E-03  3.250E-03
 GAM EFF   0.         0.         0.         0.
 GM      2.789E-03  1.972E-03  1.142E-03  1.142E-03
 GDS       0.         0.         0.         0.
 GMB       0.         0.         0.         0.

****      SMALL-SIGNAL TRANSFER CHARACTERISTICS

I(VIBIAS)/VCC                            =  1.346E-11
INPUT RESISTANCE AT          VCC         =  3.456E+10
OUTPUT RESISTANCE AT I(VIBIAS)           =  1.457E+11
```

```
BIAS CIRCUIT
* REAL CASE: LAMBDA > 0 AND INCLUDE BODY EFFECT
* ALSO USE FINITE BETA AND EARLY VOLTAGE
* AND RB > 0 IN THE BIPOLAR TRANSISTORS
******
VCC    100 0  3   AC  1
M1     3   3  2   0   CMOSN W=100U L=1U
M2     5   3  1   0   CMOSN W=50U  L=1U
M3     3   4  100 100 CMOSP W=50U  L=1U
M4     4   4  100 100 CMOSP W=50U  L=1U
Q1     0   0  1   PNP 10
Q2     0   0  2   PNP
* THE FOLLOWING ELEMENT IS INSERTED TO MEASURE IBIAS
VIBIAS 4 5  0
.MODEL PNP PNP IS=2E-15 BF=50 VAF=50 RB=300
.MODEL CMOSN NMOS LEVEL=1 VTO=0.6  KP=194U
+ LD=0.09U TOX=80E-10 LAMBDA=0.02439 GAMMA=0.283
.MODEL CMOSP PMOS LEVEL=1 VTO=-0.8 KP=65U
+ LD=0.09U TOX=80E-10 LAMBDA=0.04878
* COX    = 3.9(8.854E-14)/(80E-8) = 4.32E-7
* GAMMA  = SQRT(2(Q)(EPSILON)(NA))/COX
* GAMMAN =
*      SQRT(2(1.6E-19)(11.7)(8.854E-14)(4E16+5E15))/4.32E-7 = 0.283
* GAMMAP DOESN'T MATTER
*      BECAUSE THERE IS NO BODY EFFECT ON M3 AND M4
* LAMBDAN = (DXD/DVDS)/LEFF = 0.02/0.82 = 0.02439 V^(-1)
* LAMBDAP = (DXD/DVDS)/LEFF = 0.04/0.82 = 0.04878 V^(-1)
* CHANNEL-LENGTH MODULATION HAS A SIGNIFICANT EFFECT.
* IN PRACTICE, CASCODES ARE USUALLY USED TO REDUCE THIS EFFECT
* WHENEVER * THE POWER-SUPPLY VOLTAGE IS LARGE ENOUGH
* TO ACCOMODATE THE CASCODES.  FOR EXAMPLE, SEE FIG. 4.50,
*  WHERE CASCODES ARE APPLIED TO A VBE REFERENCE.
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.TF    I(VIBIAS) VCC
.END
 ****  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
   NODE      =VOLTAGE      NODE      =VOLTAGE      NODE      =VOLTAGE
+0:1        = 6.104E-01 0:2        = 6.722E-01 0:3        = 1.545E+00
+0:4        = 1.786E+00 0:5        = 1.786E+00 0:100      = 3.000E+00

SUBCKT
ELEMENT  0:Q1       0:Q2
MODEL    0:PNP      0:PNP
 IB     -7.046E-06 -7.124E-06
 IC     -3.523E-04 -3.562E-04
 VBE    -6.104E-01 -6.722E-01
 VCE    -6.104E-01 -6.722E-01
 VBC       0.         0.
 VS     -2.114E-04 -2.137E-03
 POWER   2.194E-04  2.442E-04
 BETAD   5.000E+01  5.000E+01
 GM      1.361E-02  1.377E-02
 RPI     3.670E+03  3.630E+03
 RX      3.000E+01  3.000E+02
 RO      1.419E+05  1.403E+05
 BETAAC  4.997E+01  4.997E+01

**** MOSFETS
SUBCKT
ELEMENT  0:M1       0:M2       0:M3       0:M4
MODEL    0:CMOSN    0:CMOSN    0:CMOSP    0:CMOSP
 ID      3.633E-04  3.594E-04 -3.633E-04 -3.594E-04
 IBS    -6.722E-15 -6.104E-15    0.         0.
 IBD    -1.546E-14 -1.786E-14  1.454E-14  1.214E-14
 VGS     8.734E-01  9.352E-01 -1.213E+00 -1.213E+00
 VDS     8.734E-01  1.175E+00 -1.454E+00 -1.213E+00
 VBS    -6.722E-01 -6.104E-01    0.         0.
 VTH     7.000E-01  6.921E-01 -8.000E-01 -8.000E-01
 VDSAT   1.734E-01  2.430E-01 -4.138E-01 -4.138E-01
 BETA    2.416E-02  1.217E-02  4.245E-03  4.198E-03
 GAM EFF 2.830E-01  2.830E-01    0.         0.
 GM      4.190E-03  2.957E-03  1.756E-03  1.737E-03
 GDS     8.677E-06  8.520E-06  1.655E-05  1.655E-05
 GMB     5.257E-04  3.804E-04    0.         0.

****      SMALL-SIGNAL TRANSFER CHARACTERISTICS
I(VIBIAS)/VCC                            =  8.374E-05
INPUT RESISTANCE AT          VCC         =  5.445E+03
OUTPUT RESISTANCE AT I(VIBIAS)           =  3.410E+04
```

4.37



$R = \frac{1}{2}(R_1 + R_2)$, $I_c = \frac{1}{2}(I_{01} + I_{02})$

$$\frac{\Delta I_c}{I_c} = \frac{1}{1 + \frac{g_m R}{\kappa}} \frac{\Delta I_s}{I_s} + \frac{\frac{g_m R}{\kappa}}{1 + \frac{g_m R}{\kappa}} \left[-\frac{\Delta R}{R} + \frac{\Delta \kappa}{\kappa} \right]$$

$$\simeq \frac{1}{1 + g_m R} \frac{\Delta I_s}{I_s} + \frac{g_m R}{1 + g_m R} \left[-\frac{\Delta R}{R} \right] \rightarrow (1)$$

We want $\frac{\Delta I_c}{I_c} = 0.01$

Now $\frac{\Delta I_s}{I_s} = \frac{\Delta V_{BE}}{V_T} = \frac{2}{26} = 0.077$

$\frac{\Delta R}{R} = 0.005$

$\therefore$ Worst case in (1)

$$0.01 = \frac{1}{1 + x}(0.077) + \frac{x}{1 + x}(0.005)$$

where $x = g_m R$. Solve for x.

$x = g_m R = 13.4$

$\therefore \frac{q I_c R}{KT} = 13.4$

$\therefore I_c R = 13.4 \times 26\ \text{mV} = 0.348\ \text{V}$

4.38

From (4.315),

$$V_{OS} = V_T \left[\frac{\Delta I_{SP}}{I_{SP}} - \frac{\Delta I_{SN}}{I_{SN}} + \frac{2}{\beta_F} \right]$$

Worst case is,

$$V_{OS} = 26\left(0.05 + 0.05 + \frac{2}{15}\right) \text{mV}$$

$$= 6.1 \text{ mV}$$

4.39

If Q_3 and Q_4 have emitter resistors R_3 and R_4, then

$$\frac{I_{C_3}}{\alpha_3} R_3 + V_{BE_3} = \frac{I_{C_4}}{\alpha_4} R_4 + V_{BE_4}$$

From (4.296), the mismatch in I_{C_3} and I_{C_4} is

$$\frac{\Delta I_C}{I_C} \simeq \frac{1}{1+g_m R} \frac{\Delta I_S}{I_S} + \frac{g_m R}{1+g_m R}\left[\frac{-\Delta R}{R} + \frac{\Delta \alpha}{\alpha}\right]$$

$$= \frac{1}{1 + \frac{50\times10^{-6}}{26\times10^{-3}}(2000)}(0.05)$$

$$+ \frac{3.85}{1+3.85}\left[0.005 + \frac{0.1}{15}\right]$$

(Using $\frac{\Delta\alpha}{\alpha} = \frac{1}{\beta}\frac{\Delta\beta}{\beta}$)

Thus, $\frac{\Delta I_C}{I_C} = 1.96 \times 10^{-2}$

Again using (4.315) with

$$\frac{\Delta I_{SP}}{I_{SP}} = \frac{\Delta I_C}{I_C} = 1.96\times10^{-2}$$

We have

$$V_{OS} = 26\left[0.0196 + 0.05 + \frac{2}{15}\right] \text{mV}$$

$$= 5.3 \text{ mV}$$

4.40 From (4.339),

$$V_{OS} = V_{t_1} - V_{t_2} + \frac{V_{ov_N}}{2}\left[\frac{V_{t_3} - V_{t_4}}{\frac{|V_{ov_P}|}{2}} + \frac{\Delta(W/L)_P}{(W/L)_P} - \frac{\Delta(W/L)_N}{(W/L)_N}\right]$$

$$V_{ov_N} = \sqrt{\frac{2(I_{TAIL}/2)}{k'_N\,(W/L)_N}}$$

$$k'_N = 194\ \mu A/V^2$$

$$(W/L)_N = \frac{(W/L)_1 + (W/L)_2}{2} = 10$$

$$V_{ov_N} = \sqrt{\frac{100\mu}{194\mu(10)}} = 227 \text{ mV}$$

$$|V_{ov_P}| = \sqrt{\frac{2(I_{TAIL}/2)}{k'_P\,(W/L)_P}}$$

$$k'_P = 65\ \mu A/V^2$$

$$(W/L)_P = \frac{(W/L)_3 + (W/L)_4}{2} = 30$$

$$V_{ov_P} = \sqrt{\frac{100\mu}{65\mu(30)}} = 227 \text{ mV}$$

Worst case is:

$$V_{OS} = 10\text{ mV} + \frac{227\text{ mV}}{2}\left[\frac{20\text{ mV}}{227\text{ mV}} + 0.05 + 0.05\right]$$

$$= 10\text{ mV} + 113\text{ mV}(0.188) = 31.4\text{ mV}$$

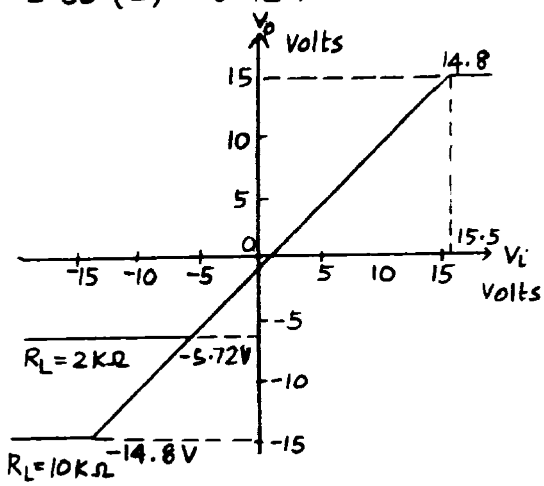
CHAPTER 5

5.1

(a) $I_R = \dfrac{V_{CC} - V_{BE_3}}{R_3} = \dfrac{15 - 0.7}{5K} = 2.86\ mA$

Thus, $I_Q = 2.86\ mA$

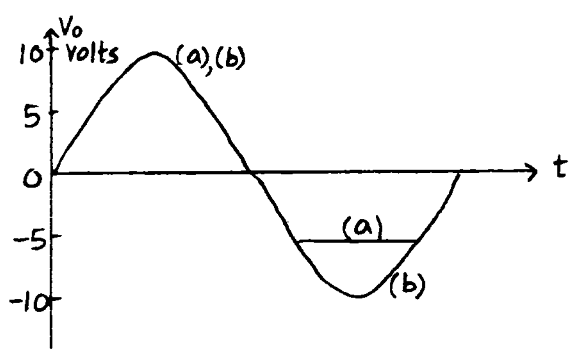
$I_Q R_L = 2.86\,(2) = 5.72\ V$



(b) $I_Q R_L = 2.86 \times 10 = 28.6\ V$

Thus, the lower limit on V_o is $(-V_{CC} + V_{CE})$

(c)




```
EMITTER FOLLOWER OUTPUT STAGE, RL = 2 KOHMS
******
VCC    100   0   15
VEE    200   0   -15
Q1     100   1   2     NPN
Q2     2     3   200   NPN
Q3     3     3   200   NPN
R3     0     3   5K
RL     2     0   2K
VI     1     0   SIN  0  10  10K  0 0
.MODEL NPN NPN RB=200 BF=200 VAF=130 IS=5E-15
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.DC VI -16 16 1
.PLOT DC V(2)
.TRAN 4U 200U
.PLOT TRAN V(2)
.FOUR 10K V(2)
.END

 ******  DC TRANSFER CURVES      TNOM=  27.000 TEMP=  27.000
   VOLT       V(2)
(A       )   -1.000E+01       0.          1.000E+01     2.000E+01    3.000E+01
                  +            +             +             +            +
-1.600E+01 -6.02E+00-+-----A+------+------+------+------+------+------+------+-
-1.500E+01 -6.02E+00 +     A+      +      +      +      +      +      +      +
-1.400E+01 -6.02E+00 +     A+      +      +      +      +      +      +      +
-1.300E+01 -6.02E+00 +     A+      +      +      +      +      +      +      +
-1.200E+01 -6.02E+00 +     A+      +      +      +      +      +      +      +
-1.100E+01 -6.02E+00 +     A+      +      +      +      +      +      +      +
-1.000E+01 -6.02E+00 +     A+      +      +      +      +      +      +      +
-9.000E+00 -6.02E+00 +     A+      +      +      +      +      +      +      +
-8.000E+00 -6.02E+00 +     A+      +      +      +      +      +      +      +
-7.000E+00 -6.02E+00 +     A+      +      +      +      +      +      +      +
-6.000E+00 -6.02E+00-+-----A+------+------+------+------+------+------+------+-
-5.000E+00 -5.62E+00 +     A+      +      +      +      +      +      +      +
-4.000E+00 -4.66E+00 +      A      +      +      +      +      +      +      +
-3.000E+00 -3.67E+00 +      + A    +      +      +      +      +      +      +
-2.000E+00 -2.68E+00 +      +  A   +      +      +      +      +      +      +
-1.000E+00 -1.69E+00 +      +    A +      +      +      +      +      +      +
  0.       -6.99E-01 +      +     A+      +      +      +      +      +      +
 1.000E+00  2.96E-01-+      +      A      +      +      +      +      +      +
 2.000E+00  1.29E+00 +      +      + A    +      +      +      +      +      +
 3.000E+00  2.28E+00 +      +      +  A   +      +      +      +      +      +
 4.000E+00  3.28E+00-+------+------+----A-+------+------+------+------+------+-
 5.000E+00  4.28E+00 +      +      +     A+      +      +      +      +      +
 6.000E+00  5.27E+00 +      +      +      A      +      +      +      +      +
 7.000E+00  6.27E+00 +      +      +      + A    +      +      +      +      +
 8.000E+00  7.27E+00 +      +      +      +  A   +      +      +      +      +
 9.000E+00  8.26E+00 +      +      +      +    A +      +      +      +      +
 1.000E+01  9.26E+00 +      +      +      +     A+      +      +      +      +
 1.100E+01  1.02E+01 +      +      +      +      A      +      +      +      +
 1.200E+01  1.12E+01 +      +      +      +      + A    +      +      +      +
 1.300E+01  1.22E+01 +      +      +      +      +  A   +      +      +      +
 1.400E+01  1.32E+01-+------+------+------+------+----A-+------+------+------+-
 1.500E+01  1.42E+01 +      +      +      +      +     A+      +      +      +
 1.600E+01  1.49E+01 +      +      +      +      +      A      +      +      +
                     +             +             +             +             +
 ****  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
   NODE      =VOLTAGE      NODE      =VOLTAGE      NODE      =VOLTAGE
+0:1         =   0.        0:2       =-6.990E-01 0:3         =-1.429E+01
+0:100       = 1.500E+01 0:200       =-1.500E+01

**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT   0:Q1        0:Q2        0:Q3
MODEL     0:NPN       0:NPN       0:NPN
 IB        1.240E-05   1.416E-05   1.416E-05
 IC        2.765E-03   3.127E-03   2.831E-03
 VBE       6.990E-01   7.028E-01   7.028E-01
 VCE       1.569E+01   1.430E+01   7.028E-01
 VBC      -1.500E+01  -1.359E+01   0.
 VS       -1.500E+01   6.990E-01   1.429E+01
 POWER     4.342E-02   4.473E-02   2.000E-03
 BETAD     2.230E+02   2.209E+02   2.000E+02
 GM        1.069E-01   1.209E-01   1.094E-01
 RPI       2.086E+03   1.827E+03   1.827E+03
 RX        2.000E+02   2.000E+02   2.000E+02
 RO        5.243E+04   4.591E+04   4.591E+04
 BETAAC    2.230E+02   2.208E+02   1.999E+02
```

```
******  TRANSIENT ANALYSIS        TNOM=  27.000 TEMP=  27.000
    TIME      V(2)
(A        )     -1.000E+01  -5.000E+00      0.       5.000E+00   1.000E+01
                     +           +           +           +           +

        0. -6.99E-01-+-----+-----+-----+---A-+-----+-----+-----+-----+-
 4.000E-06  1.77E+00 +     +     +     +     +   A +     +     +     +
 8.000E-06  4.09E+00 +     +     +     +     +     +   A +     +     +
 1.200E-05  6.12E+00 +     +     +     +     +     +     +  A  +     +
 1.600E-05  7.71E+00 +     +     +     +     +     +     +     +A    +
 2.000E-05  8.70E+00 +     +     +     +     +     +     +     +  A  +
 2.400E-05  9.20E+00 +     +     +     +     +     +     +     +    A+
 2.800E-05  9.09E+00 +     +     +     +     +     +     +     +   A +
 3.200E-05  8.31E+00 +     +     +     +     +     +     +     + A   +
 3.600E-05  6.97E+00 +     +     +     +     +     +     +    A+     +
 4.000E-05  5.11E+00-+-----+-----+-----+-----+-----+-----A-----+-----+-
 4.400E-05  2.93E+00 +     +     +     +     +     +A    +     +     +
 4.800E-05  5.39E-01 +     +     +     +     + A   +     +     +     +
 5.200E-05 -1.94E+00 +     +     +     + A   +     +     +     +     +
 5.600E-05 -4.32E+00 +     +     + A   +     +     +     +     +     +
 6.000E-05 -5.74E+00 +     +   A +     +     +     +     +     +     +
 6.400E-05 -6.02E+00 +     +  A  +     +     +     +     +     +     +
 6.800E-05 -6.02E+00 +     +  A  +     +     +     +     +     +     +
 7.200E-05 -6.02E+00 +     +  A  +     +     +     +     +     +     +
 7.600E-05 -6.02E+00 +     +  A  +     +     +     +     +     +     +
 8.000E-05 -6.02E+00-+-----+---A-+-----+-----+-----+-----+-----+-----+-
 8.400E-05 -6.02E+00 +     +  A  +     +     +     +     +     +     +
 8.800E-05 -6.02E+00 +     +  A  +     +     +     +     +     +     +
 9.200E-05 -5.45E+00 +     +    A+     +     +     +     +     +     +
 9.600E-05 -3.16E+00 +     +     +   A +     +     +     +     +     +
 1.000E-04 -6.99E-01 +     +     +     +   A +     +     +     +     +
 1.040E-04  1.76E+00 +     +     +     +     +   A +     +     +     +
 1.080E-04  4.06E+00 +     +     +     +     +     +   A +     +     +
 1.120E-04  6.07E+00 +     +     +     +     +     +     +  A  +     +
 1.160E-04  7.71E+00 +     +     +     +     +     +     +     +A    +
 1.200E-04  8.70E+00-+-----+-----+-----+-----+-----+-----+-----+--A--+-
 1.240E-04  9.20E+00 +     +     +     +     +     +     +     +    A+
 1.280E-04  9.09E+00 +     +     +     +     +     +     +     +   A +
 1.320E-04  8.31E+00 +     +     +     +     +     +     +     + A   +
 1.360E-04  6.97E+00 +     +     +     +     +     +     +    A+     +
 1.400E-04  5.11E+00 +     +     +     +     +     +     A     +     +
 1.440E-04  2.93E+00 +     +     +     +     +     +A    +     +     +
 1.480E-04  5.39E-01 +     +     +     +     + A   +     +     +     +
 1.520E-04 -1.94E+00 +     +     +     + A   +     +     +     +     +
 1.560E-04 -4.32E+00 +     +     + A   +     +     +     +     +     +
 1.600E-04 -5.74E+00-+-----+---A-+-----+-----+-----+-----+-----+-----+-
 1.640E-04 -6.02E+00 +     +  A  +     +     +     +     +     +     +
 1.680E-04 -6.02E+00 +     +  A  +     +     +     +     +     +     +
 1.720E-04 -6.02E+00 +     +  A  +     +     +     +     +     +     +
 1.760E-04 -6.02E+00 +     +  A  +     +     +     +     +     +     +
 1.800E-04 -6.02E+00 +     +  A  +     +     +     +     +     +     +
 1.840E-04 -6.02E+00 +     +  A  +     +     +     +     +     +     +
 1.880E-04 -6.02E+00 +     +  A  +     +     +     +     +     +     +
 1.920E-04 -5.45E+00 +     +    A+     +     +     +     +     +     +
 1.960E-04 -3.16E+00 +     +     +   A +     +     +     +     +     +
 2.000E-04 -6.99E-01-+-----+-----+-----+---A-+-----+-----+-----+-----+-
                     +           +           +           +           +
```

******

FOURIER COMPONENTS OF TRANSIENT RESPONSE V(2)

DC COMPONENT =   2.870D-01

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	9.999E+03	8.159E+00	1.000E+00	-3.476E-02	0.
2	2.000E+04	1.250E+00	1.533E-01	-8.984E+01	-8.980E+01
3	3.000E+04	6.333E-01	7.761E-02	-2.819E-02	6.576E-03
4	4.000E+04	1.590E-01	1.948E-02	8.787E+01	8.790E+01
5	5.000E+04	8.093E-02	9.919E-03	3.654E+00	3.689E+00
6	6.000E+04	1.156E-01	1.417E-02	8.832E+01	8.835E+01
7	7.000E+04	4.861E-02	5.957E-03	1.722E+02	1.723E+02
8	8.000E+04	2.064E-02	2.530E-03	1.008E+02	1.008E+02
9	9.000E+04	2.816E-02	3.451E-03	1.784E+02	1.784E+02

TOTAL HARMONIC DISTORTION =   1.739E+01 PERCENT

```
EMITTER FOLLOWER OUTPUT STAGE, RL = 10 KOHMS
******
VCC   100  0  15
VEE   200  0  -15
Q1    100  1  2    NPN
Q2    2    3  200  NPN
Q3    3    3  200  NPN
R3    0    3  5K
RL    2    0  10K
VI    1    0  SIN  0  10  10K  0 0
.MODEL NPN NPN RB=200 BF=200 VAF=130 IS=5E-15
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.DC VI -16 16 1
.PLOT DC V(2)
.TRAN 4U 200U
.PLOT TRAN V(2)
.FOUR 10K V(2)
.END
```

```
******  DC TRANSFER CURVES        TNOM=  27.000 TEMP=  27.000
    VOLT      V(2)
(A        )     -2.000E+01  -1.000E+01      0.       1.000E+01   2.000E+01
                     +           +           +           +           +

-1.600E+01 -1.49E+01-+-----A-----+-----+-----+-----+-----+-----+-----+-
-1.500E+01 -1.49E+01 +     A     +     +     +     +     +     +     +
-1.400E+01 -1.46E+01 +     A     +     +     +     +     +     +     +
-1.300E+01 -1.36E+01 +     + A   +     +     +     +     +     +     +
-1.200E+01 -1.26E+01 +     +  A  +     +     +     +     +     +     +
-1.100E+01 -1.16E+01 +     +   A +     +     +     +     +     +     +
-1.000E+01 -1.06E+01 +     +    A+     +     +     +     +     +     +
-9.000E+00 -9.68E+00 +     +     A     +     +     +     +     +     +
-8.000E+00 -8.68E+00 +     +     + A   +     +     +     +     +     +
-7.000E+00 -7.69E+00 +     +     +  A  +     +     +     +     +     +
-6.000E+00 -6.69E+00-+-----+-----+---A-+-----+-----+-----+-----+-----+-
-5.000E+00 -5.69E+00 +     +     +    A+     +     +     +     +     +
-4.000E+00 -4.69E+00 +     +     +     A     +     +     +     +     +
-3.000E+00 -3.69E+00 +     +     +     + A   +     +     +     +     +
-2.000E+00 -2.69E+00 +     +     +     +  A  +     +     +     +     +
-1.000E+00 -1.70E+00 +     +     +     +   A +     +     +     +     +
        0. -7.02E-01 +     +     +     +    A+     +     +     +     +
 1.000E+00  2.97E-01 +     +     +     +     A     +     +     +     +
 2.000E+00  1.29E+00 +     +     +     +     + A   +     +     +     +
 3.000E+00  2.29E+00 +     +     +     +     +  A  +     +     +     +
 4.000E+00  3.29E+00-+-----+-----+-----+-----+---A-+-----+-----+-----+-
 5.000E+00  4.29E+00 +     +     +     +     +    A+     +     +     +
 6.000E+00  5.29E+00 +     +     +     +     +     A     +     +     +
 7.000E+00  6.29E+00 +     +     +     +     +     + A   +     +     +
 8.000E+00  7.28E+00 +     +     +     +     +     +  A  +     +     +
 9.000E+00  8.28E+00 +     +     +     +     +     +   A +     +     +
 1.000E+01  9.28E+00 +     +     +     +     +     +    A+     +     +
 1.100E+01  1.02E+01 +     +     +     +     +     +     A     +     +
 1.200E+01  1.12E+01 +     +     +     +     +     +     + A   +     +
 1.300E+01  1.22E+01 +     +     +     +     +     +     +  A  +     +
 1.400E+01  1.32E+01-+-----+-----+-----+-----+-----+-----+---A-+-----+-
 1.500E+01  1.42E+01 +     +     +     +     +     +     +    A+     +
 1.600E+01  1.49E+01 +     +     +     +     +     +     +     A     +
                     +           +           +           +           +
```

```
****  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
   NODE      =VOLTAGE      NODE     =VOLTAGE      NODE      =VOLTAGE
+0:1         =    0.       0:2      =-7.017E-01  0:3        =-1.429E+01
+0:100       = 1.500E+01   0:200    =-1.500E+01
```

**** BIPOLAR JUNCTION TRANSISTORS

SUBCKT

ELEMENT	0:Q1	0:Q2	0:Q3
MODEL	0:NPN	0:NPN	0:NPN
IB	1.364E-05	1.416E-05	1.416E-05
IC	3.043E-03	3.127E-03	2.831E-03
VBE	7.017E-01	7.028E-01	7.028E-01
VCE	1.570E+01	1.429E+01	7.028E-01
VBC	-1.500E+01	-1.359E+01	0.
VS	-1.500E+01	7.017E-01	1.429E+01
POWER	4.780E-02	4.472E-02	2.000E-03
BETAD	2.230E+02	2.209E+02	2.000E+02
GM	1.176E-01	1.209E-01	1.094E-01
RPI	1.895E+03	1.827E+03	1.827E+03
RX	2.000E+02	2.000E+02	2.000E+02
RO	4.764E+04	4.591E+04	4.591E+04
BETAAC	2.230E+02	2.208E+02	1.999E+02

```
****** TRANSIENT ANALYSIS          TNOM=  27.000 TEMP=  27.000
  TIME        V(2)
(A      )   -2.000E+01   -1.000E+01     0.          1.000E+01   2.000E+01

0.          -7.02E-01
4.000E-06    1.78E+00
8.000E-06    4.11E+00
1.200E-05    6.13E+00
1.600E-05    7.73E+00
2.000E-05    8.72E+00
2.400E-05    9.22E+00
2.800E-05    9.10E+00
3.200E-05    8.33E+00
3.600E-05    6.99E+00
4.000E-05    5.12E+00
4.400E-05    2.94E+00
4.800E-05    5.40E-01
5.200E-05   -1.95E+00
5.600E-05   -4.35E+00
6.000E-05   -6.53E+00
6.400E-05   -8.35E+00
6.800E-05   -9.73E+00
7.200E-05   -1.05E+01
7.600E-05   -1.06E+01
8.000E-05   -1.01E+01
8.400E-05   -9.09E+00
8.800E-05   -7.53E+00
9.200E-05   -5.51E+00
9.600E-05   -3.18E+00
1.000E-04   -7.02E-01
1.040E-04    1.76E+00
1.080E-04    4.07E+00
1.120E-04    6.09E+00
1.160E-04    7.73E+00
1.200E-04    8.72E+00
1.240E-04    9.22E+00
1.280E-04    9.10E+00
1.320E-04    8.33E+00
1.360E-04    6.99E+00
1.400E-04    5.12E+00
1.440E-04    2.94E+00
1.480E-04    5.40E-01
1.520E-04   -1.95E+00
1.560E-04   -4.35E+00
1.600E-04   -6.53E+00
1.640E-04   -8.35E+00
1.680E-04   -9.73E+00
1.720E-04   -1.05E+01
1.760E-04   -1.06E+01
1.800E-04   -1.01E+01
1.840E-04   -9.09E+00
1.880E-04   -7.53E+00
1.920E-04   -5.51E+00
1.960E-04   -3.18E+00
2.000E-04   -7.02E-01
```

******

FOURIER COMPONENTS OF TRANSIENT RESPONSE V(2)

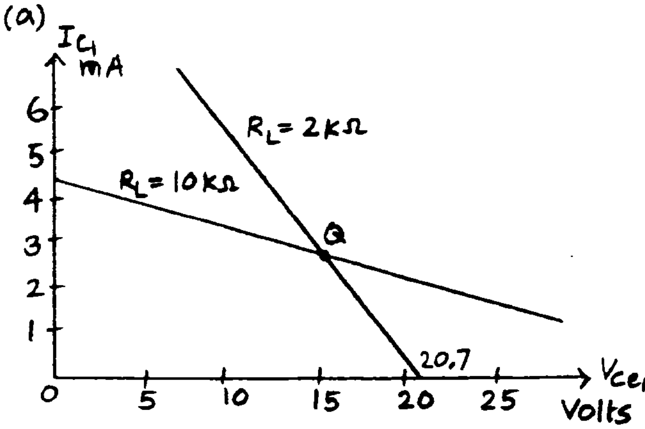
DC COMPONENT = -7.007D-01

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	9.999E+03	9.950E+00	1.000E+00	-7.121E-03	0.
2	2.000E+04	1.361E-03	1.368E-04	-4.854E+01	-4.853E+01
3	3.000E+04	5.184E-03	5.210E-04	1.545E+02	1.545E+02
4	4.000E+04	6.781E-05	6.815E-06	2.441E+01	2.441E+01
5	5.000E+04	3.059E-03	3.075E-04	1.394E+02	1.394E+02
6	6.000E+04	9.325E-06	9.372E-07	-1.650E+01	-1.650E+01
7	7.000E+04	1.951E-03	1.961E-04	-1.577E+02	-1.577E+02
8	8.000E+04	6.078E-05	6.109E-06	-2.101E+01	-2.100E+01
9	9.000E+04	1.086E-02	1.091E-03	-1.996E+01	-1.996E+01

TOTAL HARMONIC DISTORTION = 1.270E-01 PERCENT

5.2

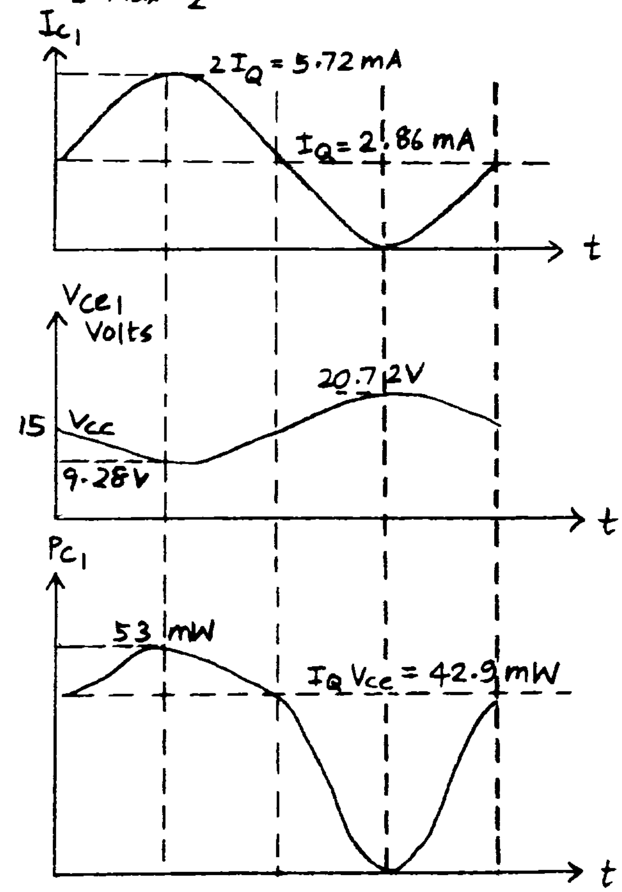
(a)



(b) $R_L = 2K\Omega$

$\hat{V}_{om} = 5.72\ V$, $\hat{I}_{om} = 2.86\,mA$

$\therefore P_L I_{max} = \frac{1}{2} \times 5.72 \times 2.86\ mW = 8.2\ mW$

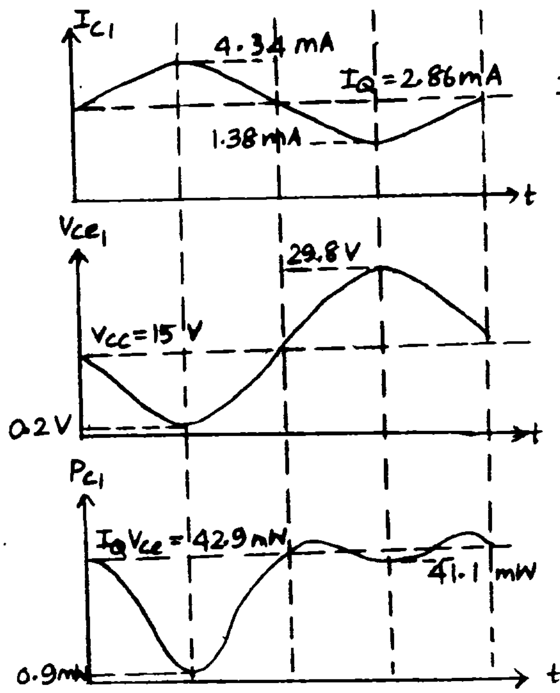


$\underline{R_L = 10\,k\Omega}$

$\hat{V}_{om} = V_{CC} - V_{CE} = 14.8\,V$

$\hat{I}_{om} = \dfrac{\hat{V}_{om}}{R_L} = \dfrac{14.8}{10} = 1.48\,mA$

$\therefore P_L\big|_{max} = \frac{1}{2} \times 14.8 \times 1.48 = 11.0\,mW$



(c) $\underline{R_L = 2\,k\Omega}$

$\eta = \dfrac{P_L}{P_{SUPPLY}} = \dfrac{8.2}{2 \times 42.9} = 9.6\%$

$R_L = 10\,k\Omega$

$\eta_c = \dfrac{11}{2 \times 42.9} = 12.8\%$

(d) For maximum efficiency,

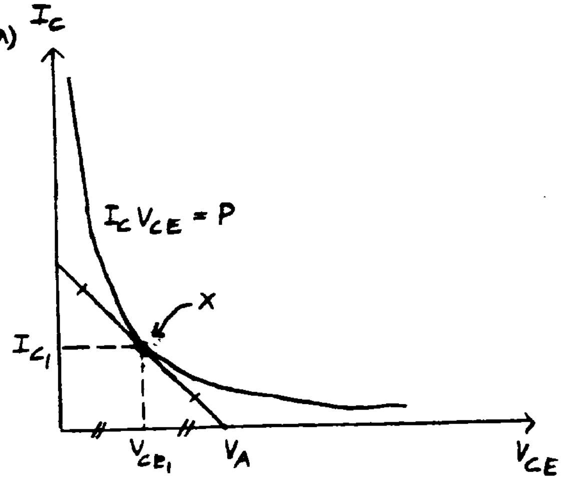
$R_L = \dfrac{V_{CC} - V_{CE(sat.)}}{I_Q} = \dfrac{14.8}{2.86}\,k\Omega$

$= 5.17\,k\Omega$

$P_L = \dfrac{1}{2}\dfrac{\hat{V}_{om}^2}{R_L} = \dfrac{1}{2}\dfrac{(14.8)^2}{5.18}\,mW = 21.1\,mW$

$\underline{5.3}$

(a)



At any point the slope of the hyperbola is

$$\frac{dI_C}{dV_{ce}} = \frac{d}{dV_{ce}}\frac{P}{V_{ce}} = \frac{-P}{V_{ce}^2} = \frac{-I_C}{V_{ce}}$$

At X, $\dfrac{dI_C}{dV_{ce}} = \dfrac{-I_{C1}}{V_{ce1}}$

The slope of the tangent is thus $\dfrac{-I_C}{V_{ce1}}$, and thus

$$\frac{-I_C}{V_A - V_{ce1}} = \frac{-I_{C1}}{V_{ce1}}$$

$\therefore V_A = 2V_{ce1}$

$\therefore$ X is the midpoint of the tangent.

(b) Maximum dissipation occurs at midpoint of the load line

$R_L = 2\,k\Omega$. Midpoint is where

$V_{ce1} = \dfrac{20.7}{2} = 10.35\,V$

corresponding current is

$I_{C1} = \dfrac{10.35\,V}{2\,k\Omega} = 5.18\,mA$

$\therefore P_{C1}\big|_{MAX} = 10.35 \times 5.18 = 53.6\,mW$

$R_L = 10\,K\Omega$

Mid-point is where

$V_{ce_1} = \frac{1}{2}(15 + 2.86 \times 10) = 21.8\,V$

corresponding current is

$I_{c_1} = 2.86 - \frac{21.8-15}{10} = 2.18\,mA$

$\therefore P_{c_1}\big|_{MAX} = 21.8 \times 2.18 = 47.5\,mW$

(c) Since V_{cc} is constant, the average power drawn from the supplies is independent of signal level and equals $2V_{cc}I_Q$.

Thus, average power dissipated in Q_1 + average power dissipated in R_L = $V_{cc}I_Q$. Thus, the average power in $Q_1 = V_{cc}I_Q - \frac{1}{2}\frac{\hat{V}_{om}^2}{R_L} = P_{av}$

$R_L = 2\,K\Omega$

$P_{av} = 42.9 - 8.2 = 34.7\,mW$

$R_L = 10\,K\Omega$

$P_{av} = 42.9 - 11 = 31.9\,mW$

5.4

$R_L = 2\,k\Omega$

$\hat{I}_{om} = 2.86\,mA$, $\hat{V}_{om} = 5.72\,V$

$\therefore$ base current of Q_1 has a peak signal value $= \frac{1}{\beta}\hat{I}_{om} = 0.0286\,mA$

Since voltage gain is unity, peak input voltage $= \hat{V}_{om}$

$\therefore$ average signal power delivered is

$P_i = \frac{1}{2} \times 0.0286 \times 5.72\,mW$

$\therefore P_i = 0.082\,mW$

$\therefore$ Power gain $= \frac{P_L|_{MAX}}{P_i} = \frac{8.2}{0.082}$

$= 100$

$R_L = 10\,K\Omega$

$\frac{1}{\beta}\hat{I}_{om} = \frac{1.48}{100} = 0.0148\,mA$

$\hat{V}_{om} = 14.8\,V$

$\therefore P_i = \frac{1}{2} \times 0.0148 \times 14.8 = 0.11\,mW$

Power gain $= \frac{11}{0.11} = 100$

5.5

$\hat{V}_o = 1V$; $\therefore \hat{I}_o = \frac{\hat{V}_{om}}{R_L} = \frac{1}{2}\,mA$

$I_Q = 2.86\,mA$

Quiescent

$A_{V_Q} = \frac{R_L}{R_L + \frac{1}{g_m}} = \frac{2000}{2000+9.1} = 0.9955$

$V_o = 1V$ $\quad I_c = 3.36\,mA$

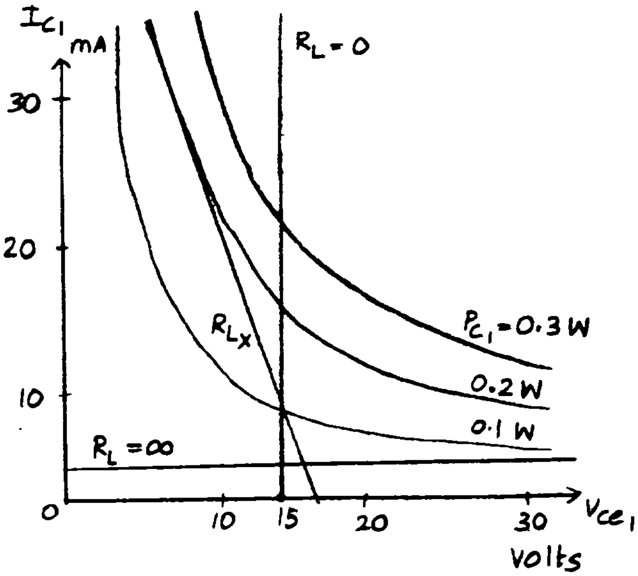
$A_V = \frac{2000}{2000+7.7} = 0.9962$

$V_o = -1V$ $\quad I_c = 2.36\,mA$

$A_V = \frac{2000}{2000+11} = 0.9945$

5.6

(a)



For $R_L = 0$, $I_{c_1}\big|_{MAX} = \beta I_{B_1} = 100 \times 0.3$
$= 30$ mA

$\therefore\ P_{c_1}\big|_{MAX} = 30 \times 15 = 450$ mW

$R_L = \infty$ has max. value of P_{c_1} of approx. 0.1 W at $V_{ce_1} = 30$ V

(b) From the graph $R_L = R_{Lx}$ is the minimum value of R_L for $P_{c_1} < 0.2$ W

This has a value

$R_{Lx} \cong 310\ \Omega$

5.7

$$A_V = \frac{g_m}{g_m + g_{mb}} = \frac{1}{1+\chi}$$

From (1.200), $\chi = \dfrac{\gamma}{2\sqrt{2\phi_f + V_{SB}}}$

(a) When $v_i = \max$

From (5.62),

$$V_o = -3.1 + \left(-0.25 + \sqrt{0.25^2 + 0.5 - 0.8 + 0.5\sqrt{0.6} + 3.1}\right)^2$$

$= -0.68906$ V

$V_{SB} = -0.68906 + 2.5 = 1.81094$ V

$$\chi^+ = \frac{0.5}{2\sqrt{0.6 + 1.81094}} = 0.16101$$

$$A_V^+ = \frac{1}{1 + 0.16101} = 0.86132$$

(b) When $v_i = 0$,

From (5.62),

$$V_o = -3.1 + \left(-0.25 + \sqrt{0.25^2 - 0.8 + 0.5\sqrt{0.6} + 3.1}\right)^2$$

$= -1.11683$ V

$V_{SB} = -1.11683 + 2.5 = 1.38317$ V

$$\chi_Q = \frac{0.5}{2\sqrt{0.6 + 1.38317}} = 0.17753$$

$$A_{V_Q} = \frac{1}{1 + 0.17753} = 0.84923$$

(c) When $v_i = \min$

From (5.62),

$$V_o = -3.1 + \left(-0.25 + \sqrt{0.25^2 - 0.5 - 0.8 + 0.5\sqrt{0.6} + 3.1}\right)^2$$

$= -1.53767$ V

$V_{SB} = -1.53767 + 2.5 = 0.96233$ V

$$\chi^- = \frac{0.5}{2\sqrt{0.6 + 0.96233}} = 0.20001$$

$$A_V^- = \frac{1}{1 + 0.20001} = 0.83333$$

5.8

(a) $v_o = a_1 v_i + a_2 v_i^2 + a_3 v_i^3 + \cdots$

$$A_v = \frac{dv_o}{dv_i} = a_1 + 2a_2 v_i + 3a_3 v_i^2 + \cdots$$

(b) Let $v_i = \hat{v}_i \sin \omega t$

$$A_v^+ = a_1 + 2a_2 \hat{v}_i + 3a_3 v_i^2 + \cdots$$

$$A_{v_Q} = a_1$$

$$A_v^- = a_1 - 2a_2 \hat{v}_i + 3a_3 \hat{v}_i^2$$

(c) $$E^+ = \frac{A_v^+ - A_{v_Q}}{A_{v_Q}} = \frac{2a_2 \hat{v}_i + 3a_3 \hat{v}_i^2}{a_1}$$

$$E^- = \frac{A_v^- - A_{v_Q}}{A_{v_Q}} = \frac{-2a_2 \hat{v}_i + 3a_3 \hat{v}_i^2}{a_1}$$

$$E^+ + E^- = \frac{6a_3 \hat{v}_i^2}{a_1}$$

$$E^+ - E^- = \frac{4a_2 \hat{v}_i}{a_1}$$

(d) From (5.54), $H_{D_2} = \frac{1}{2} \frac{a_2}{a_1} \hat{v}_i = \frac{E^+ - E^-}{8}$

From (5.57), $H_{D_3} = \frac{1}{4} \frac{a_3}{a_1} \hat{v}_i^2 = \frac{E^+ + E^-}{24}$

(e) $$E^+ = \frac{A_v^+ - A_{v_Q}}{A_{v_Q}} = \frac{0.86132 - 0.84923}{0.84923} = 0.01423$$

$$E^- = \frac{A_v^- - A_{v_Q}}{A_{v_Q}} = \frac{0.83333 - 0.84923}{0.84923} = -0.01872$$

$$H_{D_2} = \frac{E^+ - E^-}{8} = \frac{0.01423 + 0.01872}{8} = 0.00412$$

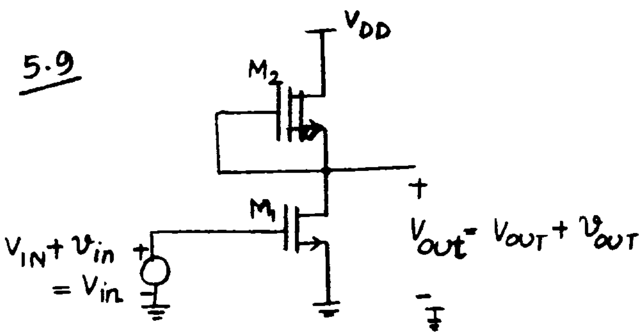
$$H_{D_3} = \frac{E^+ + E^-}{24} = \frac{0.01423 - 0.01872}{24} = -1.87 \times 10^{-4}$$

Example gives,

$$H_{D_2} = 0.0040$$

$$H_{D_3} = -1.8 \times 10^{-4}$$

5.9



$$I_{d_2} = I_{D_2} + i_{d_2} = f(V_{out})$$

$$= \frac{k'}{2}\left(\frac{W}{L}\right)_2 \left[V_{t_0}(m_2) + \gamma\left(\sqrt{V_{out}+2\phi_f} - \sqrt{2\phi_f}\right)\right]^2$$

$$f'(V_{out}) = k'\left(\frac{W}{L}\right)_2 \left[V_{t_0}(m_2) + \gamma\left(\sqrt{V_{out}+2\phi_f} - \sqrt{2\phi_f}\right)\right] \cdot \frac{\gamma}{2}(V_{out}+2\phi_f)^{-1/2}$$

$$f''(V_{out}) = k'\left(\frac{W}{L}\right)_2 \left[V_{t_0}(m_2) + \gamma\left(\sqrt{V_{out}+2\phi_f} - \sqrt{2\phi_f}\right)\right) \cdot \left(-\frac{\gamma}{4}\right)(V_{out}+2\phi_f)^{-3/2} + \frac{\gamma}{2}\left(V_{out}+2\phi_f\right)^{-1/2} \cdot k'\left(\frac{W}{L}\right)_2 \frac{\gamma}{2}(V_{out}+2\phi_f)^{-1/2}$$

$$I_{d_2} = B_0 + B_1 v_{out} + B_2 v_{out}^2 + \cdots$$

$$B_0 = f(V_{out} = V_{OUT})$$

$$= \frac{k'}{2}\left(\frac{W}{L}\right)_2 \left[V_{t_0}(m_2) + \gamma\left(\sqrt{V_{OUT}+2\phi_f} - \sqrt{2\phi_f}\right)\right]^2$$

$$= I_Q$$

$$B_1 = f'(V_{out} = V_{OUT})$$

$$= \sqrt{\frac{k'}{2}\left(\frac{W}{L}\right)_2} \left[V_{t_0}(m_2) + \gamma\left(\sqrt{V_{OUT}+2\phi_f} - \sqrt{2\phi_f}\right)\right] \times \cdot \sqrt{\frac{k'}{2}\left(\frac{W}{L}\right)_2}\, \gamma\,(V_{OUT}+2\phi_f)^{-1/2}$$

$$= \sqrt{I_Q}\sqrt{\frac{k'}{2}\left(\frac{W}{L}\right)_2}\, \gamma\,(V_{OUT}+2\phi_f)^{-1/2}$$

$$B_2 = \frac{f''(V_{out} = V_{OUT})}{2!}$$

$$B_2 = \frac{k'}{2}\left(\frac{W}{L}\right)_2 \left[V_{t_0}(m_2) + \gamma\left(\sqrt{V_{OUT}+2\phi_f} - \sqrt{2\phi_f}\right)\right) \cdot \left(-\frac{\gamma}{4}\right)(V_{OUT}+2\phi_f)^{-3/2} + \frac{\gamma}{4}(V_{OUT}+2\phi_f)^{-1/2} \cdot k'\left(\frac{W}{L}\right)_2 \left(\frac{\gamma}{2}\right)(V_{OUT}+2\phi_f)^{-1/2}$$

$$B_2 = \sqrt{\frac{k'}{2}\left(\frac{W}{L}\right)_2} \left[V_{t_0}(m_2) + \gamma\left(\sqrt{V_{OUT}+2\phi_f} - \sqrt{2\phi_f}\right)\right) \cdot \sqrt{\frac{k'}{2}\left(\frac{W}{L}\right)_2}\left(-\frac{\gamma}{4}\right)(V_{OUT}+2\phi_f)^{-\frac{3}{2}} + \frac{\gamma^2}{4}\frac{k'}{2}\left(\frac{W}{L}\right)_2 (V_{OUT}+2\phi_f)^{-1}$$

$$B_2 = -\sqrt{I_Q}\sqrt{\frac{k'}{2}\left(\frac{W}{L}\right)_2}\,\frac{\gamma}{4}(V_{OUT}+2\phi_f)^{-\frac{3}{2}} + \frac{\gamma^2}{4}\frac{k'}{2}\left(\frac{W}{L}\right)_2 (V_{OUT}+2\phi_f)^{-1}$$

$$I_{d_2} = I_{D_2} + i_{d_2} = B_0 + B_1 v_{out} + B_2 v_{out}^2 + \cdots$$

But, $I_{D_2} = B_0 = I_Q$

So, $i_{d_1} = i_{d_2} = B_1 v_{out} + B_2 v_{out}^2 + \cdots$

Invert,

$v_{out} = b_1 i_{d_2} + b_2 i_{d_2}^2 + \cdots$ and $i_{d_2} = i_{d_1}$

$$v_{out} = b_1 i_{d_1} + b_2 i_{d_1}^2 + \cdots$$

Find i_{d_1}

$$I_{d_1} = I_{D_1} + i_{d_1} = \frac{k'}{2}\left(\frac{W}{L}\right)_1 (V_{IN} + v_{in} - V_{t_0}(m_1))^2$$

$$i_{d_1} = \frac{k'}{2}\left(\frac{W}{L}\right)_1 \left[(V_{IN} - V_{t_0}(m_1))^2 + v_{in}^2 + 2(V_{IN} - V_{t_0}(m_1))v_{in} - (V_{IN} - V_{t_0}(m_1))^2 \right.$$

$$= \frac{k'}{2}\left(\frac{W}{L}\right)_1 \left[v_{in}^2 + 2(V_{IN} - V_{t_0}(m_1))v_{in}\right]$$

$$v_{out} = b_1 i_{d_1} + b_2 i_{d_1}^2 + \ldots$$

$$v_{out} = b_1 \left\{ \frac{K'}{2}\left(\frac{W}{L}\right)_1 \left[v_{in}^2 + 2(V_{IN} - V_{to(m_1)}) v_{in} \right] \right\} + b_2 \left\{ \frac{K'}{2}\left(\frac{W}{L}\right)_1 \left[v_{in}^2 + 2(V_{IN} - V_{to(m_1)}) v_{in} \right] \right\} + \ldots$$

$$v_{out} = b_1 \frac{K'}{2}\left(\frac{W}{L}\right)_1 2(V_{IN} - V_{to(m_1)}) v_{in} + b_1 \frac{K'}{2}\left(\frac{W}{L}\right)_1 v_{in}^2 + b_2 \left[\frac{K'}{2}\left(\frac{W}{L}\right)_1\right]^2 4 (V_{IN} - V_{to(m_1)})^2 v_{in}^2 + \ldots$$

$$v_{out} = a_1 v_{in} + a_2 v_{in}^2 + \ldots$$

$$a_1 = b_1 \frac{K'}{2}\left(\frac{W}{L}\right)_1 2 (V_{IN} - V_{to(m_1)})$$

$$a_2 = b_1 \frac{K'}{2}\left(\frac{W}{L}\right)_1 + b_2 \left[\frac{K'}{2}\left(\frac{W}{L}\right)_1\right]^2 4 (V_{IN} - V_{to(m_1)})^2$$

From (5·46), $b_1 = \frac{1}{B_1}$

$$a_1 = \frac{\frac{K'}{2}\left(\frac{W}{L}\right)_1 2 (V_{IN} - V_{to(m_1)})}{B_1} = \frac{\frac{K'}{2}\left(\frac{W}{L}\right)_1 2 (V_{IN} - V_{to(m_1)})}{\sqrt{I_Q}\sqrt{\frac{K'}{2}\left(\frac{W}{L}\right)_2}\,\gamma\,(V_{OUT} + 2\phi_f)^{-\frac{1}{2}}}$$

$$a_1 = \frac{\sqrt{\frac{K'}{2}\left(\frac{W}{L}\right)_2}\; 2\sqrt{\frac{K'}{2}\left(\frac{W}{L}\right)_1}\;(V_{IN} - V_{to(m_1)})}{\sqrt{I_Q}\sqrt{\frac{K'}{2}\left(\frac{W}{L}\right)_2}\,\gamma\,(V_{OUT} + 2\phi_f)^{-\frac{1}{2}}}$$

since $\sqrt{I_Q} = \sqrt{\frac{K'}{2}\left(\frac{W}{L}\right)_1}\,(V_{IN} - V_{to(m_1)})$

$$a_1 = \frac{2}{\gamma}\sqrt{\frac{(W/L)_1}{(W/L)_2}}\,(V_{OUT} + 2\phi_f)^{1/2}$$

$$a_2 = b_1 \frac{K'}{2}\left(\frac{W}{L}\right)_1 + b_2 \left[\frac{K'}{2}\left(\frac{W}{L}\right)_1\right]^2 4 (V_{IN} - V_{to(m_1)})^2$$

From (5·47), $b_2 = -\frac{B_2}{B_1^3}$

$$a_2 = \frac{\frac{K'}{2}\left(\frac{W}{L}\right)_1}{B_1} - \frac{B_2}{B_1^3}\frac{K'}{2}\left(\frac{W}{L}\right)_1 \frac{K'}{2}\left(\frac{W}{L}\right)_1 (V_{IN} - V_{to(m_1)})^2 4$$

$$a_2 = \frac{\frac{K'}{2}\left(\frac{W}{L}\right)_1}{B_1} - \frac{B_2}{B_1^3}\frac{K'}{2}\left(\frac{W}{L}\right)_1 4 I_Q$$

$$a_2 = \frac{\frac{K'}{2}\left(\frac{W}{L}\right)_1}{\sqrt{I_Q}\sqrt{\frac{K'}{2}\left(\frac{W}{L}\right)_2}\,\gamma\,(V_{OUT} + 2\phi_f)^{-\frac{1}{2}}} + \frac{\left\{\sqrt{I_Q}\sqrt{\frac{K'}{2}\left(\frac{W}{L}\right)_2}\frac{\gamma}{4}(V_{OUT}+2\phi_f)^{-\frac{3}{2}} - \frac{\gamma^2}{4}\frac{K'}{2}\left(\frac{W}{L}\right)_2 (V_{OUT}+2\phi_f)^{-1}\right\}}{I_Q\sqrt{I_Q}\,\frac{K'}{2}\left(\frac{W}{L}\right)_2\sqrt{\frac{K'}{2}\left(\frac{W}{L}\right)_2}\,\gamma^3 (V_{OUT}+2\phi_f)^{-\frac{3}{2}}} \cdot \frac{K'}{2}\left(\frac{W}{L}\right)_1 4 I_Q$$

$$a_2 = \frac{\frac{K'}{2}\left(\frac{W}{L}\right)_1}{\sqrt{I_Q}\sqrt{\frac{K'}{2}\left(\frac{W}{L}\right)_2}\,\gamma\,(V_{OUT} + 2\phi_f)^{-\frac{1}{2}}} + \left(\frac{W}{L}\right)_1 \Big/ \left(\frac{W}{L}\right)_2 \gamma^2 - \frac{\frac{K'}{2}\left(\frac{W}{L}\right)_1}{\sqrt{I_Q}\sqrt{\frac{K'}{2}\left(\frac{W}{L}\right)_2}\,\gamma\,(V_{OUT} + 2\phi_f)^{-\frac{1}{2}}}$$

$$a_2 = \frac{(W/L)_1}{(W/L)_2\gamma^2}$$

From (5·54),

$$HD_2 = \frac{1}{2}\frac{a_2}{a_1}\hat{v}_i$$

$$HD_2 = \frac{\frac{1}{2}\frac{(W/L)_1}{(W/L)_2\gamma^2}\hat{v}_i}{\frac{2}{\gamma}\sqrt{\frac{(W/L)_1}{(W/L)_2}}\sqrt{V_{OUT}+2\phi_f}}$$

$$HD_2 = \frac{1}{4}\sqrt{\frac{(W/L)_1}{(W/L)_2}}\,\frac{1}{\gamma}\,\frac{1}{\sqrt{V_{OUT}+2\phi_f}}\,\hat{v}_i$$

$$= \frac{1}{4}\sqrt{\frac{100}{100}}\,\frac{1}{0.5}\,\frac{1}{\sqrt{1+2(0.3)}}(0.01)$$

$$\cong 0.4\%$$

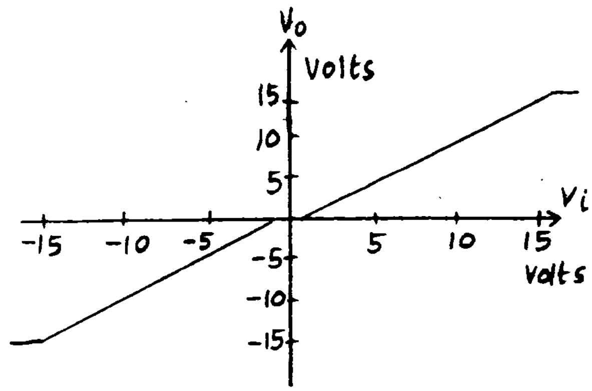
```
HD2 FOR COMMON-SOURCE AMPLIFIER WITH DEPLETION LOAD
******
VDD     100     0   3
M1      2   1   0   0    CMOSN1 W=100U L=1U
M2      100  2   2   0    CMOSN2 W=100U L=1U
.MODEL CMOSN1 NMOS LEVEL=1 LAMBDA=0M VTO=0.6
+ GAMMA=0.5 PHI=0.6 KP=200U
.MODEL CMOSN2 NMOS LEVEL=1 LAMBDA=0M VTO=-0.6
+ GAMMA=0.5 PHI=0.6 KP=200U
VIN     1       3        SIN      (0       0.01      1K)
VINDC   3       0        0.9548
* THE DC INPUT IS ADJUSTED BY TRIAL AND ERROR
* UNTIL THE DC OUTPUT = 1 VOLT
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.TR     100U    2M
.PLOT   TRAN    V(2)
.FOUR   1K      V(2)
.END
**** OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
  NODE      =VOLTAGE       NODE      =VOLTAGE       NODE     =VOLTAGE
+0:1        = 9.548E-01 0:2        = 1.000E+00 0:3        = 9.548E-01
+0:100      = 3.000E+00
**** MOSFETS
SUBCKT
ELEMENT  0:M1        0:M2
MODEL    0:CMOSN1    0:CMOSN2
 ID        1.259E-03  1.259E-03
 IBS        0.        -1.000E-14
 IBD      -1.000E-14 -3.000E-14
 VGS       9.548E-01   0.
 VDS       1.000E+00  1.999E+00
 VBS        0.        -1.000E+00
 VTH       6.000E-01 -3.548E-01
 VDSAT     3.548E-01  3.548E-01
 BETA      2.000E-02  2.000E-02
 GAM EFF   5.000E-01  5.000E-01
 GM        7.096E-03  7.096E-03
 GDS        0.         0.
 GMB       2.290E-03  1.402E-03
******  TRANSIENT ANALYSIS       TNOM=  27.000 TEMP=  27.000
   TIME        V(2)
(A        )      9.000E-01      9.500E-01      1.000E-00      1.050E+00      1.100E+00
                     +              +              +              +              +
  0.         1.00E+00-+------+------+------+------A------+------+------+------+-
 1.000E-04   9.71E-01 +      +      +     A+      +      +      +      +      +
 2.000E-04   9.53E-01 +      +     +A      +      +      +      +      +      +
 3.000E-04   9.53E-01 +      +     +A      +      +      +      +      +      +
 4.000E-04   9.71E-01 +      +      +     A+      +      +      +      +      +
 5.000E-04   1.00E+00 +      +      +      +      A      +      +      +      +
 6.000E-04   1.03E+00 +      +      +      +      +     +A      +      +      +
 7.000E-04   1.04E+00 +      +      +      +      +      +      A      +      +
 8.000E-04   1.04E+00 +      +      +      +      +      +      A      +      +
 9.000E-04   1.03E+00 +      +      +      +      +     +A      +      +      +
 1.000E-03   1.00E+00-+------+------+------+------A------+------+------+------+-
 1.100E-03   9.71E-01 +      +      +     A+      +      +      +      +      +
 1.200E-03   9.53E-01 +      +     +A      +      +      +      +      +      +
 1.300E-03   9.53E-01 +      +     +A      +      +      +      +      +      +
 1.400E-03   9.71E-01 +      +      +     A+      +      +      +      +      +
 1.500E-03   1.00E+00 +      +      +      +      A      +      +      +      +
 1.600E-03   1.03E+00 +      +      +      +      +     +A      +      +      +
 1.700E-03   1.04E+00 +      +      +      +      +      +      A      +      +
 1.800E-03   1.04E+00 +      +      +      +      +      +      A      +      +
 1.900E-03   1.03E+00 +      +      +      +      +     +A      +      +      +
 2.000E-03   1.00E+00-+------+------+------+------A------+------+------+------+-
                     +              +              +              +              +
******
FOURIER COMPONENTS OF TRANSIENT RESPONSE V(2)
DC COMPONENT =    1.000D+00
```

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	1.000E+03	5.038E-02	1.000E+00	1.800E+02	0.
2	2.000E+03	1.966E-04	3.903E-03	-9.135E+01	-2.713E+02
3	3.000E+03	8.333E-06	1.654E-04	-7.803E+01	-2.580E+02
4	4.000E+03	5.605E-07	1.113E-05	-1.465E+02	-3.265E+02
5	5.000E+03	1.724E-05	3.422E-04	-3.464E+01	-2.146E+02
6	6.000E+03	6.125E-07	1.216E-05	-1.233E+02	-3.033E+02
7	7.000E+03	1.065E-05	2.115E-04	-6.563E+00	-1.865E+02
8	8.000E+03	2.798E-07	5.554E-06	1.587E+02	-2.120E+01
9	9.000E+03	4.674E-05	9.278E-04	1.490E+02	-3.096E+01

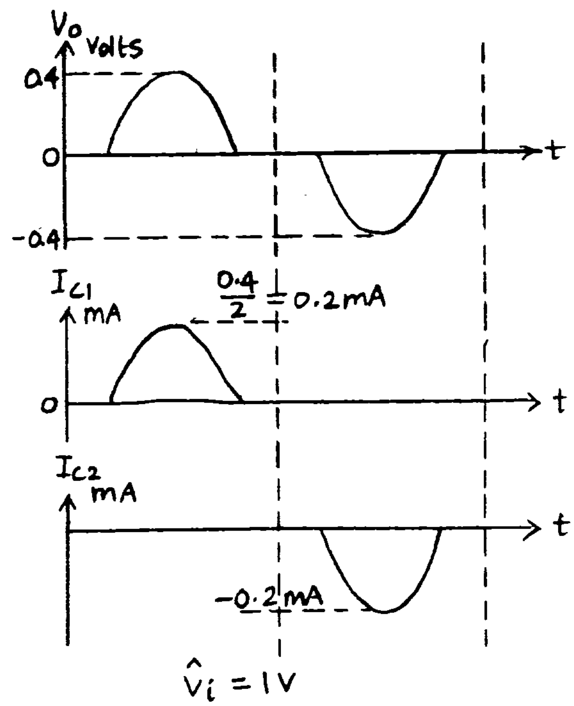
TOTAL HARMONIC DISTORTION =   4.035E-01 PERCENT

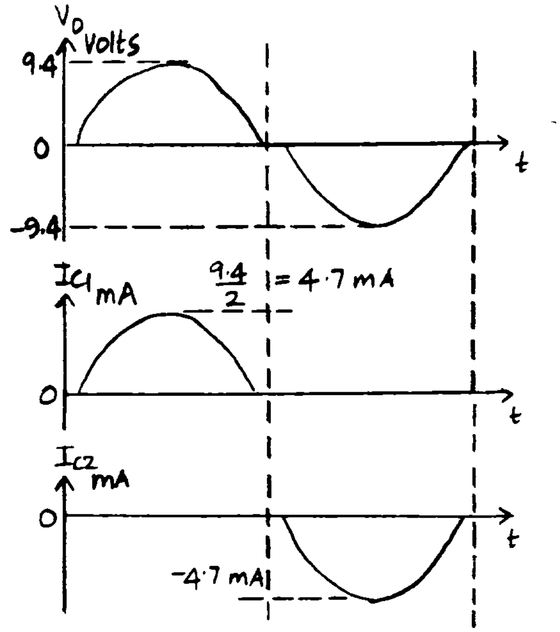
5.10

(a)

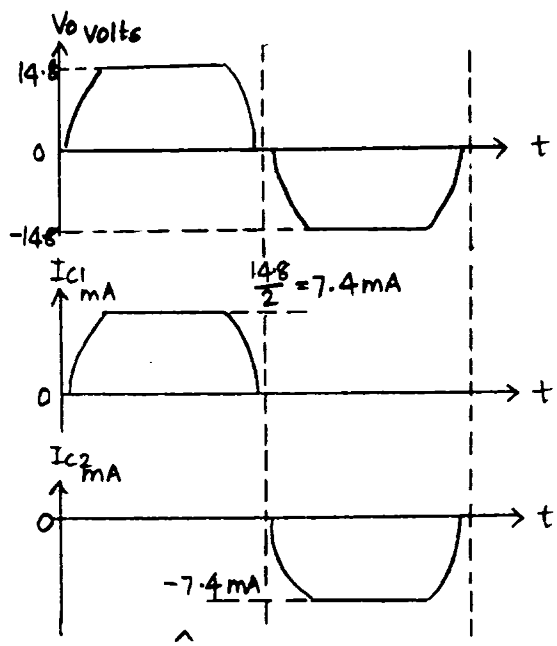


(b)





$\hat{V}_i = 10$ V



$\hat{V}_i = 20$ V

```
CLASS-B OUTPUT STAGE  (PEAK INPUT AMPLITUDE = 1 V)
VCC      100     0   15
VEE      200     0   -15
Q1       100     1   2   NPN
Q2       200     1   2   PNP
RL       2       0   2K
.MODEL NPN NPN RB=100 BF=100 IS=1E-16 RC=20 VAF=130
.MODEL PNP PNP RB=100 BF=100 IS=1E-16 RC=20 VAF=50
VIN      1       0          SIN      0  1  10K 0  0
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.DC VIN -15 15 0.5
.PLOT DC V(2)
.TR      4U       200U
.PLOT    TRAN     V(2)
.FOUR    10K      V(2)
.END
 ******  DC TRANSFER CURVES        TNOM=  27.000 TEMP=  27.000
    VOLT      V(2)
(A       )  -2.000E+01    -1.000E+01    0.            1.000E+01    2.000E+01
                     +             +             +             +             +
-1.500E+01 -1.41E+01-+------+A-----+------+------+------+------+------+------+-
-1.450E+01 -1.36E+01 +      + A    +      +      +      +      +      +      +
-1.400E+01 -1.31E+01 +      +  A   +      +      +      +      +      +      +
-1.350E+01 -1.26E+01 +      +  A   +      +      +      +      +      +      +
-1.300E+01 -1.21E+01 +      +   A  +      +      +      +      +      +      +
-1.250E+01 -1.16E+01 +      +    A +      +      +      +      +      +      +
-1.200E+01 -1.11E+01 +      +    A +      +      +      +      +      +      +
-1.150E+01 -1.06E+01 +      +     A+      +      +      +      +      +      +
-1.100E+01 -1.01E+01 +      +      A      +      +      +      +      +      +
-1.050E+01 -9.68E+00 +      +      A      +      +      +      +      +      +
-1.000E+01 -9.18E+00-+------+------+A-----+------+------+------+------+------+-
-9.500E+00 -8.68E+00 +      +      + A    +      +      +      +      +      +
-9.000E+00 -8.18E+00 +      +      +  A   +      +      +      +      +      +
-8.500E+00 -7.69E+00 +      +      +  A   +      +      +      +      +      +
-8.000E+00 -7.19E+00 +      +      +   A  +      +      +      +      +      +
-7.500E+00 -6.69E+00 +      +      +    A +      +      +      +      +      +
-7.000E+00 -6.19E+00 +      +      +    A +      +      +      +      +      +
-6.500E+00 -5.70E+00 +      +      +     A+      +      +      +      +      +
-6.000E+00 -5.20E+00 +      +      +      A      +      +      +      +      +
-5.500E+00 -4.70E+00 +      +      +      A      +      +      +      +      +
-5.000E+00 -4.21E+00-+------+------+------+A-----+------+------+------+------+-
-4.500E+00 -3.71E+00 +      +      +      + A    +      +      +      +      +
-4.000E+00 -3.21E+00 +      +      +      + A    +      +      +      +      +
-3.500E+00 -2.72E+00 +      +      +      +  A   +      +      +      +      +
-3.000E+00 -2.22E+00 +      +      +      +   A  +      +      +      +      +
-2.500E+00 -1.73E+00 +      +      +      +    A +      +      +      +      +
-2.000E+00 -1.24E+00 +      +      +      +    A +      +      +      +      +
-1.500E+00 -7.57E-01 +      +      +      +     A+      +      +      +      +
-1.000E+00 -2.83E-01 +      +      +      +      A      +      +      +      +
-5.000E-01 -6.45E-05 +      +      +      +      A      +      +      +      +
   0.         0.    -+------+------+------+------A------+------+------+------+-
 5.000E-01  5.57E-05 +      +      +      +      A      +      +      +      +
 1.000E+00  2.79E-01 +      +      +      +      A      +      +      +      +
 1.500E+00  7.53E-01 +      +      +      +      +A     +      +      +      +
 2.000E+00  1.24E+00 +      +      +      +      + A    +      +      +      +
 2.500E+00  1.73E+00 +      +      +      +      + A    +      +      +      +
 3.000E+00  2.22E+00 +      +      +      +      +  A   +      +      +      +
 3.500E+00  2.71E+00 +      +      +      +      +   A  +      +      +      +
 4.000E+00  3.21E+00 +      +      +      +      +    A +      +      +      +
 4.500E+00  3.71E+00 +      +      +      +      +    A +      +      +      +
 5.000E+00  4.20E+00-+------+------+------+------+-----A+------+------+------+-
 5.500E+00  4.70E+00 +      +      +      +      +      A      +      +      +
 6.000E+00  5.20E+00 +      +      +      +      +      A      +      +      +
 6.500E+00  5.69E+00 +      +      +      +      +      +A     +      +      +
 7.000E+00  6.19E+00 +      +      +      +      +      + A    +      +      +
 7.500E+00  6.69E+00 +      +      +      +      +      + A    +      +      +
 8.000E+00  7.19E+00 +      +      +      +      +      +  A   +      +      +
 8.500E+00  7.68E+00 +      +      +      +      +      +   A  +      +      +
 9.000E+00  8.18E+00 +      +      +      +      +      +   A  +      +      +
 9.500E+00  8.68E+00 +      +      +      +      +      +    A +      +      +
 1.000E+01  9.18E+00-+------+------+------+------+------+-----A+------+------+-
 1.050E+01  9.68E+00 +      +      +      +      +      +      A      +      +
 1.100E+01  1.01E+01 +      +      +      +      +      +      A      +      +
 1.150E+01  1.06E+01 +      +      +      +      +      +      +A     +      +
 1.200E+01  1.11E+01 +      +      +      +      +      +      + A    +      +
 1.250E+01  1.16E+01 +      +      +      +      +      +      + A    +      +
 1.300E+01  1.21E+01 +      +      +      +      +      +      +  A   +      +
 1.350E+01  1.26E+01 +      +      +      +      +      +      +   A  +      +
 1.400E+01  1.31E+01 +      +      +      +      +      +      +   A  +      +
 1.450E+01  1.36E+01 +      +      +      +      +      +      +    A +      +
 1.500E+01  1.41E+01-+------+------+------+------+------+------+-----A+------+-
                     +             +             +             +             +
```

```
****** TRANSIENT ANALYSIS      TNOM=  27.000 TEMP=  27.000
   TIME       V(2)
(A        )   -4.000E-01  -2.000E-01     0.        2.000E-01   4.000E-01
                     +           +           +           +           +

 0.         0.        +-----+-----+-----+-----A-----+-----+-----+-----+-
4.000E-06   0.        +     +     +     +     A     +     +     +     +
8.000E-06  2.75E-05   +     +     +     +     A     +     +     +     +
1.200E-05  2.58E-02   +     +     +     +     + A   +     +     +     +
1.600E-05  1.41E-01   +     +     +     +     +     + A   +     +     +
2.000E-05  2.29E-01   +     +     +     +     +     +     + A   +     +
2.400E-05  2.74E-01   +     +     +     +     +     +     +   A +     +
2.800E-05  2.63E-01   +     +     +     +     +     +     +  A  +     +
3.200E-05  1.94E-01   +     +     +     +     +     +     A     +     +
3.600E-05  8.18E-02   +     +     +     +     +    A+     +     +     +
4.000E-05  1.29E-02  -+-----+-----+-----+-----+A----+-----+-----+-----+-
4.400E-05  1.38E-05   +     +     +     +     A     +     +     +     +
4.800E-05   0.        +     +     +     +     A     +     +     +     +
5.200E-05   0.        +     +     +     +     A     +     +     +     +
5.600E-05 -2.75E-06   +     +     +     +     A     +     +     +     +
6.000E-05 -6.89E-03   +     +     +     +     A     +     +     +     +
6.400E-05 -8.87E-02   +     +     +     +A    +     +     +     +     +
6.800E-05 -1.97E-01   +     +     A     +     +     +     +     +     +
7.200E-05 -2.67E-01   +     + A   +     +     +     +     +     +     +
7.600E-05 -2.81E-01   +     +A    +     +     +     +     +     +     +
8.000E-05 -2.32E-01  -+-----+---A-+-----+-----+-----+-----+-----+-----+-
8.400E-05 -1.43E-01   +     +     +  A  +     +     +     +     +     +
8.800E-05 -2.77E-02   +     +     +     +   A +     +     +     +     +
9.200E-05 -3.19E-05   +     +     +     +     A     +     +     +     +
9.600E-05   0.        +     +     +     +     A     +     +     +     +
1.000E-04   0.        +     +     +     +     A     +     +     +     +
1.040E-04  7.92E-07   +     +     +     +     A     +     +     +     +
1.080E-04  2.06E-03   +     +     +     +     A     +     +     +     +
1.120E-04  3.42E-02   +     +     +     +     + A   +     +     +     +
1.160E-04  1.41E-01   +     +     +     +     +     + A   +     +     +
1.200E-04  2.29E-01  -+-----+-----+-----+-----+-----+-----+-A---+-----+-
1.240E-04  2.74E-01   +     +     +     +     +     +     +   A +     +
1.280E-04  2.63E-01   +     +     +     +     +     +     +  A  +     +
1.320E-04  1.94E-01   +     +     +     +     +     +     A     +     +
1.360E-04  8.18E-02   +     +     +     +     +    A+     +     +     +
1.400E-04  1.29E-02   +     +     +     +     +A    +     +     +     +
1.440E-04  1.38E-05   +     +     +     +     A     +     +     +     +
1.480E-04   0.        +     +     +     +     A     +     +     +     +
1.520E-04   0.        +     +     +     +     A     +     +     +     +
1.560E-04 -2.75E-06   +     +     +     +     A     +     +     +     +
1.600E-04 -6.89E-03  -+-----+-----+-----+-----A-----+-----+-----+-----+-
1.640E-04 -8.87E-02   +     +     +     +A    +     +     +     +     +
1.680E-04 -1.97E-01   +     +     A     +     +     +     +     +     +
1.720E-04 -2.67E-01   +     + A   +     +     +     +     +     +     +
1.760E-04 -2.81E-01   +     +A    +     +     +     +     +     +     +
1.800E-04 -2.32E-01   +     +   A +     +     +     +     +     +     +
1.840E-04 -1.43E-01   +     +     +  A  +     +     +     +     +     +
1.880E-04 -2.77E-02   +     +     +     +   A +     +     +     +     +
1.920E-04 -3.19E-05   +     +     +     +     A     +     +     +     +
1.960E-04   0.        +     +     +     +     A     +     +     +     +
2.000E-04   0.       -+-----+-----+-----+-----A-----+-----+-----+-----+-
                      +           +           +           +           +
```

```
******
FOURIER COMPONENTS OF TRANSIENT RESPONSE V(2)
DC COMPONENT =  -8.789D-04
```

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	9.999E+03	1.830E-01	1.000E+00	-4.672E-03	0.
2	2.000E+04	1.020E-03	5.575E-03	9.129E+01	9.129E+01
3	3.000E+04	9.341E-02	5.105E-01	-1.798E+02	-1.798E+02
4	4.000E+04	8.243E-05	4.505E-04	1.329E+02	1.329E+02
5	5.000E+04	1.125E-02	6.151E-02	1.156E+00	1.160E+00
6	6.000E+04	2.129E-04	1.164E-03	-8.186E+01	-8.186E+01
7	7.000E+04	9.939E-03	5.432E-02	4.287E+00	4.291E+00
8	8.000E+04	6.480E-05	3.542E-04	-4.752E+01	-4.752E+01
9	9.000E+04	8.940E-04	4.886E-03	-1.399E+02	-1.399E+02

```
   TOTAL HARMONIC DISTORTION =    5.171E+01  PERCENT
**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT  0:Q1         0:Q2
MODEL    0:NPN        0:PNP
 IB      -1.000E-16   1.000E-16
 IC       2.115E-16  -2.300E-16
 VBE      3.692E-14   3.692E-14
 VCE      1.500E+01  -1.500E+01
 VBC     -1.500E+01   1.500E+01
 VS      -1.500E+01   1.500E-09
 POWER    3.173E-15   3.450E-15
```

```
****  OPERATING POINT INFORMATION     TNOM=  27.000 TEMP=  27.000
   NODE     =VOLTAGE      NODE     =VOLTAGE      NODE     =VOLTAGE
+0:1        =  0.         0:2      =-3.692E-14  0:100     = 1.500E+01
+0:200      =-1.500E+01
```

```
CLASS-B OUTPUT STAGE  (PEAK INPUT AMPLITUDE = 10 V)
******
VCC      100      0     15
VEE      200      0     -15
Q1       100      1     2     NPN
Q2       200      1     2     PNP
RL       2        0     2K
.MODEL NPN NPN RB=100 BF=100 IS=1E-16 RC=20 VAF=130
.MODEL PNP PNP RB=100 BF=100 IS=1E-16 RC=20 VAF=50
VIN      1        0           SIN      0  10 10K 0  0
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.TR      4U       200U
.PLOT    TRAN     V(2)
.FOUR    10K      V(2)
.END
```

```
****** TRANSIENT ANALYSIS      TNOM=  27.000 TEMP=  27.000
   TIME       V(2)
(A        )   -1.000E+01  -5.000E+00     0.        5.000E+00   1.000E+01
                     +           +           +           +           +

 0.         0.        +-----+-----+-----+-----A-----+-----+-----+-----+-
4.000E-06  1.71E+00   +     +     +     +     +   A +     +     +     +
8.000E-06  4.00E+00   +     +     +     +     +     +   A +     +     +
1.200E-05  6.00E+00   +     +     +     +     +     +     + A   +     +
1.600E-05  7.63E+00   +     +     +     +     +     +     +     A     +
2.000E-05  8.62E+00   +     +     +     +     +     +     +     + A   +
2.400E-05  9.12E+00   +     +     +     +     +     +     +     +   A +
2.800E-05  9.00E+00   +     +     +     +     +     +     +     +  A  +
3.200E-05  8.23E+00   +     +     +     +     +     +     +     +A    +
3.600E-05  6.89E+00   +     +     +     +     +     +     +   A +     +
4.000E-05  5.03E+00  -+-----+-----+-----+-----+-----+-----A-----+-----+-
4.400E-05  2.87E+00   +     +     +     +     +     +A    +     +     +
4.800E-05  8.59E-01   +     +     +     +     + A   +     +     +     +
5.200E-05 -5.75E-01   +     +     +     +   A +     +     +     +     +
5.600E-05 -2.89E+00   +     +     +    A+     +     +     +     +     +
6.000E-05 -5.06E+00   +     +     A     +     +     +     +     +     +
6.400E-05 -6.87E+00   +     + A   +     +     +     +     +     +     +
6.800E-05 -8.23E+00   +   A +     +     +     +     +     +     +     +
7.200E-05 -9.00E+00   +  A  +     +     +     +     +     +     +     +
7.600E-05 -9.16E+00   + A   +     +     +     +     +     +     +     +
8.000E-05 -8.62E+00  -+---A-+-----+-----+-----+-----+-----+-----+-----+-
8.400E-05 -7.60E+00   +     A     +     +     +     +     +     +     +
8.800E-05 -6.04E+00   +     +  A  +     +     +     +     +     +     +
9.200E-05 -4.02E+00   +     +     + A   +     +     +     +     +     +
9.600E-05 -1.72E+00   +     +     +     + A   +     +     +     +     +
1.000E-04   0.        +     +     +     +     A     +     +     +     +
1.040E-04  1.71E+00   +     +     +     +     +   A +     +     +     +
1.080E-04  3.99E+00   +     +     +     +     +     +   A +     +     +
1.120E-04  5.99E+00   +     +     +     +     +     +     + A   +     +
1.160E-04  7.63E+00   +     +     +     +     +     +     +     A     +
1.200E-04  8.62E+00  -+-----+-----+-----+-----+-----+-----+-----+--A--+-
1.240E-04  9.12E+00   +     +     +     +     +     +     +     +   A +
1.280E-04  9.00E+00   +     +     +     +     +     +     +     +  A  +
1.320E-04  8.23E+00   +     +     +     +     +     +     +     +A    +
1.360E-04  6.89E+00   +     +     +     +     +     +     +   A +     +
1.400E-04  5.03E+00   +     +     +     +     +     +     A     +     +
1.440E-04  2.87E+00   +     +     +     +     +     +A    +     +     +
1.480E-04  8.59E-01   +     +     +     +     + A   +     +     +     +
1.520E-04 -5.75E-01   +     +     +     +   A +     +     +     +     +
1.560E-04 -2.89E+00   +     +     +    A+     +     +     +     +     +
1.600E-04 -5.06E+00  -+-----+-----A-----+-----+-----+-----+-----+-----+-
1.640E-04 -6.87E+00   +     + A   +     +     +     +     +     +     +
1.680E-04 -8.23E+00   +   A +     +     +     +     +     +     +     +
1.720E-04 -9.00E+00   +  A  +     +     +     +     +     +     +     +
1.760E-04 -9.16E+00   + A   +     +     +     +     +     +     +     +
1.800E-04 -8.62E+00   +   A +     +     +     +     +     +     +     +
1.840E-04 -7.60E+00   +     A     +     +     +     +     +     +     +
1.880E-04 -6.04E+00   +     +  A  +     +     +     +     +     +     +
1.920E-04 -4.02E+00   +     +     + A   +     +     +     +     +     +
1.960E-04 -1.72E+00   +     +     +     + A   +     +     +     +     +
2.000E-04   0.       -+-----+-----+-----+-----A-----+-----+-----+-----+-
                      +           +           +           +           +
```

******

FOURIER COMPONENTS OF TRANSIENT RESPONSE V(2)

DC COMPONENT = -8.955D-04

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	9.999E+03	8.945E+00	1.000E+00	-2.161E-01	0.
2	2.000E+04	6.121E-04	6.842E-05	7.039E+01	7.060E+01
3	3.000E+04	3.095E-01	3.459E-02	-1.744E+02	-1.742E+02
4	4.000E+04	1.480E-03	1.654E-04	1.171E+02	1.173E+02
5	5.000E+04	1.651E-01	1.845E-02	-1.708E+02	-1.706E+02
6	6.000E+04	1.231E-03	1.376E-04	1.133E+02	1.135E+02
7	7.000E+04	1.006E-01	1.125E-02	-1.663E+02	-1.661E+02
8	8.000E+04	8.272E-04	9.247E-05	1.224E+02	1.227E+02
9	9.000E+04	5.414E-02	6.052E-03	-1.558E+02	-1.556E+02

TOTAL HARMONIC DISTORTION = 4.123E+00 PERCENT

```
**** OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
 NODE    =VOLTAGE     NODE     =VOLTAGE      NODE     =VOLTAGE
+0:1     =  0.        0:2      =-3.692E-14 0:100      = 1.500E+01
+0:200   =-1.500E+01
**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT  0:Q1        0:Q2
MODEL    0:NPN       0:PNP
 IB      -1.000E-16  1.000E-16
 IC       2.115E-16 -2.300E-16
 VBE      3.692E-14  3.692E-14
 VCE      1.500E+01 -1.500E+01
 VBC     -1.500E+01  1.500E+01
 VS      -1.500E+01  1.500E-09
 POWER    3.173E-15  3.450E-15
```

```
CLASS-B OUTPUT STAGE  (PEAK INPUT AMPLITUDE = 20 V)
******
VCC      100      0    15
VEE      200      0    -15
Q1       100      1    2    NPN
Q2       200      1    2    PNP
RL       2        0    2K
.MODEL NPN NPN RB=100 BF=100 IS=1E-16 RC=20 VAF=130
.MODEL PNP PNP RB=100 BF=100 IS=1E-16 RC=20 VAF=50
VIN      1        0         SIN      0  20 10K 0  0
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.TR      4U       200U
.PLOT    TRAN     V(2)
.FOUR    10K      V(2)
.END
```

```
**** OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
 NODE    =VOLTAGE     NODE     =VOLTAGE      NODE     =VOLTAGE
+0:1     =  0.        0:2      =-3.692E-14 0:100      = 1.500E+01
+0:200   =-1.500E+01

**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT  0:Q1        0:Q2
MODEL    0:NPN       0:PNP
 IB      -1.000E-16  1.000E-16
 IC       2.115E-16 -2.300E-16
 VBE      3.692E-14  3.692E-14
 VCE      1.500E+01 -1.500E+01
 VBC     -1.500E+01  1.500E+01
 VS      -1.500E+01  1.500E-09
 POWER    3.173E-15  3.450E-15
```

```
******  TRANSIENT ANALYSIS      TNOM=  27.000 TEMP=  27.000
   TIME       V(2)
(A        )         -2.000E+01    -1.000E+01    0.            1.000E+01     2.000E+01
                     +             +             +             +             +
 0.         0.       +------+------+------+------A------+------+------+------+
 4.000E-06  4.18E+00 +      +      +      +      +     A+      +      +      +
 8.000E-06  8.77E+00 +      +      +      +      +      +    A +      +      +
 1.200E-05  1.28E+01 +      +      +      +      +      +      +   A  +      +
 1.600E-05  1.50E+01 +      +      +      +      +      +      +      A      +
 2.000E-05  1.53E+01 +      +      +      +      +      +      +      +A     +
 2.400E-05  1.55E+01 +      +      +      +      +      +      +      +A     +
 2.800E-05  1.55E+01 +      +      +      +      +      +      +      +A     +
 3.200E-05  1.52E+01 +      +      +      +      +      +      +      A      +
 3.600E-05  1.45E+01 +      +      +      +      +      +      +     A+      +
 4.000E-05  1.08E+01-+------+------+------+------+------+------+A-----+------+
 4.400E-05  6.51E+00 +      +      +      +      +      + A    +      +      +
 4.800E-05  1.97E+00 +      +      +      +      +  A   +      +      +      +
 5.200E-05 -1.74E+00 +      +      +      +     A +      +      +      +      +
 5.600E-05 -6.55E+00 +      +      +    A +      +      +      +      +      +
 6.000E-05 -1.09E+01 +      +     A+      +      +      +      +      +      +
 6.400E-05 -1.45E+01 +      +A     +      +      +      +      +      +      +
 6.800E-05 -1.52E+01 +      A      +      +      +      +      +      +      +
 7.200E-05 -1.54E+01 +     A+      +      +      +      +      +      +      +
 7.600E-05 -1.55E+01 +     A+      +      +      +      +      +      +      +
 8.000E-05 -1.53E+01-+-----A+------+------+------+------+------+------+------+
 8.400E-05 -1.50E+01 +      A      +      +      +      +      +      +      +
 8.800E-05 -1.28E+01 +      +  A   +      +      +      +      +      +      +
 9.200E-05 -8.76E+00 +      +      + A    +      +      +      +      +      +
 9.600E-05 -4.15E+00 +      +      +      +A     +      +      +      +      +
 1.000E-04  0.       +      +      +      +      A      +      +      +      +
 1.040E-04  4.17E+00 +      +      +      +      +     A+      +      +      +
 1.080E-04  8.74E+00 +      +      +      +      +      +    A +      +      +
 1.120E-04  1.27E+01 +      +      +      +      +      +      +   A  +      +
 1.160E-04  1.50E+01 +      +      +      +      +      +      +      A      +
 1.200E-04  1.53E+01-+------+------+------+------+------+------+------+A-----+
 1.240E-04  1.55E+01 +      +      +      +      +      +      +      +A     +
 1.280E-04  1.55E+01 +      +      +      +      +      +      +      +A     +
 1.320E-04  1.52E+01 +      +      +      +      +      +      +      A      +
 1.360E-04  1.45E+01 +      +      +      +      +      +      +     A+      +
 1.400E-04  1.08E+01 +      +      +      +      +      +      +A     +      +
 1.440E-04  6.51E+00 +      +      +      +      +      + A    +      +      +
 1.480E-04  1.97E+00 +      +      +      +      +  A   +      +      +      +
 1.520E-04 -1.74E+00 +      +      +      +     A +      +      +      +      +
 1.560E-04 -6.55E+00 +      +      +    A +      +      +      +      +      +
 1.600E-04 -1.09E+01-+------+-----A+------+------+------+------+------+------+
 1.640E-04 -1.45E+01 +      +A     +      +      +      +      +      +      +
 1.680E-04 -1.52E+01 +      A      +      +      +      +     .+      +      +
 1.720E-04 -1.54E+01 +     A+      +      +      +      +      +      +      +
 1.760E-04 -1.55E+01 +     A+      +      +      +      +      +      +      +
 1.800E-04 -1.53E+01 +     A+      +      +      +      +      +      +      +
 1.840E-04 -1.50E+01 +      A      +      +      +      +      +      +      +
 1.880E-04 -1.28E+01 +      +  A   +      +      +      +      +      +      +
 1.920E-04 -8.76E+00 +      +      + A    +      +      +      +      +      +
 1.960E-04 -4.15E+00 +      +      +      +A     +      +      +      +      +
 2.000E-04  0.       +------+------+------+------A------+------+------+------+
                     +             +             +             +             +
```

******

FOURIER COMPONENTS OF TRANSIENT RESPONSE V(2)

DC COMPONENT = -1.246D-04

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	9.999E+03	1.696E+01	1.000E+00	-1.072E-01	0.
2	2.000E+04	1.866E-03	1.100E-04	7.729E+00	7.836E+00
3	3.000E+04	9.753E-01	5.748E-02	-1.358E+00	-1.251E+00
4	4.000E+04	1.161E-03	6.840E-05	1.193E+02	1.194E+02
5	5.000E+04	6.865E-01	4.046E-02	-1.782E+02	-1.781E+02
6	6.000E+04	2.384E-03	1.405E-04	1.552E+02	1.553E+02
7	7.000E+04	1.539E-01	9.071E-03	-1.693E+02	-1.692E+02
8	8.000E+04	9.693E-04	5.713E-05	1.271E+02	1.272E+02
9	9.000E+04	9.105E-02	5.367E-03	-1.859E+01	-1.848E+01

TOTAL HARMONIC DISTORTION = 7.108E+00 PERCENT

5.11

$$\hat{V}_o = V_{CC} - V_{CE(sat.)} = 11.8\text{ V}$$

$$I_{supply} = \frac{1}{\pi}\,\frac{\hat{V}_o}{R_L} = \frac{1}{\pi}\,\frac{11.8}{1} = 3.75\text{ mA}$$

Supply power $= P_{supply}$

$$= I_{supply} \times 2V_{cc} = 3.75 \times 24\text{ mW}$$

$$= 90.2\text{ mW}$$

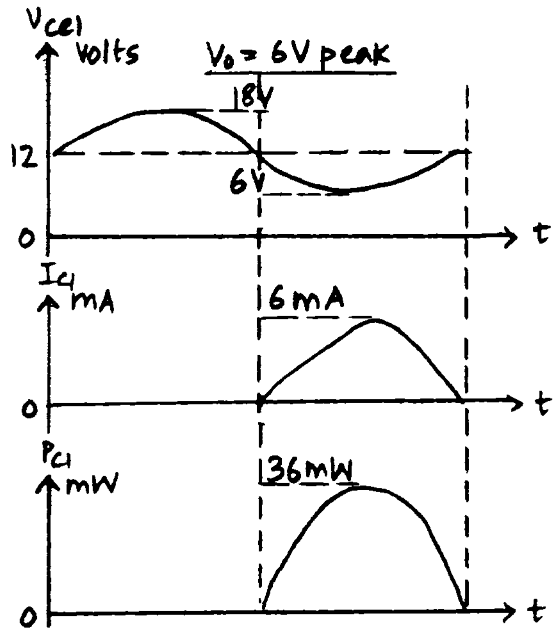
Power delivered to R_L

$$P_L = \frac{1}{2}\,\frac{\hat{V}_o^2}{R_L} = \frac{1}{2}\,\frac{11.8^2}{1} = 69.5\text{ mW}$$

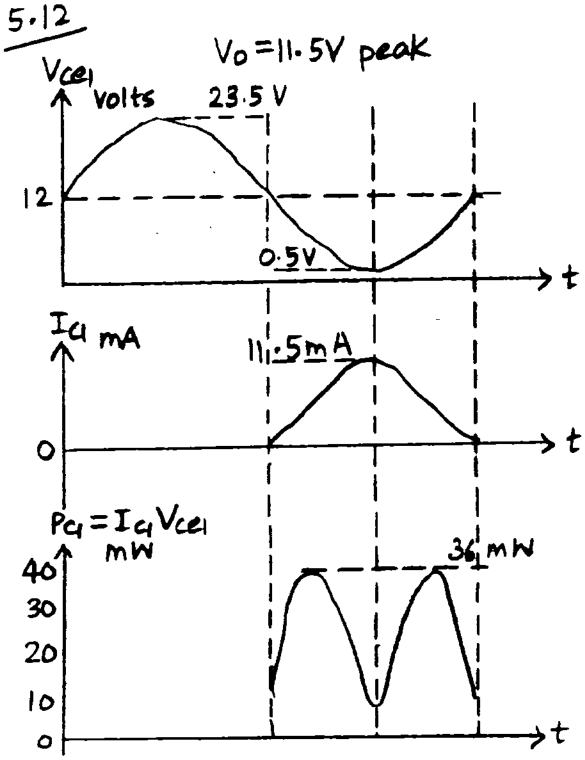
$$\eta_c = \frac{69.6}{90.2} = 77.2\,\%$$

Max. device dissipation occurs when $I_c = \dfrac{V_{cc}}{2R_L} = 6\text{ mA}$

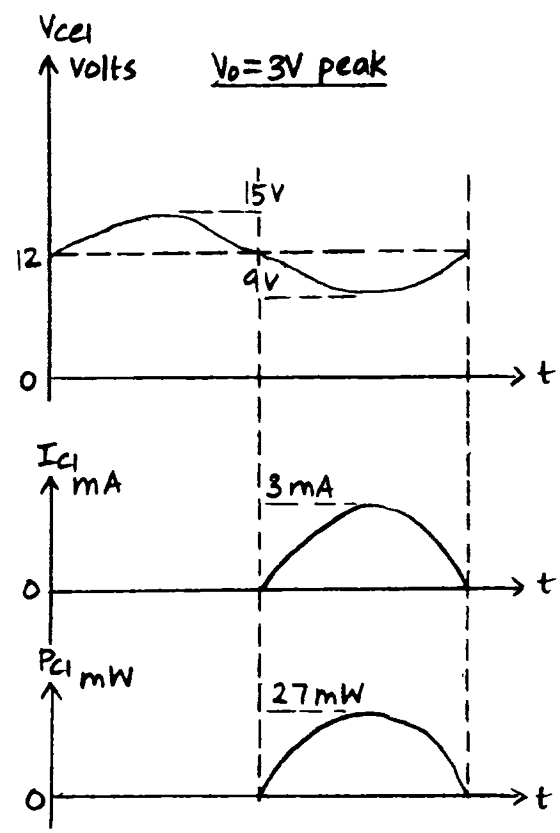
$$\therefore\ P_c = I_c V_{ce} = 6 \times 6 = 36\text{ mW}$$



5.12



Peak P_{c1} occurs for $V_{CE} = 6$V



5.13

$V_o = 0$

$I_{C_1} = I_{C2} = I_{C3} = I_{C4} \simeq 0.1 \text{ mA}$

$V_i = V_{BE_2} = -V_T \ln \frac{10^{-4}}{10^{-15}} = -659 \text{ mV}$

$V_o = 5V$

$I_{C_1} \simeq \frac{V_o}{R_L} = 5 \text{ mA}$

$V_{BE_1} = 26 \ln \frac{5\times10^{-3}}{10^{-15}} = 760 \text{ mV}$

$I_{B_1} = \frac{5}{150} = 0.033 \text{ mA}$

$\therefore I_{C_3} = I_{C_4} = 0.1 - 0.033 = 0.066 \text{ mA}$

$\therefore V_{BE_3} = V_{BE_4} = 26 \ln \frac{0.066\times10^{-3}}{10^{-15}} = 648 \text{ mV}$

$\therefore V_{BE_2} = -(2\times648 - 760) = -536 \text{ mV}$

$\therefore I_{C2} = 10^{-15} e^{536/26} = 0.9 \ \mu A$

$V_i = V_o + V_{BE_2} = 5 - 0.536 = 4.46 V$

$V_o = 10V$

$I_{C_1} \simeq V_o/R_L = 10 \text{ mA}$

$V_{BE_1} = 26 \ln \frac{10\times10^{-3}}{10^{-15}} = 778 \text{ mV}$

$I_{B_1} = \frac{10}{150} = 0.066 \text{ mA}$

$\therefore I_{C_3} = I_{C_4} = 0.1 - 0.066 = 0.033 \text{ mA}$

$\therefore V_{BE_3} = V_{BE_4} = 26 \ln \frac{0.033\times10^{-3}}{10^{-15}} = 630 \text{mV}$

$\therefore V_{BE_2} = -(2\times630 - 778) = -481 \text{ mV}$

$\therefore I_{C_2} = 10^{-15} e^{481/26} = 0.1 \ \mu A$

$V_i = V_o + V_{BE_2} = 10 - 0.48 = 9.52 V$

$V_o = -5V$

$I_{C_2} \simeq \frac{V_o}{R_L} \simeq -5 \text{ mA}$

$\therefore V_{BE_2} = -760 \text{ mV}$

$I_{C_3} = I_{C_4} \simeq 0.1 \text{ mA}$

$\therefore V_{BE_3} = V_{BE_4} = 26 \ln \frac{10^{-4}}{10^{-15}} = 659 \text{ mV}$

$\therefore V_{BE_1} = 2\times659 - 760 = 557 \text{ mV}$

$\therefore I_{C_1} = 10^{-15} e^{557/26} = 2 \ \mu A$

$V_i = V_o + V_{BE_2} = -5 - 0.76 = -5.76 V$

$V_o = -10 V$

$I_{C_2} \simeq -10 \text{ mA}$

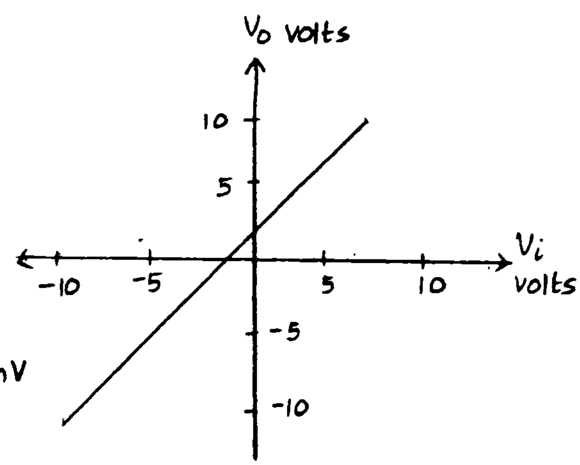
$V_{BE_2} = -778 \text{ mV}$

$V_{BE_3} = V_{BE_4} = 659 \text{ mV}$

$\therefore V_{BE_1} = 2\times659 - 778 = 539 \text{ mV}$

$\therefore I_{C_1} = 1 \ \mu A$

$V_i = V_o + V_{BE_2} = -10.78 V$



5.14

(a) $R_L = 10\,K\Omega$

$$V_o^- = -V_{cc} + V_{CE_3(sat.)} + V_{be_2}$$
$$= -15 + 0.2 + 0.7 = -14.1\ V$$

$$V_o^+ = \frac{V_{cc} - V_{be1}}{1 + \frac{R_1}{\beta_1 R_L}} = \frac{15 - 0.7}{1 + \frac{20}{50 \times 10}} = 13.8\ V$$

$R_L = 2\,K\Omega$

$$V_o^- = -14.1\ V$$

$$V_o^+ = \frac{15 - 0.7}{1 + \frac{20}{100}} = 11.9\ V$$

(b) $R_L = 10\,K\Omega$

$$P_L|_{MAX} = \frac{1}{2}\frac{\hat{V}_o^2}{R_L} = \frac{1}{2}\frac{13.8^2}{10} = 9.52\ mW$$

$$I_{supply} = \frac{1}{\pi}\frac{\hat{V}_o}{R_L} = \frac{1}{\pi}\frac{13.8}{10} = 0.44\ mA$$

$$P_{supply} = 2 \times 15 \times 0.44 = 13.2\ mW$$

$$\eta_c = \frac{9.52}{13.2} = 72.1\%$$

Average power dissipated per device

$$= \frac{1}{2}(P_{supply} - P_L)$$
$$= \frac{1}{2}(13.2 - 9.52) = 1.84\ mW$$

$R_L = 2\,K\Omega$

$$P_L|_{MAX} = \frac{1}{2}\frac{11.9^2}{2} = 35.4\ mW$$

$$I_{supply} = \frac{1}{\pi}\frac{11.9}{2} = 1.89\ mA$$

$$P_{supply} = 2 \times 15 \times 1.89 = 56.8\ mW$$

$$\eta_c = \frac{35.4}{56.8} = 62.3\%$$

Average power dissipated per device

$$= \frac{1}{2} \times (56.8 - 35.4) = 10.7\ mW$$

5.15

(a) $R_L = 10\,K\Omega$

$$V_o^- = -V_{cc} + V_{CE_{17}(sat.)} + V_{be_{23}} + V_{be_{20}}$$
$$= -15 + 0.2 + 0.7 + 0.7 = -13.4\ V$$

$$V_o^+ = V_{cc} - V_{CE13A(sat.)} - V_{be14}$$
$$= 15 - 0.2 - 0.7 = 14.1\ V$$

$R_L = 1\,K\Omega$

$$V_o^- = -13.4\ V$$
$$V_o^+ = 14.1\ V$$

$R_L = 200\,\Omega$

$$V_o^- = -13.4\ V$$

For positive outputs, Q_{14} is limited to a current

$$I_o|_{MAX} = \beta_{14} \times 0.22 = 200 \times 0.22 = 44\ mA$$

$$\therefore V_o^+ = 44 \times 0.2 = 8.8\ V$$

(b) $R_L = 1\,K\Omega$

$$P_L|_{MAX} = \frac{1}{2}\frac{\hat{V}_o^2}{R_L} = \frac{1}{2}\frac{13.4^2}{1} = 89.8\ mW$$

$$I_{supply} = \frac{1}{\pi}\frac{\hat{V}_o}{R_L} = \frac{1}{\pi}\frac{13.4}{1} = 4.27\ mA$$

$$P_{supply} = 2 \times V_{cc} \times I_{supply}$$
$$= 30 \times 4.27 = 128\ mW$$

$$\therefore \eta_c = \frac{89.8}{128} = 70\%$$

Peak dissipation occurs for

$$V_o = V_{ce} = \frac{V_{cc}}{2} = 7.5\ V$$

$$I_c = \frac{V_o}{R_L} = 7.5\ mA$$

$$\therefore P_c = 7.5 \times 7.5 = 56.3\ mW$$

5.16

(a) Peak device dissipation $= \frac{V_{CC}^2}{4R_L}$

Put $\frac{V_{CC}^2}{4R_L} = 100 \times 10^{-3}$

$\therefore R_L = \frac{15^2}{400 \times 10^{-3}} = 563\,\Omega$

MAX. $P_L = \frac{1}{2}\frac{\hat{V}_o^2}{R_L} = \frac{1}{2}\frac{13.4^2}{0.563} = 160$ mW

$I_{supply} = \frac{1}{\pi}\frac{\hat{V}_o}{R_L} = \frac{1}{\pi}\frac{13.4}{0.563} = 7.58$ mA

$P_{supply} = 30 \times 7.58 = 227$ mW

$\eta_c = \frac{160}{227} = 70.4\%$

(b) $\frac{V_{CC}^2}{4R_L} = 200 \times 10^{-3}$

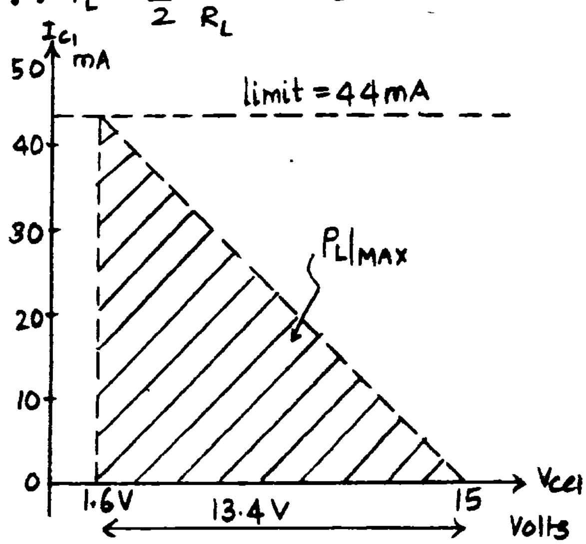
$\therefore R_L = 282\,\Omega$

However for this value of R_L, the output current is limited

$I_o|_{max} = \beta_{14} \times 0.22 = 44$ mA

$\therefore V_o^+ = 0.282 \times 44 = 12.4\text{ V} = \hat{V}_o$

$\therefore P_L = \frac{1}{2}\frac{\hat{V}_o^2}{R_L} = 273$ mW



Max. P_L occurs as shown above where $R_L = \frac{13.4}{44} = 304\,\Omega$

(note: Max. device dissipation is less than 200 mW)

$\therefore P_L = \frac{1}{2}\frac{\hat{V}_o^2}{R_L} = \frac{1}{2}\frac{13.4^2}{304} = 295$ mW

$I_{supply} = \frac{1}{\pi}\frac{\hat{V}_o}{R_L} = 14.0$ mA

$P_{supply} = 14.0 \times 30 = 420$ mW

$\eta_c = \frac{295}{420} = 70\%$

5.17

$V_o = -10\text{V},\ R_L = 1\text{k}\Omega$

$\therefore\ I_{C20} \cong -\dfrac{10}{1} = -10\text{ mA}$

$V_{BE20} = -V_T \ln \dfrac{10^{-2}}{10^{-14}} = -718\text{ mV}$

$I_{C19} = I_{C18} = 0.22\text{ mA}$

$\therefore\ V_{BE19} = V_{BE18} = 619\text{ mV}$

$\therefore\ V_{BE14} = 2 \times 619 - 718 = 520\text{ mV}$

$\therefore\ I_{C14} = 10^{-14} e^{520/26} = 4.9\ \mu\text{A}$

$I_{C23} = 0.22\text{ mA} + I_{B20} = 0.42\text{ mA}$

5.18

(a) $V_o^+ = V_{cc} - V_{CE_3(sat)} - V_{be_5} - V_{be_4}$

$= 12 - 0.2 - 0.7 - 0.7 = 10.4\text{ V}$

$V_o^- = -V_{cc} + V_{CE_2(sat)} + V_{be_1} + V_{D_1}$

$= -12 + 0.2 + 0.7 + 0.7 = 10.4\text{ V}$

(b) For $V_o = 0$, D_1, Q_4 and Q_5 are off

$P_Q = 2 \times 12 \times 2\text{ mW} = 48\text{ mW}$

(c) $P_L|_{max.} = \dfrac{1}{2}\dfrac{10.4^2}{8} = 6.76\text{ W}$

$I_{supply} = \dfrac{1}{\pi}\dfrac{\hat{V}_o}{R_L} = \dfrac{1}{\pi}\dfrac{10.4}{8} = 414\text{ mA}$

$\therefore\ P_{supply} = 2 \times 12 \times 414 \times 10^{-3} = 9.94\text{ W}$

$P_{supply} + P_Q = 9.99\text{ W}$

$\therefore\ \eta = \dfrac{6.76}{9.99} = 67.7\%$

$P_C|_{max.} = \dfrac{1}{4}\dfrac{V_{CC}^2}{R_L} = \dfrac{1}{4}\dfrac{12^2}{8} = 4.5\text{ W}$

```
ALL-NPN DARLINGTON OUTPUT STAGE
******
VCC      100      0   12
VEE      200      0   -12
Q1       5        7   200   NPN
Q2       5        6   7     NPN_SMALL
Q3       3        10  100   PNP
Q4       100      3   9     NPN_SMALL
Q5       100      9   8     NPN
QD1      8        8   5     NPN
QD2      4        4   5     NPN_SMALL
QD3      3        3   4     NPN_SMALL
RL       8        0   8
* IN FIG. 5.42, VBIAS COULD BE ADJUSTED BY TRIAL AND ERROR
* TO SET THE COLLECTOR CURRENT OF Q3 EQUAL TO 2 MA,
* BUT THIS PROCESS MAY REQUIRE MANY ITERATIONS.
* SO INSTEAD, Q6 AND IBIAS ARE ADDED TO FORM A
* CURRENT MIRROR TO SET UP THE DC COLLECTOR CURRENT IN Q3.
* HERE ONLY TWO ITERATIONS ARE REQUIRED
* BECAUSE CURRENT MIRRORS ARE LINEAR.
Q6       10        10  100   PNP
IBIAS    10        200 1.523M
.MODEL NPN       NPN RB=1   BF=100 IS=1E-15 RC=0.2 VAF=30
.MODEL NPN_SMALL NPN RB=100 BF=100 IS=1E-17 RC=20  VAF=30
.MODEL PNP       PNP RB=100 BF=100 IS=1E-16 RC=50  VAF=30
* THE DC INPUT VOLTAGE IS ADJUSTED BY TRIAL AND ERROR
* TO SET THE DC OUTPUT VOLTAGE TO ZERO.
VIN      6         200      1.45
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.DC VIN  1  2.5  0.05
.PLOT DC V(8)
.END

****** DC TRANSFER CURVES        TNOM=  27.000 TEMP=  27.000
   VOLT       V(8)
(A       )   -2.000E+01    -1.000E+01     0.           1.000E+01     2.000E+01
                      +             +             +             +             +

1.000E+00  1.01E+01-+------+------+------+------+------+------A------+------+-
1.050E+00  1.01E+01 +      +      +      +      +      +      A      +      +
1.100E+00  1.01E+01 +      +      +      +      +      +      A      +      +
1.150E+00  1.01E+01 +      +      +      +      +      +      A      +      +
1.200E+00  1.01E+01 +      +      +      +      +      +      A      +      +
1.250E+00  1.01E+01 +      +      +      +      +      +      A      +      +
1.300E+00  1.01E+01 +      +      +      +      +      +      A      +      +
1.350E+00  1.01E+01 +      +      +      +      +      +      A      +      +
1.400E+00  9.97E+00 +      +      +      +      +      +      A      +      +
1.450E+00 -2.80E-03 +      +      +      +      A      +      +      +      +
1.500E+00 -3.31E-02-+------+------+------+------A------+------+------+------+-
1.550E+00 -1.12E-01 +      +      +      +      A      +      +      +      +
1.600E+00 -3.15E-01 +      +      +      +      A      +      +      +      +
1.650E+00 -8.23E-01 +      +      +      +     A+      +      +      +      +
1.700E+00 -1.99E+00 +      +      +      +   A  +      +      +      +      +
1.750E+00 -4.34E+00 +      +      +      +A     +      +      +      +      +
1.800E+00 -8.00E+00 +      +      +  A   +      +      +      +      +      +
1.850E+00 -9.84E+00 +      +      A      +      +      +      +      +      +
1.900E+00 -9.87E+00 +      +      A      +      +      +      +      +      +
1.950E+00 -9.89E+00 +      +      A      +      +      +      +      +      +
2.000E+00 -9.91E+00-+------+------A------+------+------+------+------+------+-
2.050E+00 -9.92E+00 +      +      A      +      +      +      +      +      +
2.100E+00 -9.94E+00 +      +      A      +      +      +      +      +      +
2.150E+00 -9.95E+00 +      +      A      +      +      +      +      +      +
2.200E+00 -9.96E+00 +      +      A      +      +      +      +      +      +
2.250E+00 -9.97E+00 +      +      A      +      +      +      +      +      +
2.300E+00 -9.99E+00 +      +      A      +      +      +      +      +      +
2.350E+00 -1.00E+01 +      +      A      +      +      +      +      +      +
2.400E+00 -1.00E+01 +      +      A      +      +      +      +      +      +
2.450E+00 -1.00E+01 +      +      A      +      +      +      +      +      +
2.500E+00 -1.00E+01-+------+------A------+------+------+------+------+------+-
                    +             +             +             +             +
```

```
****  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
  NODE      =VOLTAGE      NODE      =VOLTAGE      NODE      =VOLTAGE
+0:3        = 1.016E+00 0:4         = 1.634E-01 0:5         =-6.900E-01
+0:6        =-1.055E+01 0:7         =-1.127E+01 0:8         =-2.796E-03
+0:9        = 5.112E-01 0:10        = 1.121E+01 0:100       = 1.200E+01
+0:200      =-1.200E+01
```

**** BIPOLAR JUNCTION TRANSISTORS

SUBCKT

ELEMENT	0:Q1	0:Q2	0:Q3	0:Q4	0:Q5
MODEL	0:NPN	0:NPN_SMAL	0:PNP	0:NPN_SMAL	0:NPN
IB	1.725E-05	1.289E-07	-1.497E-05	3.096E-11	4.272E-09
IC	2.333E-03	1.712E-05	-2.001E-03	4.230E-09	5.908E-07
VBE	7.288E-01	7.212E-01	-7.861E-01	5.057E-01	5.140E-01
VCE	1.131E+01	1.058E+01	-1.098E+01	1.148E+01	1.200E+01
VBC	-1.058E+01	-9.860E+00	1.019E+01	-1.098E+01	-1.148E+01
VS	6.905E-01	6.904E-01	-1.121E+01	-1.200E+01	-1.200E+01
POWER	2.640E-02	1.813E-04	2.198E-02	4.861E-08	7.093E-06
BETAD	1.352E+02	1.328E+02	1.336E+02	1.366E+02	1.383E+02
GM	9.016E-02	6.616E-04	7.730E-02	1.634E-07	2.283E-05
RPI	1.499E+03	2.007E+05	1.728E+03	8.354E+08	6.054E+06
RX	1.000E+00	1.000E+02	1.000E+02	1.000E+02	1.000E+00
RO	1.739E+04	2.328E+06	2.004E+04	9.689E+09	7.022E+07
BETAAC	1.351E+02	1.327E+02	1.335E+02	1.365E+02	1.382E+02

SUBCKT

ELEMENT	0:QD1	0:QD2	0:QD3	0:Q6
MODEL	0:NPN	0:NPN_SMAL	0:NPN_SMAL	0:PNP
IB	3.466E-06	1.983E-05	1.983E-05	-1.497E-05
IC	3.466E-04	1.981E-03	1.981E-03	-1.493E-03
VBE	6.873E-01	8.535E-01	8.535E-01	-7.861E-01
VCE	6.873E-01	8.535E-01	8.535E-01	-7.861E-01
VBC	0.	0.	0.	0.
VS	2.865E-03	-1.238E-01	-9.772E-01	-1.121E+01
POWER	2.406E-04	1.707E-03	1.707E-03	1.186E-03
BETAD	9.999E+01	9.987E+01	9.987E+01	9.975E+01
GM	1.339E-02	7.651E-02	7.651E-02	5.768E-02
RPI	7.462E+03	1.304E+03	1.304E+03	1.728E+03
RX	1.000E+00	1.000E+02	1.000E+02	1.000E+02
RO	8.655E+04	1.512E+04	1.512E+04	2.004E+04
BETAAC	9.991E+01	9.978E+01	9.978E+01	9.967E+01

5.19

(a) $V_o^+ = V_{CC} - V_{BE_2} - V_{CE_7(sat)}$

$= 15 - 0.7 - 0.2 = 14.1\ V$

$V_o^- = -V_{CC} + V_{CE_1(sat)} + V_{BE_3}$

$= -15 + 0.2 + 0.7 = -14.1\ V$

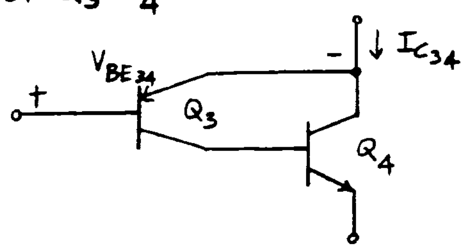
(b) $I_{C_7} = 0.15\ mA$

$\therefore I_{C_5} = I_{C_6} \simeq 0.15\ mA$

$\therefore V_{BE_5} = V_{BE_6} = V_T \ln \frac{0.15\times10^{-3}}{10^{-14}} = 609\ mV$

$I_{C_1} \simeq 0.15\ mA$

For Q_3-Q_4



$I_{C_{34}} = (\beta_4+1)\, I_{S_3}\, e^{-V_{BE34}/V_T}$

$2V_{BE6} = V_{BE_2} - V_{BE34}$

$= V_T \ln \frac{I_{C_2}}{I_{S_2}} + V_T \ln \frac{I_{C_{34}}}{(\beta_4+1) I_{S_3}}$

But $I_{C_{34}} = I_{C_2}$, because $V_o = 0$

$\therefore 1218\ mV = 26 \ln \frac{I_{C_2}^2}{I_{S_2}(\beta_4+1) I_{S_3}}$

$\therefore \frac{1218}{26} = \ln \frac{I_{C_2}^2}{10^{-14}\times 151\times 10^{-15}}$

$\therefore I_{C_2} = 0.58\ mA$

(c) $P_C\big|_{max} = \frac{V_{CC}^2}{4R_L} = 100\times10^{-3}\ W$

$\therefore R_L = \frac{225}{0.4} = 563\ \Omega$

This requires $I_{C2(peak)} = \frac{14.1}{563} = 25\,mA$

But $\beta_2 \times 0.15 = 150 \times 0.15 = 22.5\,mA$

$\therefore$ Q_2 cannot supply this current

max. power occurs when

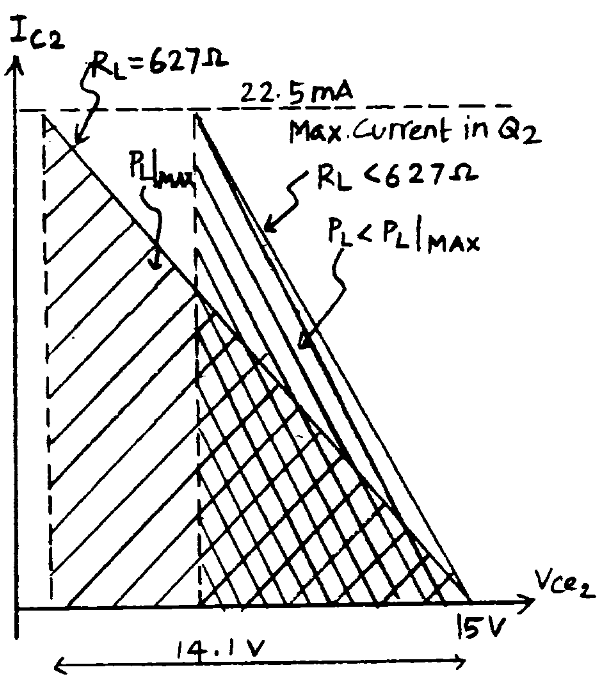
$$\frac{14.1}{R_L} = 22.5\,mA$$

$\therefore$ $R_L = 627\,\Omega$ — then $P_C|_{max} < 100\,mW$

$$\therefore P_L = \frac{1}{2}\frac{\hat{V}_o^2}{R_L} = \frac{1}{2}\frac{14.1^2}{627} = 159\,mW$$

Peak current in Q_4 = 22.5 mA

Peak current in $Q_3 = \frac{22.5}{150} = 0.15\,mA$



5.20

(a) Bias $V_o = 0$

$|I_{C_5}| = 100\,\mu A$

$|I_{C_6}| = 500\,\mu A$

$|I_{D_3}| = |I_{B_5}| + |I_{B_6}|$

$= \frac{600\,\mu A}{20} = 30\,\mu A$

$|I_{D_1}| = \frac{V_{BE_3}}{R_1} = \frac{0.8}{10K} = 80\,\mu A$

$I_{C_3} = 500 - 80 = 420\,\mu A$

$|I_{D_2}| = \frac{V_{BE_2}}{R_2} = \frac{0.8}{10K} = 80\,\mu A$

From KVL,

$V_{GS_1} + V_{BE_1} = V_{GS_2} + V_{BE_3}$

(where $V_{GS_1} < 0$ and $V_{GS_2} < 0$)

Since $I_{D_1} = I_{D_2}$, $V_{GS_1} = V_{GS_2}$

Then $V_{BE_1} = V_{BE_3}$ as expected

Then $I_{C_1} = I_{C_3} = 420\,\mu A$

and $I_{C_2} = I_{C_1} - |I_{D_2}| = 340\,\mu A$

(b) Maximum swing

$V_o^+ = 5 - V_{BE_1} - V_{CE_6(sat)} - |I_{C_6} R_4|$

$= 5 - 0.8 - 0.1 - 500\mu(100)$

$= 4.05\text{ V}$

Minimum swing

If $V_i = -5V$, Q_1 is off

$V_o^- = V_i + V_{SG_2} = V_i + |V_{GS_2}|$

$V_o^- = V_i + |V_{t_2}| + |V_{GS_2} - V_{t_2}|$

If M_2 operates in the active region,

$|V_{GS_2} - V_{t_2}| = \sqrt{\frac{2|I_{D_2}|}{k'(W/L)_2}}$

$= \sqrt{\frac{2(80)}{26(500)}} = 0.11\text{ V}$

and $V_o^- = -5 + 0.7 + 0.11 = -4.19\text{ V}$

But then $V_{SD_2} = V_o - (~~-5+~~ V_{BE_2})$

$= V_o - (-5 + 0.8)$

$= V_o + 4.2$

$= -4.19 + 4.2 = 0.01\text{ V}$

since $V_{SD_2} < |V_{GS_2} - V_{t_2}|$,

M_2 operates in the triode region

A quadratic equation could be solved to find V_{SD_2}, but it is not worth the trouble because V_o^- is set mainly by the supply voltage and V_{BE_2}

For simplicity, assume $V_{SD_2} = 0.1\text{ V}$

Then $V_o^- = -5 + V_{BE_2} + V_{SD_2}$

$= -5 + 0.8 + 0.1$

$= -4.1\text{ V}$

```
BICMOS CLASS-AB OUTPUT STAGE (CHECK HAND CALCULATION)
******
VCC      100     0  5
VEE      200     0  -5
Q1       21      7  10    NPN   25
Q2       110     13 200   NPN   25
Q3       7       8  9     NPN   25
Q5       6       4  3     PNP
Q6       7       4  5     PNP   5
M1       8       8  7     7     PMOS1   W=500U  L=1U
M2       113     9  10    10    PMOS1   W=500U  L=1U
M3       0       6  4     4     PMOS2   W=2U    L=2U
R1       8       9  10K
R2       13      200 10K
R3       100     3  500
R4       100     5  100
RL       10      0  200
IBIAS    6       0  100U
* ZERO-VOLTAGE VOLTAGE SOURCES TO MEASURE TRANSISTOR CURRENTS
VIC1     100     21  0
VID2     113     13  0
VIC2     10      110 0
.MODEL NPN   NPN  BF=80 IS=1E-18
.MODEL PNP   PNP  BF=20 IS=1E-18
.MODEL PMOS1 PMOS KP=26U VTO=-0.7 LAMBDA=0 LD=0
.MODEL PMOS2 PMOS KP=26U VTO=-0.7 LAMBDA=0 LD=0
* THE DC INPUT VOLTAGE IS ADJUSTED BY TRIAL AND ERROR
*TO SET THE DC OUTPUT VOLTAGE TO ZERO.
VI       9       0        -0.8093
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.END

 ****  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
   NODE      =VOLTAGE      NODE      =VOLTAGE      NODE      =VOLTAGE
+0:3        = 4.947E+00 0:4         = 4.113E+00 0:5         = 4.947E+00
+0:6        = 1.894E+00 0:7         = 7.913E-01 0:8         =-2.225E-02
+0:9        =-8.093E-01 0:10        = 3.255E-03 0:13        =-4.218E+00
+0:21       = 5.000E+00 0:100       = 5.000E+00 0:110       = 3.255E-03
+0:113      =-4.218E+00 0:200       =-5.000E+00

**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT  0:Q1        0:Q2        0:Q3        0:Q5        0:Q6
MODEL    0:NPN       0:NPN       0:NPN       0:PNP       0:PNP
 IB       5.341E-06  4.175E-06  5.135E-06 -5.000E-06 -2.500E-05
 IC       4.273E-04  3.340E-04  4.108E-04 -1.000E-04 -5.000E-04
 VBE      7.881E-01  7.817E-01  7.871E-01 -8.338E-01 -8.338E-01
 VCE      4.996E+00  5.003E+00  1.600E+00 -3.052E+00 -4.156E+00
 VBC     -4.208E+00 -4.221E+00 -8.136E-01  2.219E+00  3.322E+00
 VS      -5.000E+00 -3.255E-03 -7.913E-01 -4.113E+00 -4.113E+00
 POWER    2.139E-03  1.674E-03  6.616E-04  3.095E-04  2.099E-03
 BETAD    8.000E+01  8.000E+01  8.000E+01  2.000E+01  2.000E+01
 GM       1.652E-02  1.291E-02  1.588E-02  3.866E-03  1.933E-02
 RPI      4.842E+03  6.194E+03  5.036E+03  5.172E+03  1.034E+03
 RX        0.         0.         0.         0.         0.
 RO       1.683E+17  1.688E+17  3.254E+16  2.219E+18  6.644E+17
 BETAAC   8.000E+01  8.000E+01  8.000E+01  2.000E+01  2.000E+01

**** MOSFETS
SUBCKT
ELEMENT  0:M1       0:M2       0:M3
MODEL    0:PMOS1    0:PMOS1    0:PMOS2
 ID      -8.384E-05 -8.235E-05 -3.000E-05
 IBS      0.         0.         0.
 IBD      8.136E-15  4.222E-14  4.114E-14
 VGS     -8.136E-01 -8.126E-01 -2.219E+00
 VDS     -8.136E-01 -4.221E+00 -4.113E+00
 VBS      0.         0.         0.
 VTH     -7.000E-01 -7.000E-01 -7.000E-01
 VDSAT   -1.136E-01 -1.126E-01 -1.519E+00
 BETA     1.300E-02  1.300E-02  2.600E-05
 GAM EFF  0.         0.         0.
 GM       1.476E-03  1.463E-03  3.950E-05
 GDS      0.         0.         0.
 GMB      0.         0.         0.
```

```
BICMOS CLASS-AB OUTPUT STAGE (PEAK OUTPUT AMPLITUDE = 2 V)
* BIPOLAR PARAMETERS FROM FIG. 2.32 AND
* PMOS PARAMETERS FROM TABLE 2.3
******
VCC      100     0  5
VEE      200     0  -5
Q1       21      7  10    NPN   25
Q2       110     13 200   NPN   25
Q3       7       8  9     NPN   25
Q5       6       4  3     PNP
Q6       7       4  5     PNP   5
M1       8       8  7     7     PMOS1   W=500U  L=1U
M2       113     9  10    10    PMOS1   W=500U  L=1U
M3       0       6  4     4     PMOS2   W=2U    L=2U
R1       8       9  10K
R2       13      200 10K
R3       100     3  500
R4       100     5  100
RL       10      0  200
IBIAS    6       0  100U
* ZERO-VOLTAGE VOLTAGE SOURCES TO MEASURE TRANSISTOR CURRENTS
VIC1     100     21  0
VID2     113     13  0
VIC2     10      110 0
.MODEL NPN  NPN  RB=400 BF=80 IS=6E-18 VAF=35
.MODEL PNP  PNP  RB=200 BF=20 IS=6E-18 VAF=30
.MODEL PMOS1 PMOS KP=26U VTO=-0.7 LAMBDA=0.0625 LD=0.18U
.MODEL PMOS2 PMOS KP=26U VTO=-0.7 LAMBDA=0.0244 LD=0.18U
* LAMBDA1 = (DXD/DVDS)/LEFF = 0.04/(1-2*0.18) = 0.0625 V^(-1)
* LAMBDA2 = (DXD/DVDS)/LEFF = 0.04/(2-2*0.18) = 0.0244 V^(-1)

* THE DC INPUT VOLTAGE IS ADJUSTED BY TRIAL AND ERROR
*TO SET THE DC OUTPUT VOLTAGE TO ZERO.
* THE PEAK INPUT AMPLITUDE IS SET BY TRIAL AND ERROR
* SO THAT THE PEAK OUTPUT AMPLITUDE IS 2 V.
VI       9        0        SIN     -0.8093  2.08 10K  0  0
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.DC VI -5 5 0.5
.PLOT DC V(10)

.TRAN 4U 100U
.PLOT TRAN I(VIC1)
.PLOT TRAN I(VIC2)
.PLOT TRAN I(VID2)
.PLOT TRAN V(10)
.FOUR 10K V(10)
.END

 ******  DC TRANSFER CURVES       TNOM=  27.000 TEMP=  27.000
    VOLT        V(10)
(A        )    -1.000E+01   -5.000E+00      0.         5.000E+00    1.000E+01
                    +            +            +            +            +
-5.000E+00 -4.06E+00-+------+------+--A---+------+------+------+------+------+-
-4.500E+00 -3.63E+00 +      +      +   A  +      +      +      +      +      +
-4.000E+00 -3.14E+00 +      +      +    A +      +      +      +      +      +
-3.500E+00 -2.65E+00 +      +      +      A      +      +      +      +      +
-3.000E+00 -2.16E+00 +      +      +      +A     +      +      +      +      +
-2.500E+00 -1.67E+00 +      +      +      + A    +      +      +      +      +
-2.000E+00 -1.18E+00 +      +      +      +   A  +      +      +      +      +
-1.500E+00 -7.01E-01 +      +      +      +    A +      +      +      +      +
-1.000E+00 -2.14E-01 +      +      +      +     A+      +      +      +      +
-5.000E-01  2.58E-01 +      +      +      +      +A     +      +      +      +
 0.         7.29E-01-+------+------+------+------+-A----+------+------+------+-
 5.000E-01  1.21E+00 +      +      +      +      +  A   +      +      +      +
 1.000E+00  1.70E+00 +      +      +      +      +    A +      +      +      +
 1.500E+00  2.19E+00 +      +      +      +      +     A+      +      +      +
 2.000E+00  2.68E+00 +      +      +      +      +      +A     +      +      +
 2.500E+00  3.17E+00 +      +      +      +      +      + A    +      +      +
 3.000E+00  3.66E+00 +      +      +      +      +      +  A   +      +      +
 3.500E+00  4.06E+00 +      +      +      +      +      +   A  +      +      +
 4.000E+00  4.07E+00 +      +      +      +      +      +   A  +      +      +
 4.500E+00  4.07E+00 +      +      +      +      +      +   A  +      +      +
 5.000E+00  4.07E+00-+------+------+------+------+------+---A--+------+------+-
                    +            +            +            +            +
```

**** OPERATING POINT INFORMATION TNOM= 27.000 TEMP= 27.000

NODE	=VOLTAGE	NODE	=VOLTAGE	NODE	=VOLTAGE
+0:3	= 4.947E+00	0:4	= 4.160E+00	0:5	= 4.946E+00
+0:6	= 2.206E+00	0:7	= 7.179E-01	0:8	=-6.835E-02
+0:9	=-8.093E-01	0:10	=-2.920E-02	0:13	=-4.249E+00
+0:21	= 5.000E+00	0:100	= 5.000E+00	0:110	=-2.920E-02
+0:113	=-4.249E+00	0:200	=-5.000E+00		

**** BIPOLAR JUNCTION TRANSISTORS

SUBCKT

ELEMENT	0:Q1	0:Q2	0:Q3	0:Q5	0:Q6
MODEL	0:NPN	0:NPN	0:NPN	0:PNP	0:PNP
IB	6.547E-06	7.341E-06	5.166E-06	-4.694E-06	-2.280E-05
IC	5.879E-04	6.581E-04	4.226E-04	-1.000E-04	-5.084E-04
VBE	7.471E-01	7.501E-01	7.410E-01	-7.867E-01	-7.860E-01
VCE	5.029E+00	4.970E+00	1.527E+00	-2.741E+00	-4.229E+00
VBC	-4.282E+00	-4.220E+00	-7.862E-01	1.954E+00	3.443E+00
VS	-5.000E+00	2.920E-02	-7.179E-01	-4.161E+00	-4.161E+00
POWER	2.961E-03	3.277E-03	6.492E-04	2.778E-04	2.168E-03
BETAD	8.978E+01	8.964E+01	8.179E+01	2.130E+01	2.229E+01
GM	2.271E-02	2.543E-02	1.633E-02	3.863E-03	1.964E-02
RPI	3.950E+03	3.523E+03	5.006E+03	5.510E+03	1.134E+03
RX	1.600E+01	1.600E+01	1.600E+01	2.000E+02	4.000E+01
RO	6.682E+04	5.959E+04	8.468E+04	3.195E+05	6.578E+04
BETAAC	8.972E+01	8.958E+01	8.173E+01	2.128E+01	2.227E+01

**** MOSFETS

SUBCKT

ELEMENT	0:M1	0:M2	0:M3
MODEL	0:PMOS1	0:PMOS1	0:PMOS2
ID	-7.926E-05	-8.235E-05	-2.750E-05
IBS	0.	0.	0.
IBD	7.862E-15	4.221E-14	4.161E-14
VGS	-7.862E-01	-7.801E-01	-1.954E+00
VDS	-7.862E-01	-4.220E+00	-4.160E+00
VBS	0.	0.	0.
VTH	-7.000E-01	-7.000E-01	-7.000E-01
VDSAT	-8.625E-02	-8.010E-02	-1.254E+00
BETA	2.131E-02	2.567E-02	3.493E-05
GAM EFF	0.	0.	0.
GM	1.838E-03	2.056E-03	4.383E-05
GDS	4.722E-06	4.072E-06	6.091E-07
GMB	0.	0.	0.

```
****** TRANSIENT ANALYSIS        TNOM=  27.000 TEMP=  27.000
   TIME       I(VIC1)
(A        )  -5.000E-03     0.           5.000E-03     1.000E-02     1.500E-02
                       +             +             +             +             +
  0.        5.88E-04-+------+------+-A----+------+------+------+------+------+-
 4.000E-06  2.26E-03 +      +      +     A+      +      +      +      +      +
 8.000E-06  4.53E-03 +      +      +      +     A+      +      +      +      +
 1.200E-05  6.55E-03 +      +      +      +      +    A +      +      +      +
 1.600E-05  8.14E-03 +      +      +      +      +      + A    +      +      +
 2.000E-05  9.21E-03 +      +      +      +      +      +    A +      +      +
 2.400E-05  9.68E-03 +      +      +      +      +      +     A+      +      +
 2.800E-05  9.52E-03 +      +      +      +      +      +     A+      +      +
 3.200E-05  8.74E-03 +      +      +      +      +      +  A   +      +      +
 3.600E-05  7.40E-03 +      +      +      +      +      A      +      +      +
 4.000E-05  5.57E-03-+------+------+------+------+-A----+------+------+------+-
 4.400E-05  3.41E-03 +      +      +      + A    +      +      +      +      +
 4.800E-05  1.13E-03 +      +      +  A   +      +      +      +      +      +
 5.200E-05  4.45E-04 +      +      +A     +      +      +      +      +      +
 5.600E-05  2.74E-04 +      +      +A     +      +      +      +      +      +
 6.000E-05  1.81E-04 +      +      +A     +      +      +      +      +      +
 6.400E-05  1.29E-04 +      +      A      +      +      +      +      +      +
 6.900E-05  1.02E-04 +      +      A      +      +      +      +      +      +
 7.200E-05  8.84E-05 +      +      A      +      +      +      +      +      +
 7.600E-05  8.57E-05 +      +      A      +      +      +      +      +      +
 8.000E-05  9.35E-05-+------+------A------+------+------+------+------+------+-
 8.400E-05  1.13E-04 +      +      A      +      +      +      +      +      +
 8.800E-05  1.52E-04 +      +      A      +      +      +      +      +      +
 9.200E-05  2.22E-04 +      +      +A     +      +      +      +      +      +
 9.600E-05  3.49E-04 +      +      +A     +      +      +      +      +      +
 1.000E-04  5.88E-04 +      +      + A    +      +      +      +      +      +
                       +             +             +             +             +
```

```
****** TRANSIENT ANALYSIS        TNOM=  27.000 TEMP=  27.000
   TIME       I(VIC2)
(A        )     0.           5.000E-03     1.000E-02     1.500E-02     2.000E-02
                     +             +             +             +             +
  0.        6.58E-04-+-A----+------+------+------+------+------+------+------+-
 4.000E-06  7.94E-12 A      +      +      +      +      +      +      +      +
 8.000E-06  5.85E-12 A      +      +      +      +      +      +      +      +
 1.200E-05  6.31E-12 A      +      +      +      +      +      +      +      +
 1.600E-05  6.65E-12 A      +      +      +      +      +      +      +      +
 2.000E-05  6.86E-12 A      +      +      +      +      +      +      +      +
 2.400E-05  6.96E-12 A      +      +      +      +      +      +      +      +
 2.800E-05  6.93E-12 A      +      +      +      +      +      +      +      +
 3.200E-05  6.77E-12 A      +      +      +      +      +      +      +      +
 3.600E-05  6.49E-12 A      +      +      +      +      +      +      +      +
 4.000E-05  6.09E-12-A------+------+------+------+------+------+------+------+-
 4.400E-05  5.60E-12 A      +      +      +      +      +      +      +      +
 4.800E-05  7.19E-06 A      +      +      +      +      +      +      +      +
 5.200E-05  1.76E-03 +    A +      +      +      +      +      +      +      +
 5.600E-05  4.02E-03 +      +   A  +      +      +      +      +      +      +
 6.000E-05  6.13E-03 +      +      +  A   +      +      +      +      +      +
 6.400E-05  7.91E-03 +      +      +      +A     +      +      +      +      +
 6.800E-05  9.22E-03 +      +      +      +    A +      +      +      +      +
 7.200E-05  9.98E-03 +      +      +      +      A      +      +      +      +
 7.600E-05  1.01E-02 +      +      +      +      A      +      +      +      +
 8.000E-05  9.67E-03-+------+------+------+-----A+------+------+------+------+-
 8.400E-05  8.62E-03 +      +      +      +  A   +      +      +      +      +
 8.800E-05  7.06E-03 +      +      +     A+      +      +      +      +      +
 9.200E-05  5.10E-03 +      +      A      +      +      +      +      +      +
 9.600E-05  2.90E-03 +      +A     +      +      +      +      +      +      +
 1.000E-04  6.58E-04 + A    +      +      +      +      +      +      +      +
                     +             +             +             +             +
```

```
****** TRANSIENT ANALYSIS        TNOM=  27.000 TEMP=  27.000
   TIME       I(VID2)
(A        )     0.           1.000E-04     2.000E-04     3.000E-04     4.000E-04
                     +             +             +             +             +
  0.        8.23E-05-+------+----A-+------+------+------+------+------+------+-
 4.000E-06  2.50E-05 +  A   +      +      +      +      +      +      +      +
 8.000E-06  6.79E-06 +A     +      +      +      +      +      +      +      +
 1.200E-05  1.36E-06 A      +      +      +      +      +      +      +      +
 1.600E-05  5.51E-08 A      +      +      +      +      +      +      +      +
 2.000E-05  1.38E-11 A      +      +      +      +      +      +      +      +
 2.400E-05  1.40E-11 A      +      +      +      +      +      +      +      +
 2.800E-05  1.39E-11 A      +      +      +      +      +      +      +      +
 3.200E-05  1.36E-11 A      +      +      +      +      +      +      +      +
 3.600E-05  4.26E-07 A      +      +      +      +      +      +      +      +
 4.000E-05  3.41E-06-A------+------+------+------+------+------+------+------+-
 4.400E-05  1.35E-05 + A    +      +      +      +      +      +      +      +
 4.800E-05  5.55E-05 +      +A     +      +      +      +      +      +      +
 5.200E-05  9.74E-05 +      +      A      +      +      +      +      +      +
 5.600E-05  1.26E-04 +      +      +   A  +      +      +      +      +      +
 6.000E-05  1.52E-04 +      +      +      A      +      +      +      +      +
 6.400E-05  1.74E-04 +      +      +      +  A   +      +      +      +      +
 6.800E-05  1.90E-04 +      +      +      +     A+      +      +      +      +
 7.200E-05  2.00E-04 +      +      +      +      A      +      +      +      +
 7.600E-05  2.02E-04 +      +      +      +      A      +      +      +      +
 8.000E-05  1.96E-04-+------+------+------+-----A+------+------+------+------+-
 8.400E-05  1.83E-04 +      +      +      +    A +      +      +      +      +
 8.800E-05  1.63E-04 +      +      +      + A    +      +      +      +      +
 9.200E-05  1.39E-04 +      +      +     A+      +      +      +      +      +
 9.600E-05  1.12E-04 +      +      + A    +      +      +      +      +      +
 1.000E-04  8.23E-05 +      +    A +      +      +      +      +      +      +
                     +             +             +             +             +
```

```
******  TRANSIENT ANALYSIS        TNOM=  27.000 TEMP=  27.000
  TIME        V(10)
(A       )  -4.000E+00    -2.000E+00      0.          2.000E+00     4.000E+00
                     +             +             +             +             +
       0.  -2.92E-02 +------+------+------+------A------+------+------+------+-
4.000E-06   4.51E-01 +      +      +      +      +  A   +      +      +      +
8.000E-06   9.15E-01 +      +      +      +      +     A+      +      +      +
1.200E-05   1.32E+00 +      +      +      +      +      + A    +      +      +
1.600E-05   1.64E+00 +      +      +      +      +      +   A  +      +      +
2.000E-05   1.86E+00 +      +      +      +      +      +     A+      +      +
2.400E-05   1.95E+00 +      +      +      +      +      +      A      +      +
2.800E-05   1.92E+00 +      +      +      +      +      +     A+      +      +
3.200E-05   1.76E+00 +      +      +      +      +      +    A +      +      +
3.600E-05   1.49E+00 +      +      +      +      +      +  A   +      +      +
4.000E-05   1.12E+00 +------+------+------+------+------+A-----+------+------+-
4.400E-05   6.86E-01 +      +      +      +      +    A +      +      +      +
4.800E-05   2.15E-01 +      +      +      +      + A    +      +      +      +
5.200E-05  -2.82E-01 +      +      +      +    A +      +      +      +      +
5.600E-05  -7.74E-01 +      +      +      + A    +      +      +      +      +
6.000E-05  -1.22E+00 +      +      +    A +      +      +      +      +      +
6.400E-05  -1.59E+00 +      +      + A    +      +      +      +      +      +
6.800E-05  -1.86E+00 +      +      +A     +      +      +      +      +      +
7.200E-05  -2.01E+00 +      +      A      +      +      +      +      +      +
7.600E-05  -2.05E+00 +      +      A      +      +      +      +      +      +
8.000E-05  -1.95E+00 +------+------A------+------+------+------+------+------+-
8.400E-05  -1.73E+00 +      +      + A    +      +      +      +      +      +
8.800E-05  -1.41E+00 +      +      +   A  +      +      +      +      +      +
9.200E-05  -1.00E+00 +      +      +      A      +      +      +      +      +
9.600E-05  -5.31E-01 +      +      +      +  A   +      +      +      +      +
1.000E-04  -2.92E-02 +      +      +      +      A      +      +      +      +
                     +             +             +             +             +
******
```

FOURIER COMPONENTS OF TRANSIENT RESPONSE V(10)

DC COMPONENT = -4.333D-02

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	9.999E+03	2.004E+00	1.000E+00	4.267E-04	0.
2	2.000E+04	4.438E-03	2.215E-03	9.067E+01	9.067E+01
3	3.000E+04	6.157E-03	3.072E-03	-1.799E+02	-1.799E+02
4	4.000E+04	3.486E-03	1.740E-03	8.912E+01	8.912E+01
5	5.000E+04	1.974E-03	9.851E-04	1.794E+02	1.794E+02
6	6.000E+04	2.250E-03	1.123E-03	9.093E+01	9.093E+01
7	7.000E+04	6.148E-04	3.068E-04	1.744E+02	1.744E+02
8	8.000E+04	1.536E-03	7.664E-04	9.086E+01	9.086E+01
9	9.000E+04	4.136E-04	2.064E-04	-1.251E+01	-1.251E+01

TOTAL HARMONIC DISTORTION = 4.508E-01 PERCENT

```
BICMOS CLASS-AB OUTPUT STAGE (PEAK OUTPUT AMPLITUDE = 4 V)
* BIPOLAR PARAMETERS FROM FIG. 2.32 AND
* PMOS PARAMETERS FROM TABLE 2.3
******
VCC     100     0   5
VEE     200     0   -5
Q1      21      7   10    NPN   25
Q2      110     13  200   NPN   25
Q3      7       8   9     NPN   25
Q5      6       4   3     PNP
Q6      7       4   5     PNP   5
M1      8       8   7     7     PMOS1   W=500U  L=1U
M2      113     9   10    10    PMOS1   W=500U  L=1U
M3      0       6   4     4     PMOS2   W=2U    L=2U
R1      8       9   10K
R2      13      200 10K
R3      100     3   500
R4      100     5   100
RL      10      0   200
IBIAS   6       0   100U
* ZERO-VOLTAGE VOLTAGE SOURCES TO MEASURE TRANSISTOR CURRENTS
VIC1    100     21  0
VID2    113     13  0
VIC2    10      110 0
.MODEL NPN  NPN  RB=400 BF=80 IS=6E-18 VAF=35
.MODEL PNP  PNP  RB=200 BF=20 IS=6E-18 VAF=30
.MODEL PMOS1 PMOS KP=26U VTO=-0.7 LAMBDA=0.0625 LD=0.18U
.MODEL PMOS2 PMOS KP=26U VTO=-0.7 LAMBDA=0.0244 LD=0.18U
* LAMBDA1 = (DXD/DVDS)/LEFF = 0.04/(1-2*0.18) = 0.0625 V^(-1)
* LAMBDA2 = (DXD/DVDS)/LEFF = 0.04/(2-2*0.18) = 0.0244 V^(-1)

* THE DC INPUT VOLTAGE IS ADJUSTED BY TRIAL AND ERROR
* TO SET THE DC OUTPUT VOLTAGE TO ZERO.
* THE PEAK INPUT AMPLITUDE IS SET BY TRIAL AND ERROR
* SO THAT THE PEAK OUTPUT AMPLITUDE IS 4 V.
VI      9       0       SIN     -0.8093  4.14  10K  0  0
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.DC VI -5 5 0.5
.PLOT DC V(10)

.TRAN 4U 100U
.PLOT TRAN I(VIC1)
.PLOT TRAN I(VIC2)
.PLOT TRAN I(VID2)
.PLOT TRAN V(10)
.FOUR 10K V(10)
.END
```

**** OPERATING POINT INFORMATION   TNOM= 27.000 TEMP= 27.000

NODE	=VOLTAGE	NODE	=VOLTAGE	NODE	=VOLTAGE
+0:3	= 4.947E+00	0:4	= 4.160E+00	0:5	= 4.946E+00
+0:6	= 2.206E+00	0:7	= 7.179E-01	0:8	=-6.835E-02
+0:9	=-8.093E-01	0:10	=-2.920E-02	0:13	=-4.249E+00
+0:21	= 5.000E+00	0:100	= 5.000E+00	0:110	=-2.920E-02
+0:113	=-4.249E+00	0:200	=-5.000E+00		

**** BIPOLAR JUNCTION TRANSISTORS

SUBCKT					
ELEMENT	0:Q1	0:Q2	0:Q3	0:Q5	0:Q6
MODEL	0:NPN	0:NPN	0:NPN	0:PNP	0:PNP
IB	6.547E-06	7.341E-06	5.166E-06	-4.694E-06	-2.280E-05
IC	5.879E-04	6.581E-04	4.226E-04	-1.000E-04	-5.084E-04
VBE	7.471E-01	7.501E-01	7.410E-01	-7.867E-01	-7.860E-01
VCE	5.029E+00	4.970E+00	1.527E+00	-2.741E+00	-4.229E+00
VBC	-4.282E+00	-4.220E+00	-7.862E-01	1.954E+00	3.443E+00
VS	-5.000E+00	2.920E-02	-7.179E-01	-4.161E+00	-4.161E+00
POWER	2.961E-03	3.277E-03	6.492E-04	2.778E-04	2.168E-03
BETAD	8.978E+01	8.964E+01	8.179E+01	2.130E+01	2.229E+01
GM	2.271E-02	2.543E-02	1.633E-02	3.863E-03	1.964E-02
RPI	3.950E+03	3.523E+03	5.006E+03	5.510E+03	1.134E+03
RX	1.600E+01	1.600E+01	1.600E+01	2.000E+02	4.000E+01
RO	6.682E+04	5.959E+04	8.468E+04	3.195E+05	6.578E+04
BETAAC	8.972E+01	8.958E+01	8.173E+01	2.128E+01	2.227E+01

**** MOSFETS

SUBCKT

ELEMENT	0:M1	0:M2	0:M3
MODEL	0:PMOS1	0:PMOS1	0:PMOS2
ID	-7.926E-05	-8.235E-05	-2.750E-05
IBS	0.	0.	0.
IBD	7.862E-15	4.221E-14	4.161E-14
VGS	-7.862E-01	-7.801E-01	-1.954E+00
VDS	-7.862E-01	-4.220E+00	-4.160E+00
VBS	0.	0.	0.
VTH	-7.000E-01	-7.000E-01	-7.000E-01
VDSAT	-8.625E-02	-8.010E-02	-1.254E+00
BETA	2.131E-02	2.567E-02	3.493E-05
GAM EFF	0.	0.	0.
GM	1.838E-03	2.056E-03	4.383E-05
GDS	4.722E-06	4.072E-06	6.091E-07
GMB	0.	0.	0.

****** TRANSIENT ANALYSIS TNOM= 27.000 TEMP= 27.000

```
   TIME       I(VIC1)
(A       )    0.            5.000E-03     1.000E-02     1.500E-02     2.000E-02
                     +             +             +             +             +

 0.         5.88E-04-+-A----+------+------+------+------+------+------+------+-
 4.000E-06  4.66E-03 +      +     A+      +      +      +      +      +      +
 8.000E-06  9.29E-03 +      +      +      +     A +      +      +      +      +
 1.200E-05  1.33E-02 +      +      +      +      +      + A    +      +      +
 1.600E-05  1.66E-02 +      +      +      +      +      +      +   A  +      +
 2.000E-05  1.87E-02 +      +      +      +      +      +      +      +  A   +
 2.400E-05  1.96E-02 +      +      +      +      +      +      +      +     A+
 2.800E-05  1.93E-02 +      +      +      +      +      +      +      +    A +
 3.200E-05  1.78E-02 +      +      +      +      +      +      +      +A     +
 3.600E-05  1.51E-02 +      +      +      +      +      +      A      +      +
 4.000E-05  1:14E-02-+------+------+------+------+---A--+------+------+------+-
 4.400E-05  7.02E-03 +      +      +     A+      +      +      +      +      +
 4.800E-05  2.27E-03 +     A+      +      +      +      +      +      +      +
 5.200E-05  3.46E-04 +A     +      +      +      +      +      +      +      +
 5.600E-05  1.39E-04 A      +      +      +      +      +      +      +      +
 6.000E-05  6.29E-05 A      +      +      +      +      +      +      +      +
 6.400E-05  3.27E-05 A      +      +      +      +      +      +      +      +
 6.800E-05  2.04E-05 A      +      +      +      +      +      +      +      +
 7.200E-05  1.34E-05 A      +      +      +      +      +      +      +      +
 7.600E-05  7.17E-06 A      +      +      +      +      +      +      +      +
 8.000E-05  1.72E-05-A------+------+------+------+------+------+------+------+-
 8.400E-05  2.53E-05 A      +      +      +      +      +      +      +      +
 8.800E-05  4.51E-05 A      +      +      +      +      +      +      +      +
 9.200E-05  9.34E-05 A      +      +      +      +      +      +      +      +
 9.600E-05  2.20E-04 +A     +      +      +      +      +      +      +      +
 1.000E-04  5.88E-04 + A    +      +      +      +      +      +      +      +
                     +             +             +             +             +
```

****** TRANSIENT ANALYSIS TNOM= 27.000 TEMP= 27.000

```
   TIME       I(VIC2)
(A       )    0.            5.000E-03     1.000E-02     1.500E-02     2.000E-02
                     +             +             +             +             +

 0.         6.58E-04-+-A----+------+------+------+------+------+------+------+-
 4.000E-06  5.91E-12 A      +      +      +      +      +      +      +      +
 8.000E-06  6.88E-12 A      +      +      +      +      +      +      +      +
 1.200E-05  7.70E-12 A      +      +      +      +      +      +      +      +
 1.600E-05  8.35E-12 A      +      +      +      +      +      +      +      +
 2.000E-05  8.78E-12 A      +      +      +      +      +      +      +      +
 2.400E-05  8.97E-12 A      +      +      +      +      +      +      +      +
 2.800E-05  8.91E-12 A      +      +      +      +      +      +      +      +
 3.200E-05  8.59E-12 A      +      +      +      +      +      +      +      +
 3.600E-05  8.05E-12 A      +      +      +      +      +      +      +      +
 4.000E-05  7.31E-12-A------+------+------+------+------+------+------+------+-
 4.400E-05  6.41E-12 A      +      +      +      +      +      +      +      +
 4.800E-05  1.16E-10 A      +      +      +      +      +      +      +      +
 5.200E-05  2.91E-03 +      +A     +      +      +      +      +      +      +
 5.600E-05  7.54E-03 +      +      +      A      +      +      +      +      +
 6.000E-05  1.18E-02 +      +      +      +      +    A +      +      +      +
 6.400E-05  1.55E-02 +      +      +      +      +      +      +A     +      +
 6.800E-05  1.81E-02 +      +      +      +      +      +      +      + A    +
 7.200E-05  1.96E-02 +      +      +      +      +      +      +      +     A+
 7.600E-05  1.99E-02 +      +      +      +      +      +      +      +      A
 8.000E-05  1.90E-02-+------+------+------+------+------+------+------+---A--+-
 8.400E-05  1.69E-02 +      +      +      +      +      +      +    A +      +
 8.800E-05  1.37E-02 +      +      +      +      +      +  A   +      +      +
 9.200E-05  9.75E-03 +      +      +      +     A+      +      +      +      +
 9.600E-05  5.23E-03 +      +      +A     +      +      +      +      +      +
 1.000E-04  6.58E-04 + A    +      +      +      +      +      +      +      +
                     +             +             +             +             +
```

****** TRANSIENT ANALYSIS TNOM= 27.000 TEMP= 27.000

```
   TIME       I(VID2)
(A       )    0.            1.000E-04     2.000E-04     3.000E-04     4.000E-04
                     +             +             +             +             +

 0.         8.23E-05-+------+----A-+------+------+------+------+------+------+-
 4.000E-06  7.58E-06 +A     +      +      +      +      +      +      +      +
 8.000E-06  6.61E-08 A      +      +      +      +      +      +      +      +
 1.200E-05  1.55E-11 A      +      +      +      +      +      +      +      +
 1.600E-05  1.68E-11 A      +      +      +      +      +      +      +      +
 2.000E-05  1.77E-11 A      +      +      +      +      +      +      +      +
 2.400E-05  1.80E-11 A      +      +      +      +      +      +      +      +
 2.800E-05  1.79E-11 A      +      +      +      +      +      +      +      +
 3.200E-05  1.73E-11 A      +      +      +      +      +      +      +      +
 3.600E-05  1.62E-11 A      +      +      +      +      +      +      +      +
 4.000E-05  1.47E-11-A------+------+------+------+------+------+------+------+-
 4.400E-05  1.14E-06 A      +      +      +      +      +      +      +      +
 4.800E-05  2.88E-05 +   A  +      +      +      +      +      +      +      +
 5.200E-05  1.12E-04 +      +      + A    +      +      +      +      +      +
 5.600E-05  1.69E-04 +      +      +      +  A   +      +      +      +      +
 6.000E-05  2.24E-04 +      +      +      +      +  A   +      +      +      +
 6.400E-05  2.71E-04 +      +      +      +      +      +  A   +      +      +
 6.800E-05  3.07E-04 +      +      +      +      +      +      +A     +      +
 7.200E-05  3.29E-04 +      +      +      +      +      +      +   A  +      +
 7.600E-05  3.32E-04 +      +      +      +      +      +      +   A  +      +
 8.000E-05  3.20E-04-+------+------+------+------+------+------+--A---+------+-
 8.400E-05  2.91E-04 +      +      +      +      +      +     A+      +      +
 8.800E-05  2.49E-04 +      +      +      +      +      A      +      +      +
 9.200E-05  1.97E-04 +      +      +      +      A      +      +      +      +
 9.600E-05  1.41E-04 +      +      +     A+      +      +      +      +      +
 1.000E-04  8.23E-05 +      +    A +      +      +      +      +      +      +
                     +             +             +             +             +
```

****** TRANSIENT ANALYSIS TNOM= 27.000 TEMP= 27.000

```
   TIME       V(10)
(A       )   -1.000E+01     -5.000E+00     0.            5.000E+00     1.000E+01
                     +             +             +             +             +

 0.        -2.92E-02-+------+------+------+------A------+------+------+------+-
 4.000E-06  9.41E-01 +      +      +      +      + A    +      +      +      +
 8.000E-06  1.87E+00 +      +      +      +      +    A +      +      +      +
 1.200E-05  2.70E+00 +      +      +      +      +      +A     +      +      +
 1.600E-05  3.35E+00 +      +      +      +      +      + A    +      +      +
 2.000E-05  3.78E+00 +      +      +      +      +      +   A  +      +      +
 2.400E-05  3.97E+00 +      +      +      +      +      +   A  +      +      +
 2.800E-05  3.90E+00 +      +      +      +      +      +   A  +      +      +
 3.200E-05  3.59E+00 +      +      +      +      +      +  A   +      +      +
 3.600E-05  3.05E+00 +      +      +      +      +      + A    +      +      +
 4.000E-05  2.30E+00-+------+------+------+------+-----A+------+------+------+-
 4.400E-05  1.42E+00 +      +      +      +      +   A  +      +      +      +
 4.800E-05  4.54E-01 +      +      +      +      +A     +      +      +      +
 5.200E-05 -5.34E-01 +      +      +      +     A+      +      +      +      +
 5.600E-05 -1.51E+00 +      +      +      +  A   +      +      +      +      +
 6.000E-05 -2.40E+00 +      +      +      A      +      +      +      +      +
 6.400E-05 -3.14E+00 +      +      +    A +      +      +      +      +      +
 6.800E-05 -3.67E+00 +      +      +   A  +      +      +      +      +      +
 7.200E-05 -3.98E+00 +      +      +  A   +      +      +      +      +      +
 7.600E-05 -4.04E+00 +      +      +  A   +      +      +      +      +      +
 8.000E-05 -3.86E+00-+------+------+--A---+------+------+------+------+------+-
 8.400E-05 -3.43E+00 +      +      +   A  +      +      +      +      +      +
 8.800E-05 -2.78E+00 +      +      +     A+      +      +      +      +      +
 9.200E-05 -1.97E+00 +      +      +      +A     +      +      +      +      +
 9.600E-05 -1.03E+00 +      +      +      +   A  +      +      +      +      +
 1.000E-04 -2.92E-02 +      +      +      +      A      +      +      +      +
                     +             +             +             +             +
```

******

FOURIER COMPONENTS OF TRANSIENT RESPONSE V(10)

DC COMPONENT = -4.173D-02

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	9.999E+03	4.014E+00	1.000E+00	-6.743E-04	0.
2	2.000E+04	1.806E-03	4.499E-04	-9.748E+01	-9.748E+01
3	3.000E+04	7.591E-03	1.891E-03	1.795E+02	1.795E+02
4	4.000E+04	3.882E-03	9.670E-04	8.902E+01	8.902E+01
5	5.000E+04	6.219E-03	1.549E-03	1.783E+02	1.783E+02
6	6.000E+04	7.583E-04	1.889E-04	9.088E+01	9.088E+01
7	7.000E+04	7.987E-04	1.990E-04	1.702E+02	1.702E+02
8	8.000E+04	2.919E-03	7.272E-04	8.969E+01	8.969E+01
9	9.000E+04	1.627E-03	4.052E-04	-1.753E+02	-1.753E+02

TOTAL HARMONIC DISTORTION = 2.807E-01 PERCENT

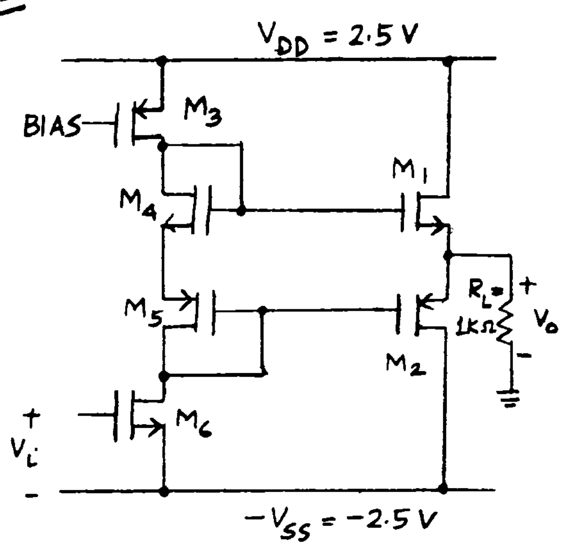
5.21

The negative limit on V_o is reached when M_6 reaches the edge of the active region

$$V_o^- = -V_{SS} + V_{ov_6} + V_{sg_2}$$
$$= -V_{SS} + V_{ov_6} - V_{gs_2}$$

and $V_{gs_2} < 0$, when M_2 conducts because M_2 is an enhancement-mode PMOS transistor.

5.22



$$\lambda_n = \frac{dX_d}{dV_{ds}} \Big/ L = 0.08$$

$$\lambda_p = \frac{dX_d}{dV_{ds}} \Big/ L = 0.04$$

$$\phi_{fn} = \frac{KT}{q} \ln \frac{4 \times 10^{15}}{1.45 \times 10^{10}} = 323\,mV$$

$$\phi_{fp} = \frac{KT}{q} \ln \frac{3 \times 10^{16}}{1.45 \times 10^{10}} = 375\,mV$$

$$2\phi_{fn} = 650\,mV$$

$$2\phi_{fp} = 750\,mV$$

Table (2.3)

$k'_n = 127\,\mu A/V$; $k'_p = 58\,\mu A/V$

$V_{tn} = 0.7\,V$; $V_{tp} = -0.7\,V$

$$C_{ox} = \frac{3.9 \times 8.854 \times 10^{-14}}{150 \times 10^{-8}} = 2.3\,\frac{fF}{\mu m^2}$$

$$\gamma_n = \frac{\sqrt{2(1.6 \times 10^{-19})\,11.6 \times 8.86 \times 10^{-14} \times 4 \times 10^{15}}}{2.3 \times 10^{-7}}$$
$$= 0.158\,\sqrt{V}$$

$$\gamma_p = \frac{\sqrt{2(1.6 \times 10^{-19})\,11.6 \times 8.86 \times 10^{-14} \times 3 \times 10^{16}}}{2.3 \times 10^{-7}}$$
$$= 0.432\,\sqrt{V}$$

For $V_o = 1V$, $V_{SB} = 1 + 2.5 = 3.5\,V$

$$V_{t_1} = 0.7 + 0.16\left(\sqrt{0.65 + 3.5} - \sqrt{0.65}\right)$$
$$= 0.9\,V$$

$$V_{ov_3} = \sqrt{\frac{2(10\mu)}{58\,(50)}} = 83\,mV$$

At peak output, we want

$$V_{GS_1} = 2.5 - 0.083 - 1 = 1.417\,V$$

$$I_{D_1} = \frac{k'}{2}\left(\frac{W}{L}\right)_1 (V_{GS_1} - V_t)^2$$

$$I_{D_1(max)} = \frac{1\,V}{1\,K} = 1\,mA$$

$$\left(\frac{W}{L}\right)_1 = \frac{2 I_{D_1}}{k'(V_{GS_1} - V_t)^2} = \frac{2\,(1000)}{127\,(1.417 - 0.9)^2} = 59$$

For $V_o = -1V$, $V_{SB} = -1 - 2.5 = -3.5$

$$V_{t_2} = -0.7 - 0.43\left(\sqrt{0.75 + 3.5} - \sqrt{0.75}\right)$$
$$= -1.21\,V$$

$$V_{OV_6} = \sqrt{\frac{2(10)}{127(25)}} = 0.079\text{ V}$$

At peak output, want

$$V_{GS_2} = -2.5 + 0.079 - (-1) = 1.421\text{ V}$$

$$\left(\frac{W}{L}\right)_2 = \frac{2(1000)}{58(-1.421+1.21)^2} = 775$$

$$I_{d_4} = |I_{d_5}| = \frac{1}{10} I_{d_1}$$

$$(W/L)_4 = \frac{(W/L)_1}{10} = 5.9$$

$$(W/L)_5 = \frac{(W/L)_2}{10} = 77.5$$

```
COMPLEMENTARY SOURCE FOLLOWER CMOS OUTPUT STAGE
******
VDD   100 0    2.5
VSS   200 0    -2.5
RL    5    0   1K
M1    100 3    5     200   NMOS W=60U L=1U
M2    200 6    5     100   PMOS W=780U L=1U
M3    3    2   100   100   PMOS W=50U L=1U
M4    3    3   4     200   NMOS W=6U  L=1U
M5    6    6   4     100   PMOS W=78U L=1U
M6    6    7   200   200   NMOS W=25U L=1U

* IN FIG. 5.31, THE BIAS VOLTAGE COULD BE ADJUSTED
* BY TRIAL AND ERROR TO SET THE DRAIN CURRENT OF M3
* EQUAL TO 10 MICROAMPS, BUT THIS PROCESS MAY REQUIRE
* MANY ITERATIONS.  SO INSTEAD, M7 AND IBIAS ARE ADDED
* TO FORM A CURRENT MIRROR TO SET UP THE DC DRAIN
* CURRENT IN M3.
M7    2    2   100   100   PMOS W=50U L=1U
IBIAS 2    200 9.9U

* THE DC INPUT IS ADJUSTED SO THAT
* THE DC OUTPUT IS APPROXIMATELY ZERO.
VI    7    200 0.7761

.MODEL PMOS PMOS KP=58U  LAMBDA=0.04 GAMMA=0.43 VTO=-0.7 LD=0
.MODEL NMOS NMOS KP=127U LAMBDA=0.08 GAMMA=0.16 VTO=0.7  LD=0
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.DC   VI  0.76  0.79  0.001
.PLOT DC V(5)
.END
```

```
******  DC TRANSFER CURVES      TNOM=  27.000 TEMP=  27.000
    VOLT       V(5)
(A         )   -2.000E+00    -1.000E-00     0.           1.000E-00     2.000E+00
                     +             +             +             +             +
7.600E-01  1.05E+00-+------+------+------+------+------+------+A-----+------+-
7.610E-01  1.05E+00 +      +      +      +      +      +      +A     +      +
7.620E-01  1.05E+00 +      +      +      +      +      +      +A     +      +
7.630E-01  1.05E+00 +      +      +      +      +      +      +A     +      +
7.640E-01  1.05E+00 +      +      +      +      +      +      +A     +      +
7.650E-01  1.05E+00 +      +      +      +      +      +      +A     +      +
7.660E-01  1.04E+00 +      +      +      +      +      +      +A     +      +
7.670E-01  1.04E+00 +      +      +      +      +      +      +A     +      +
7.680E-01  1.04E+00 +      +      +      +      +      +      +A     +      +
7.690E-01  1.03E+00 +      +      +      +      +      +      +A     +      +
7.700E-01  1.03E+00-+------+------+------+------+------+------A------+------+-
7.710E-01  8.89E-01 +      +      +      +      +      +    A +      +      +
7.720E-01  7.03E-01 +      +      +      +      +      + A    +      +      +
7.730E-01  5.25E-01 +      +      +      +      +      A      +      +      +
7.740E-01  3.56E-01 +      +      +      +      +    A +      +      +      +
7.750E-01  2.00E-01 +      +      +      +      + A    +      +      +      +
7.760E-01  2.79E-02 +      +      +      +      A      +      +      +      +
7.770E-01 -1.56E-01 +      +      +      +    A +      +      +      +      +
7.780E-01 -3.42E-01 +      +      +      + A    +      +      +      +      +
7.790E-01 -5.27E-01 +      +      +      A      +      +      +      +      +
7.800E-01 -7.10E-01-+------+------+---A--+------+------+------+------+------+-
7.810E-01 -8.91E-01 +      +      + A    +      +      +      +      +      +
7.820E-01 -9.87E-01 +      +      A      +      +      +      +      +      +
7.830E-01 -9.92E-01 +      +      A      +      +      +      +      +      +
7.840E-01 -9.95E-01 +      +      A      +      +      +      +      +      +
7.850E-01 -9.97E-01 +      +      A      +      +      +      +      +      +
7.860E-01 -9.99E-01 +      +      A      +      +      +      +      +      +
7.870E-01 -1.00E+00 +      +      A      +      +      +      +      +      +
7.880E-01 -1.00E+00 +      +      A      +      +      +      +      +      +
7 890E-01 -1.00E+00 +      +      A      +      +      +      +      +      +
7.900E-01 -1.00E+00-+------+------A------+------+------+------+------+------+-
                     +             +             +             +             +
```

**** OPERATING POINT INFORMATION   TNOM= 27.000 TEMP= 27.000

NODE	=VOLTAGE	NODE	=VOLTAGE	NODE	=VOLTAGE
+0:2	= 1.718E+00	0:3	= 1.025E+00	0:4	= 1.048E-02
+0:5	= 9.746E-03	0:6	=-1.177E+00	0:7	=-1.723E+00
+0:100	= 2.500E+00	0:200	=-2.500E+00		

**** MOSFETS

SUBCKT				
ELEMENT	0:M1	0:M2	0:M3	0:M4
MODEL	0:NMOS	0:PMOS	0:PMOS	0:NMOS
ID	1.139E-04	-1.041E-04	-1.017E-05	1.017E-05
IBS	-2.510E-14	2.490E-14	0.	-2.510E-14
IBD	-5.000E-14	5.000E-14	1.474E-14	-3.526E-14
VGS	1.016E+00	-1.187E+00	-7.814E-01	1.015E+00
VDS	2.490E+00	-2.509E+00	-1.474E+00	1.015E+00
VBS	-2.509E+00	2.490E+00	0.	-2.510E+00
VTH	8.582E-01	-1.122E+00	-7.000E-01	8.582E-01
VDSAT	1.579E-01	-6.468E-02	-8.137E-02	1.571E-01
BETA	9.138E-03	4.978E-02	3.071E-03	8.239E-04
GAM EFF	1.600E-01	4.300E-01	4.300E-01	1.600E-01
GM	1.443E-03	3.220E-03	2.499E-04	1.294E-04
GDS	7.596E-06	3.785E-06	3.840E-07	7.522E-07
GMB	6.544E-05	3.938E-04	6.936E-05	5.871E-06

SUBCKT			
ELEMENT	0:M5	0:M6	0:M7
MODEL	0:PMOS	0:NMOS	0:PMOS
ID	-1.017E-05	1.017E-05	-9.900E-06
IBS	2.490E-14	0.	0.
IBD	3.678E-14	-1.322E-14	7.814E-15
VGS	-1.188E+00	7.761E-01	-7.814E-01
VDS	-1.188E+00	1.322E+00	-7.814E-01
VBS	2.489E+00	0.	0.
VTH	-1.122E+00	7.000E-01	-7.000E-01
VDSAT	-6.550E-02	7.610E-02	-8.137E-02
BETA	4.739E-03	3.511E-03	2.991E-03
GAM EFF	4.300E-01	1.600E-01	4.300E-01
GM	3.104E-04	2.672E-04	2.433E-04
GDS	3.882E-07	7.355E-07	3.840E-07
GMB	3.797E-05	2.759E-05	6.754E-05

5-23

Assume $M_2 = \text{off}$

KCL $-I_{d_1} = V_o/R_L$

From (5.112), $\frac{k'}{2}\frac{W}{L}(V_{gs_1}+V_t)^2 = V_o/R_L$

sub in (5.110), $\frac{k'}{2}\frac{W}{L}\left\{-V_{ov} + A\left[V_o - (V_i - V_{osp})\right]\right\}^2 = \frac{V_o}{R_L}$

$$\frac{k'}{2}\frac{W}{L}\left\{V_{ov}^2 + A^2\left[V_o(-V_i - V_{osp})\right]^2 - 2AV_{ov}\left[V_o - (V_i - V_{osp})\right]\right\} = \frac{V_o}{R_L}$$

$$\frac{k'}{2}\frac{W}{L}\left\{V_{ov}^2 + A^2\left[(V_o - V_i)^2 + V_{osp}^2 + 2(V_o - V_i)V_{osp}\right] - 2AV_{ov}\left[V_o - V_i + V_{osp}\right]\right\} = V_o/R_L$$

$$V_o^2\left(\frac{k'}{2}\frac{W}{L}\right)A^2$$
$$+ V_o\left\{\frac{k'}{2}\frac{W}{L}\left[-2V_iA^2 + 2V_{osp}A^2 - 2AV_{ov}\right] - \frac{1}{R_L}\right\}$$
$$+ \frac{k'}{2}\frac{W}{L}\left\{V_{ov}^2 + V_i^2A^2 + V_{osp}^2A^2 - 2V_iV_{osp}A^2 + 2AV_{ov}V_i - 2AV_{ov}V_{osp}\right\} = 0$$

$$V_o = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$$a = \frac{k'}{2}\frac{W}{L}A^2$$

$$b = \frac{k'}{2}\frac{W}{L}A^2\left(-2V_i + V_{osp} - \frac{2V_{ov}}{A}\right) - \frac{1}{R_L}$$

$$c = \frac{k'}{2}\frac{W}{L}A^2\left(V_i^2 + \frac{V_{ov}^2}{A^2} + V_{osp}^2 - 2V_iV_{osp} + \frac{2V_{ov}V_i}{A} - \frac{2V_{ov}V_{osp}}{A}\right)$$

$$b = -k'\frac{W}{L}A^2\left(V_i + \frac{V_{ov}}{A} - V_{osp}\right) - \frac{1}{R_L}$$

$$b^2 = (k')^2\left(\frac{W}{L}\right)^2A^4\left(V_i + \frac{V_{ov}}{A} - V_{osp}\right)^2 + \frac{1}{R_L^2} + 2k'\frac{W}{L}\frac{A^2}{R_L}\left(V_i + \frac{V_{ov}}{A} - V_{osp}\right)$$

$$4ac = (k')^2\left(\frac{W}{L}\right)^2A^4\left(V_i^2 + \frac{V_{ov}^2}{A^2} + V_{osp}^2 - 2V_iV_{osp} + \frac{2V_{ov}V_i}{A} - \frac{2V_{ov}V_{osp}}{A}\right)$$

First term in b^2

$$= (k')^2\left(\frac{W}{L}\right)^2A^4\left(V_i^2 + \frac{2V_iV_{ov}}{A} - 2V_iV_{osp} - \frac{2V_{osp}V_{ov}}{A} + \left(\frac{V_{ov}}{A}\right)^2 + V_{osp}^2\right)$$

$$b^2 - 4ac = \left(\frac{1}{R_L}\right)^2 + 2k'\frac{W}{L}\frac{A^2}{R_L}\left(V_i + \frac{V_{ov}}{A} - V_{osp}\right)$$

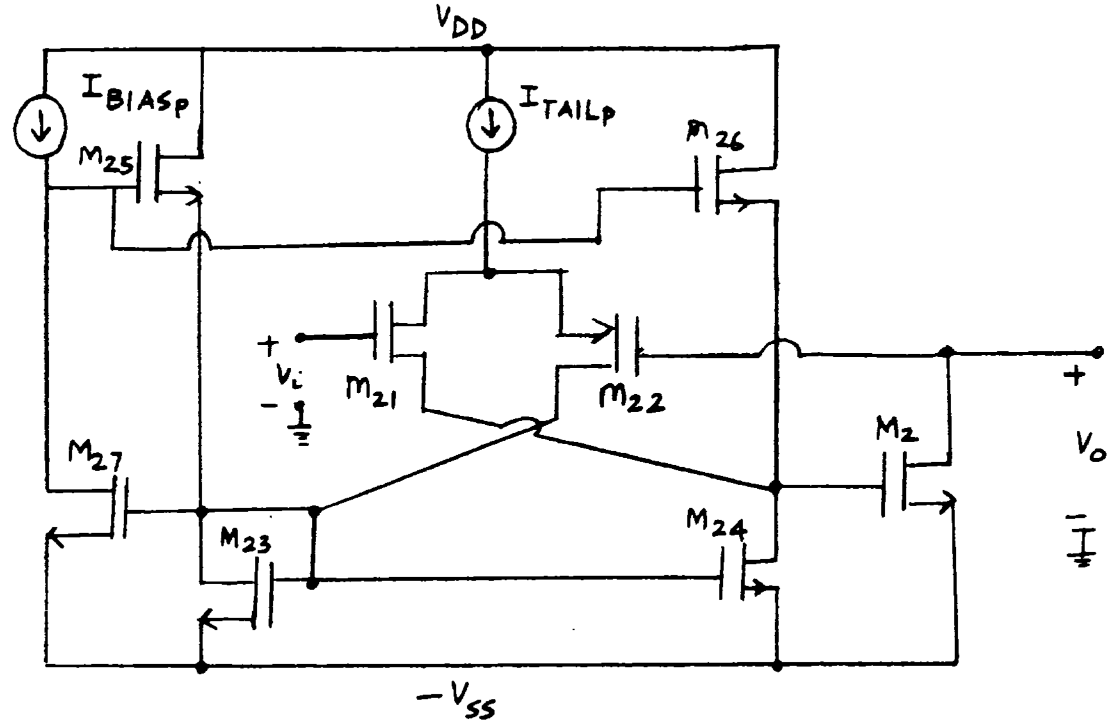
$$V_o = V_i + \frac{V_{ov}}{A} - V_{osp} + \frac{1}{k'\frac{W}{L}A^2R_L} \pm \frac{1}{k'\frac{W}{L}A^2}\sqrt{\left(\frac{1}{R_L}\right)^2 + 2k'\frac{W}{L}\frac{A^2}{R_L}\left(V_i + \frac{V_{ov}}{A} - V_{osp}\right)}$$

V_o must be less than V_i

$$V_o = V_i + \frac{V_{OV}}{A} - V_{OSp} + \frac{1}{k'\frac{W}{L}A^2R_L}$$

$$-\frac{1}{k'\frac{W}{L}A^2}\sqrt{\frac{1}{R_L^2} + 2k'\frac{W}{L}\frac{A^2}{R_L}\left(V_i + \frac{V_{OV}}{A} - V_{OSp}\right)}$$

5.24



5.25

standby power

In Fig (5.35),

$|I_{D_{17}}| + |I_{D_{13}}| + |I_{D_{14}}|$ flows from V_{DD} to $-V_{SS}$. $|I_{D_1}|$ flows from V_{DD} to M_2 in Problem (5.24)

In Problem (5.24),

$I_{D_{27}} + I_{D_{23}} + I_{D_{24}}$ flows from V_{DD} to $-V_{SS}$. I_{D_2} flows from m_1 in fig (5.35) to $-V_{SS}$

Therefore, the standby power dissipation is,

$$[|I_{D_{17}}| + |I_{D_{13}}| + |I_{D_{14}}|][V_{DD} - (-V_{SS})] + [I_{D_{27}} + I_{D_{23}} + I_{D_{24}}][V_{DD} - (-V_{SS})] + |I_{D_1}|[V_{DD} - (-V_{SS})] \le 70\text{ mW}$$

From (a) and (e),

$$\left[\frac{|I_{D_1}|}{100} + \frac{|I_{D_1}|}{10} + \frac{|I_{D_1}|}{10} + \frac{I_{D_2}}{100} + \frac{I_{D_2}}{10} + \frac{I_{D_2}}{10} + |I_{D_1}|\right]5 \le 70\text{ mW}$$

Also in standby $V_i = V_o = 0$, so $I_{RL} = 0$ and $|I_{D_1}| = I_{D_2}$

$$|I_{D_1}|[1 + 0.4 + 0.02]5 \le 70\text{ mW}$$

$$|I_{D_1}| \le 9.9\text{ mA} \simeq 10\text{ mA}$$

Use max standby current to minimize distortion

$$|I_{D_{17}}| = \frac{|I_{D_1}|}{100} = 99\ \mu A \simeq 100\ \mu A \simeq I_{BIAS}$$

$$|I_{D_{13}}| = |I_{D_{14}}| = \frac{9.9\text{ mA}}{10} = 990\ \mu A \simeq 1\text{ mA}$$

$$I_{TAIL} = 5 I_{BIAS} = 500\ \mu A$$

$$I_{D_{27}} = \frac{I_{D_2}}{100} = 99\ \mu A \simeq 100\ \mu A = I_{BIAS_P}$$

$$I_{D_{23}} = I_{D_{24}} = \frac{9.9\text{ mA}}{10} = 990\ \mu A \simeq 1\text{ mA}$$

$$I_{TAIL_P} = 5 I_{BIAS_P} = 500\ \mu A$$

Gain Error $\le 1\%$

From (5.117), $\dfrac{1}{2A g_m R_L} \le 0.01$

To minimize distortion, use the maximum allowed error-amplifier gain = 5

$$g_{m_1} \ge \frac{1}{2AR_L(0.01)} = \frac{1}{2(5)(100)(0.01)}$$

$$= 0.1\ \frac{A}{V} = 100{,}000\ \frac{\mu A}{V}$$

$$g_{m_1} = \sqrt{2 K_P' \left(\frac{W}{L}\right)_1 |I_{D_1}|}$$

From Table (2.3),

$$C_{ox} = \frac{3.9 \times 8.86 \times 10^{-14}}{150 \times 10^{-8}} = 2.3 \times 10^{-7}\ \frac{F}{cm^2}$$

$$K_P' = 2.3 \times 10^{-7} \times 250\ \frac{cm^2}{V.s} = 58\ \mu A/V^2$$

$$\sqrt{2(58)\left(\frac{W}{L}\right)_1 (10000\ \mu A)} > 100{,}000$$

$$\left(\frac{W}{L}\right)_1 \ge 8620 \simeq 8700$$

$$\left(\frac{W}{L}\right)_{17} = \frac{(W/L)_1}{100} = 87$$

$$\left(\frac{W}{L}\right)_{13} = \left(\frac{W}{L}\right)_{14} = \frac{(W/L)_1}{10} = 870$$

similarly,

$$g_{m_2} = \sqrt{2 K_n' \left(\frac{W}{L}\right)_2 I_{D_2}}$$

$$K_n' = 2.3 \times 10^{-7} \times 550 \ \frac{cm^2}{V \cdot s} = 127 \ \mu A/V^2$$

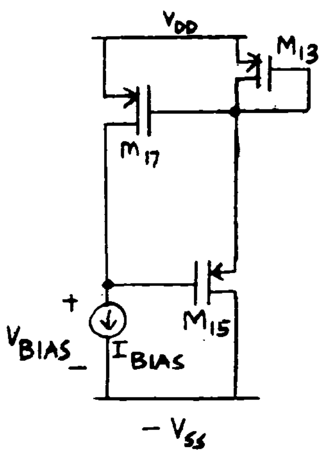
$$\sqrt{2(127)\left(W/L\right)_2 (10000 \mu A)} > 100{,}000$$

$$\left(\frac{W}{L}\right)_2 > 3940 \simeq 4000$$

$$\left(\frac{W}{L}\right)_{27} = \frac{(W/L)_2}{100} = 40$$

$$\left(\frac{W}{L}\right)_{23} = \left(\frac{W}{L}\right)_{24} = \frac{(W/L)_2}{10} = 400$$

Let V_{BIAS} = voltage across I_{BIAS}



$$V_{BIAS} = \underbrace{V_{DD} - (-V_{SS})}_{2.5-(-2.5)} - \underbrace{|V_{GS_{17}}|}_{\underbrace{|V_{t_{17}}|}_{0.7} + \underbrace{\sqrt{\frac{2 I_{BIAS}}{K_p (W/L)_{17}}}}_{\sqrt{\frac{2(100)}{58(87)}} = 0.2}} - |V_{GS_{15}}| \geq 0.5$$

$|V_{GS_{15}}|$ is max. when $|I_{D_{15}}|$ is max

That is when $I_{D_{12}} = 0$

So, $|I_{D15}|_{max} = |I_{D_{13}}| = 1 \ mA$

Note: this worst case condition may not occur in practice because M_{12} may not turn off completely

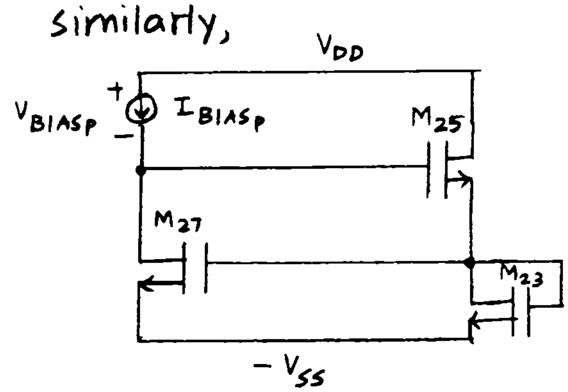
$$|V_{GS_{15}}|_{max} = \underbrace{|V_{t_{15}}|}_{0.7} + \underbrace{\sqrt{\frac{2 |I_{D_{15}}|_{max}}{K_p' \left(\frac{W}{L}\right)_{15}}}}_{\sqrt{\frac{2(1000)}{58 (W/L)_{15}}}}$$

$$5 - 0.7 - 0.2 - 0.7 - \sqrt{\frac{2(1000)}{58 (W/L)_{15}}} \geq 0.5 \ V$$

$$\sqrt{\frac{2(1000)}{58 (W/L)_{15}}} \leq 2.9 \ V$$

$$\left(W/L\right)_{15} \geq \frac{2(1000)}{58 (2.9)^2} = 4.1 \simeq 4$$

similarly,



$$V_{BIAS_P} = V_{DD} - \left[-V_{SS} + V_{GS_{27}} + V_{GS_{25}}\right] \geq 0.5 V$$

$$V_{ov_{27}} = \sqrt{\frac{2(100)}{127(40)}} = 0.2 V$$

$$V_{ov_{25(max.)}} = \sqrt{\frac{2(10) I_{BIAS}}{(W/L)_{25} 127}} \text{ when } |I_{D_{22}}| = 0$$

$$5 - 0.7 - 0.2 - 0.7 - \sqrt{\frac{2(1000)}{127 (W/L)_{25}}} \geq 0.5 V$$

$$\left(\frac{W}{L}\right)_{25} > \frac{2(1000)}{127(2.9)^2} = 1.9 \simeq 2$$

Error amplifier gain

From (5.141) for the top amp

$$A = \frac{g_{m11}}{g_{m16}} \quad \text{(ignore body effect)}$$

$$A = 5 = \sqrt{\frac{2\,(I_{TAIL}/2)\,k_n'\,(W/L)_{11}}{2\,(|I_{D14}| - I_{TAIL}/2)\,k_p'\,(\frac{W}{L})_{16}}}$$

$$= \sqrt{\frac{250(127)\,(W/L)_{11}}{750\,(58)\,(W/L)_{16}}} = \sqrt{\frac{0.73\,(W/L)_{11}}{(W/L)_{16}}}$$

But, $(W/L)_{16} = (W/L)_{15} = 4$

$$\text{So, } (W/L)_{11} = \frac{A^2 (W/L)_{16}}{0.73} = \frac{25(4)}{0.73} = 137 \simeq 140$$

Similarly, for the bottom amp,

$$A = \frac{g_{m21}}{g_{m26}}$$

$$A = 5 = \sqrt{\frac{2\,(I_{TAILP}/2)\,k_p'\,(W/L)_{21}}{2\,(I_{D24} - I_{TAILP}/2)\,k_n'\,(\frac{W}{L})_{26}}}$$

$$= \sqrt{\frac{(250)(57)\,(W/L)_{21}}{(750)(127)\,(W/L)_{26}}} = \sqrt{\frac{0.15\,(W/L)_{21}}{(W/L)_{26}}}$$

But, $(W/L)_{26} = (W/L)_{25} = 2$

$$\text{So, } (W/L)_{21} = \frac{A^2 (W/L)_{26}}{0.15} = \frac{25(2)}{0.15} = 333 \simeq 3$$

```
CMOS CLASS A/B OUTPUT STAGE
******
VDD       100       0   2.5
VSS       200       0   -2.5
M1     2    14   100 100 CMOSP L=1U   W=8700U
M11    14   1    18  18  CMOSN L=1U   W=140U
M12    13   2    18  18  CMOSN L=1U   W=140U
M13    13   13   100 100 CMOSP L=1U   W=870U
M14    14   13   100 100 CMOSP L=1U   W=870U
M15    200  17   13  13  CMOSP L=1U   W=4U
M16    200  17   14  14  CMOSP L=1U   W=4U
M17    17   13   100 100 CMOSP L=1U   W=87U

M2     2    24   200 200 CMOSN L=1U   W=4000U
M21    24   1    28  28  CMOSP L=1U   W=330U
M22    23   2    28  28  CMOSP L=1U   W=330U
M23    23   23   200 200 CMOSN L=1U   W=400U
M24    24   23   200 200 CMOSN L=1U   W=400U
M25    100  27   23  23  CMOSN L=1U   W=2U
M26    100  27   24  24  CMOSN L=1U   W=2U
M27    27   23   200 200 CMOSN L=1U   W=40U

.MODEL CMOSN NMOS LEVEL=1 LAMBDA=0M VTO=0.7  KP=127U
.MODEL CMOSP PMOS LEVEL=1 LAMBDA=0M VTO=-0.7 KP=58U

IBIASN   17        200 99U
IBIASP   100       27  99U

ITAILN   18        200 495U
ITAILP   100       28  495U

VIN      1         0 0   AC 1

RLOAD    2         0 100

.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.DC VIN -2.5 2.5 0.1
.PLOT DC V(2)

* PRINT VOLTAGES ACROSS IDEAL CURRENT SOURCES
.PRINT V(17, 200) V(18, 200) V(100, 27) V(100, 28)

.TF V(2) VIN
.AC DEC 1 1 10
.PRINT AC VM(2, 1) VM(2) VM(1)
.END
```

```
******  DC TRANSFER CURVES        TNOM=  27.000 TEMP=  27.000
       VOLT        V(2)
(A        )      -4.000E+00    -2.000E+00        0.          2.000E+00     4.000E+00
                     +             +             +             +             +
-2.500E+00 -2.28E+00-+------+----A-+------+------+------+------+------+------+-
-2.400E+00 -2.27E+00 +      +    A +      +      +      +      +      +      +
-2.300E+00 -2.25E+00 +      +    A +      +      +      +      +      +      +
-2.200E+00 -2.17E+00 +      +     A+      +      +      +      +      +      +
-2.100E+00 -2.07E+00 +      +     A+      +      +      +      +      +      +
-2.000E+00 -1.98E+00 +      +      A      +      +      +      +      +      +
-1.900E+00 -1.88E+00 +      +      +A     +      +      +      +      +      +
-1.800E+00 -1.78E+00 +      +      + A    +      +      +      +      +      +
-1.700E+00 -1.68E+00 +      +      + A    +      +      +      +      +      +
-1.600E+00 -1.58E+00 +      +      +  A   +      +      +      +      +      +
-1.500E+00 -1.48E+00-+------+------+---A--+------+------+------+------+------+-
-1.400E+00 -1.38E+00 +      +      +   A  +      +      +      +      +      +
-1.300E+00 -1.28E+00 +      +      +    A +      +      +      +      +      +
-1.200E+00 -1.18E+00 +      +      +     A+      +      +      +      +      +
-1.100E+00 -1.08E+00 +      +      +     A+      +      +      +      +      +
-1.000E+00 -9.90E-01 +      +      +      A      +      +      +      +      +
-9.000E-01 -8.91E-01 +      +      +      +A     +      +      +      +      +
-8.000E-01 -7.92E-01 +      +      +      +A     +      +      +      +      +
-7.000E-01 -6.93E-01 +      +      +      + A    +      +      +      +      +
-6.000E-01 -5.94E-01 +      +      +      +  A   +      +      +      +      +
-5.000E-01 -4.95E-01-+------+------+------+---A--+------+------+------+------+-
-4.000E-01 -3.96E-01 +      +      +      +   A  +      +      +      +      +
-3.000E-01 -2.97E-01 +      +      +      +    A +      +      +      +      +
-2.000E-01 -1.98E-01 +      +      +      +     A+      +      +      +      +
-1.000E-01 -9.90E-02 +      +      +      +     A+      +      +      +      +
  0.        0.       +      +      +      +      A      +      +      +      +
 1.000E-01  9.90E-02 +      +      +      +      +A     +      +      +      +
 2.000E-01  1.98E-01 +      +      +      +      +A     +      +      +      +
 3.000E-01  2.97E-01 +      +      +      +      + A    +      +      +      +
 4.000E-01  3.96E-01 +      +      +      +      +  A   +      +      +      +
 5.000E-01  4.95E-01-+------+------+------+------+--A---+------+------+------+-
 6.000E-01  5.94E-01 +      +      +      +      +   A  +      +      +      +
 7.000E-01  6.93E-01 +      +      +      +      +    A +      +      +      +
 8.000E-01  7.92E-01 +      +      +      +      +     A+      +      +      +
 9.000E-01  8.91E-01 +      +      +      +      +     A+      +      +      +
 1.000E+00  9.90E-01 +      +      +      +      +      A      +      +      +
 1.100E+00  1.08E+00 +      +      +      +      +      +A     +      +      +
 1.200E+00  1.18E+00 +      +      +      +      +      +A     +      +      +
 1.300E+00  1.28E+00 +      +      +      +      +      + A    +      +      +
 1.400E+00  1.38E+00 +      +      +      +      +      +  A   +      +      +
 1.500E+00  1.48E+00-+------+------+------+------+------+--A---+------+------+-
 1.600E+00  1.58E+00 +      +      +      +      +      +   A  +      +      +
 1.700E+00  1.68E+00 +      +      +      +      +      +    A +      +      +
 1.800E+00  1.78E+00 +      +      +      +      +      +    A +      +      +
 1.900E+00  1.88E+00 +      +      +      +      +      +     A+      +      +
 2.000E+00  1.98E+00 +      +      +      +      +      +      A      +      +
 2.100E+00  2.07E+00 +      +      +      +      +      +      +A     +      +
 2.200E+00  2.17E+00 +      +      +      +      +      +      +A     +      +
 2.300E+00  2.25E+00 +      +      +      +      +      +      + A    +      +
 2.400E+00  2.27E+00 +      +      +      +      +      +      + A    +      +
 2.500E+00  2.28E+00-+------+------+------+------+------+------+-A----+------+-
                     +             +             +             +             +
```

VOLT	VOLTAGE	VOLTAGE	VOLTAGE	VOLTAGE
	17	18	100	100
	200	200	27	28
-2.5000E+00	1.327E+00	-7.218E-01	9.252E-01	3.938E+00
-2.4000E+00	1.181E+00	-6.929E-01	9.280E-01	3.927E+00
-2.3000E+00	9.983E-01	-6.404E-01	9.327E-01	3.900E+00
-2.2000E+00	9.274E-01	-5.556E-01	9.311E-01	3.828E+00
-2.1000E+00	9.247E-01	-4.562E-01	9.334E-01	3.729E+00
-2.0000E+00	9.221E-01	-3.567E-01	9.358E-01	3.629E+00
-1.9000E+00	9.196E-01	-2.572E-01	9.383E-01	3.530E+00
-1.8000E+00	9.171E-01	-1.578E-01	9.407E-01	3.430E+00
-1.7000E+00	9.145E-01	-5.827E-02	9.431E-01	3.331E+00
-1.6000E+00	9.120E-01	4.121E-02	9.455E-01	3.231E+00
-1.5000E+00	9.095E-01	1.407E-01	9.480E-01	3.132E+00
-1.4000E+00	9.070E-01	2.402E-01	9.504E-01	3.032E+00
-1.3000E+00	9.044E-01	3.397E-01	9.528E-01	2.932E+00
-1.2000E+00	9.019E-01	4.392E-01	9.552E-01	2.833E+00
-1.1000E+00	8.994E-01	5.386E-01	9.577E-01	2.733E+00
-1.0000E+00	8.969E-01	6.381E-01	9.601E-01	2.634E+00
-9.0000E-01	8.944E-01	7.376E-01	9.626E-01	2.534E+00
-8.0000E-01	8.919E-01	8.371E-01	9.650E-01	2.435E+00
-7.0000E-01	8.894E-01	9.366E-01	9.675E-01	2.335E+00
-6.0000E-01	8.869E-01	1.036E+00	9.699E-01	2.236E+00
-5.0000E-01	8.844E-01	1.135E+00	9.723E-01	2.136E+00
-4.0000E-01	8.819E-01	1.235E+00	9.748E-01	2.037E+00
-3.0000E-01	8.794E-01	1.334E+00	9.773E-01	1.937E+00
-2.0000E-01	8.769E-01	1.434E+00	9.797E-01	1.838E+00
-1.0000E-01	8.744E-01	1.533E+00	9.822E-01	1.738E+00
0.	8.719E-01	1.633E+00	9.846E-01	1.639E+00
1.0000E-01	8.694E-01	1.732E+00	9.871E-01	1.539E+00
2.0000E-01	8.670E-01	1.832E+00	9.896E-01	1.440E+00
3.0000E-01	8.645E-01	1.931E+00	9.920E-01	1.340E+00
4.0000E-01	8.620E-01	2.031E+00	9.945E-01	1.241E+00
5.0000E-01	8.595E-01	2.130E+00	9.970E-01	1.141E+00
6.0000E-01	8.571E-01	2.230E+00	9.994E-01	1.042E+00
7.0000E-01	8.546E-01	2.329E+00	1.001E+00	9.427E-01
8.0000E-01	8.521E-01	2.429E+00	1.004E+00	8.432E-01
9.0000E-01	8.497E-01	2.528E+00	1.006E+00	7.437E-01
1.0000E+00	8.472E-01	2.628E+00	1.009E+00	6.442E-01
1.1000E+00	8.448E-01	2.727E+00	1.011E+00	5.447E-01
1.2000E+00	8.423E-01	2.827E+00	1.014E+00	4.452E-01
1.3000E+00	8.399E-01	2.926E+00	1.016E+00	3.457E-01
1.4000E+00	8.374E-01	3.026E+00	1.019E+00	2.462E-01
1.5000E+00	8.350E-01	3.125E+00	1.021E+00	1.467E-01
1.6000E+00	8.325E-01	3.225E+00	1.024E+00	4.723E-02
1.7000E+00	8.301E-01	3.325E+00	1.026E+00	-5.225E-02
1.8000E+00	8.277E-01	3.424E+00	1.029E+00	-1.517E-01
1.9000E+00	8.252E-01	3.524E+00	1.031E+00	-2.512E-01
2.0000E+00	8.228E-01	3.623E+00	1.034E+00	-3.507E-01
2.1000E+00	8.204E-01	3.723E+00	1.036E+00	-4.502E-01
2.2000E+00	8.180E-01	3.822E+00	1.039E+00	-5.496E-01
2.3000E+00	8.197E-01	3.894E+00	1.109E+00	-6.344E-01
2.4000E+00	8.147E-01	3.921E+00	1.288E+00	-6.870E-01
2.5000E+00	8.118E-01	3.933E+00	1.424E+00	-7.150E-01

**** OPERATING POINT INFORMATION TNOM= 27.000 TEMP= 27.000

NODE	=VOLTAGE	NODE	=VOLTAGE	NODE	=VOLTAGE
+0:1	= 0.	0:2	=-1.697E-08	0:13	= 1.601E+00
+0:14	= 1.601E+00	0:17	=-1.628E+00	0:18	=-8.669E-01
+0:23	=-1.602E+00	0:24	=-1.602E+00	0:27	= 1.515E+00
+0:28	= 8.608E-01	0:100	= 2.500E+00	0:200	=-2.500E+00

**** MOSFETS

SUBCKT

ELEMENT	0:M1	0:M11	0:M12	0:M13
MODEL	0:CMOSP	0:CMOSN	0:CMOSN	0:CMOSP
ID	-9.900E-03	2.475E-04	2.475E-04	-9.900E-04
IBS	0.	0.	0.	0.
IBD	2.500E-14	-2.469E-14	-2.469E-14	8.981E-15
VGS	-8.981E-01	8.669E-01	8.669E-01	-8.981E-01
VDS	-2.500E+00	2.468E+00	2.468E+00	-8.981E-01
VBS	0.	0.	0.	0.
VTH	-7.000E-01	7.000E-01	7.000E-01	-7.000E-01
VDSAT	-1.981E-01	1.669E-01	1.669E-01	-1.981E-01
BETA	5.046E-01	1.778E-02	1.778E-02	5.046E-02
GAM EFF	0.	0.	0.	0.
GM	9.996E-02	2.967E-03	2.967E-03	9.996E-03
GDS	0.	0.	0.	0.
GMB	0.	0.	0.	0.

SUBCKT

ELEMENT	0:M14	0:M15	0:M16	0:M17
MODEL	0:CMOSP	0:CMOSP	0:CMOSP	0:CMOSP
ID	-9.900E-04	-7.425E-04	-7.425E-04	-9.900E-05
IBS	0.	0.	0.	0.
IBD	8.981E-15	4.102E-14	4.102E-14	4.128E-14
VGS	-8.981E-01	-3.230E+00	-3.230E+00	-8.981E-01
VDS	-8.981E-01	-4.101E+00	-4.101E+00	-4.128E+00
VBS	0.	0.	0.	0.
VTH	-7.000E-01	-7.000E-01	-7.000E-01	-7.000E-01
VDSAT	-1.981E-01	-2.530E+00	-2.530E+00	-1.981E-01
BETA	5.046E-02	2.320E-04	2.320E-04	5.046E-03
GAM EFF	0.	0.	0.	0.
GM	9.996E-03	5.870E-04	5.870E-04	9.996E-04
GDS	0.	0.	0.	0.
GMB	0.	0.	0.	0.

SUBCKT

ELEMENT	0:M2	0:M21	0:M22	0:M23
MODEL	0:CMOSN	0:CMOSP	0:CMOSP	0:CMOSN
ID	9.900E-03	-2.475E-04	-2.475E-04	9.900E-04
IBS	0.	0.	0.	0.
IBD	-2.500E-14	2.463E-14	2.463E-14	-8.974E-15
VGS	8.974E-01	-8.608E-01	-8.608E-01	8.974E-01
VDS	2.500E+00	-2.463E+00	-2.463E+00	8.974E-01
VBS	0.	0.	0.	0.
VTH	7.000E-01	-7.000E-01	-7.000E-01	7.000E-01
VDSAT	1.974E-01	-1.608E-01	-1.608E-01	1.974E-01
BETA	5.080E-01	1.914E-02	1.914E-02	5.080E-02
GAM EFF	0.	0.	0.	0.
GM	1.003E-01	3.078E-03	3.078E-03	1.003E-02
GDS	0.	0.	0.	0.
GMB	0.	0.	0.	0.

SUBCKT

ELEMENT	0:M24	0:M25	0:M26	0:M27
MODEL	0:CMOSN	0:CMOSN	0:CMOSN	0:CMOSN
ID	9.900E-04	7.425E-04	7.425E-04	9.900E-05
IBS	0.	0.	0.	0.
IBD	-8.974E-15	-4.103E-14	-4.103E-14	-4.015E-14
VGS	8.974E-01	3.117E+00	3.117E+00	8.974E-01
VDS	8.974E-01	4.102E+00	4.102E+00	4.015E+00
VBS	0.	0.	0.	0.
VTH	7.000E-01	7.000E-01	7.000E-01	7.000E-01
VDSAT	1.974E-01	2.417E+00	2.417E+00	1.974E-01
BETA	5.080E-02	2.540E-04	2.540E-04	5.080E-03
GAM EFF	0.	0.	0.	0.
GM	1.003E-02	6.142E-04	6.142E-04	1.003E-03
GDS	0.	0.	0.	0.
GMB	0.	0.	0.	0.

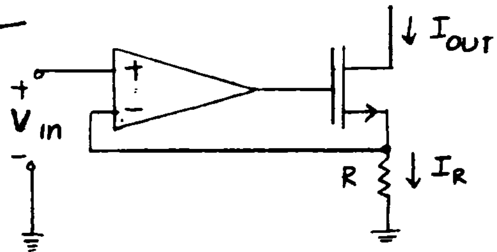
**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(2)/VIN		= 9.902E-01
INPUT RESISTANCE AT	VIN	= 1.000E+20
OUTPUT RESISTANCE AT V(2)		= 9.825E-01

****** AC ANALYSIS TNOM= 27.000 TEMP= 27.000

FREQ	VOLTAGE M	VOLTAGE M	VOLTAGE M
	2	2	1
	1		
1.0000E+00	9.825E-03	9.902E-01	1.000E+00
1.0000E+01	9.825E-03	9.902E-01	1.000E+00

6.1

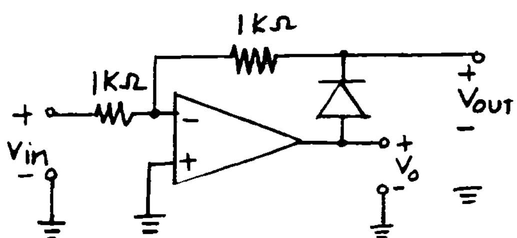


For ideal opamp,

$$I_R = \frac{V_{in}}{R} = I_{OUT}$$

$$\Rightarrow \quad I_{OUT} = \frac{V_{in}}{R}$$

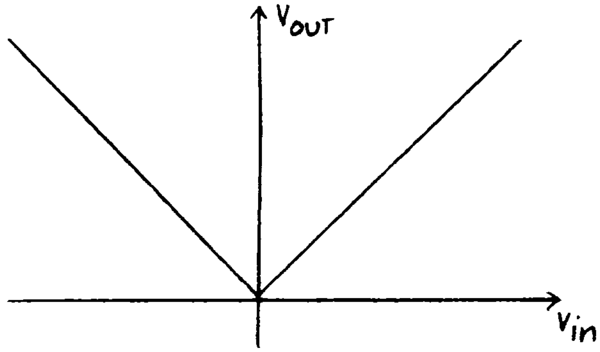
6.2



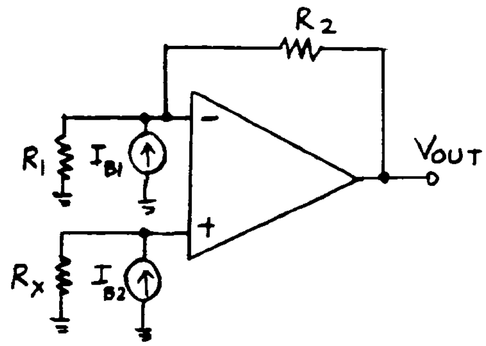
For V_{in} positive, V_o is negative, diode is reverse biased and

$V_{OUT} = V_{in}$

For V_{in} negative, V_o is positive, After the diode turns on, we have $V_{OUT} = -V_{in}$



6.3



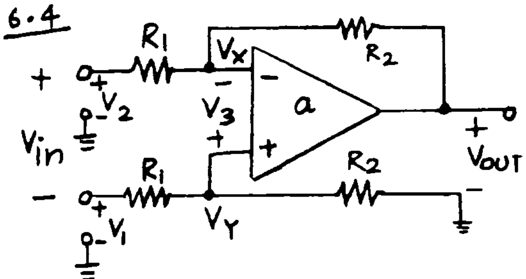
$$V_{OUT} \cong -R_2 I_{B1} + \frac{R_2 + R_1}{R_1} I_{B2} R_X$$

If $I_{B1} = I_{B2}$, then $V_{OUT} = 0$, when

$$R_2 = \frac{R_2 + R_1}{R_1} R_X$$

$$\therefore \; R_X = \frac{R_1 R_2}{R_1 + R_2} = R_1 \parallel R_2$$

6.4



$$V_3 = \frac{V_{OUT}}{a}, \quad V_Y = \frac{R_2}{R_1 + R_2} V_1$$

$$V_X = V_Y - V_3 = \frac{R_2}{R_1 + R_2} V_1 - \frac{V_{OUT}}{a} \rightarrow (1)$$

$$\frac{V_2 - V_X}{R_1} = \frac{V_X - V_{OUT}}{R_2} \longrightarrow (2)$$

Eliminating V_X from (1) & (2),

$$A_v = \frac{V_{OUT}}{V_2 - V_1} = \frac{V_{OUT}}{V_{in}}$$

$$= \frac{-R_2/R_1}{1 + \frac{1}{a}\left(1 + \frac{R_2}{R_1}\right)} \longrightarrow (3)$$

Require, $A_v \geq 999$ when a change -50%. From ③ the new gain value after a change is,

$$A_v' = \frac{-R_2/R_1}{1 + \frac{(1+R_2/R_1)}{\frac{1}{2}a}}$$

$$\approx -\frac{R_2}{R_1}\left[1 - \frac{2}{a}\left(1+\frac{R_2}{R_1}\right)\right]$$

change from nominal is,

$$A_v' - A_v = \Delta A_v = \frac{1}{a}\left(1+\frac{R_2}{R_1}\right)\frac{R_2}{R_1}$$

for $\frac{R_2}{R_1} \simeq 1000$, we require

$\Delta A_v \leq 1 \quad \therefore \; a \geq 10^6$

6.5

$$CMRR = \left(\frac{\Delta V_{os}}{\Delta V_{ic}}\right)^{-1}$$

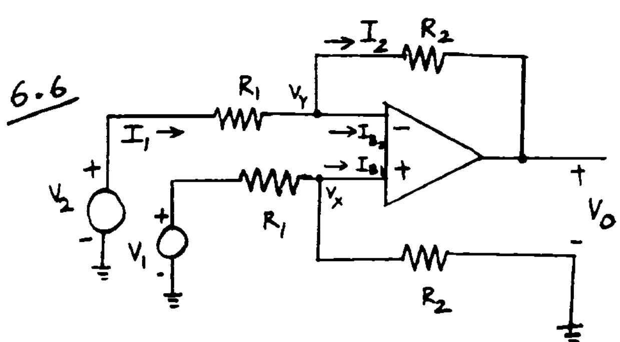
(from (6.48))

For $\Delta V_{ic} = 10V - (-10V) = 20V$,

we require $\Delta V_{os} \leq 1$ mV

$$\therefore \; CMRR \geq \left[\frac{10^{-3}}{20}\right] = 86 \text{ dB}$$

6.6



With $V_1 = V_2 = 0$

① $V_x = -I_{B1}(R_1 \| R_2) = V_Y$ (virtual null)

② $I_1 = \frac{0 - V_Y}{R_1} = I_{B2} + I_2$

$$\Rightarrow I_2 = -\frac{V_Y}{R_1} - I_{B2}.$$

③ $V_o = V_Y - I_2 R_2$

$$= V_x + \left(\frac{V_Y}{R_1} + I_{B2}\right)R_2$$

$$= V_x\left(1 + \frac{R_2}{R_1}\right) + I_{B2}R_2$$

$$= -I_{B1}\frac{R_1R_2}{R_1+R_2}\left(\frac{R_1+R_2}{R_1}\right) + I_{B2}R_2$$

$$= (I_{B2} - I_{B1})R_2 = -I_{os}R_2$$

$|I_{os}| = 100$ nA

$V_o = (100 \text{ nA})R_2 \leq 10$ mV

$$R_2 \leq \frac{10 \text{ mV}}{100 \text{ nA}} = 100 \text{ k}\Omega$$

Also, gain $= -\frac{R_2}{R_1} = -10$

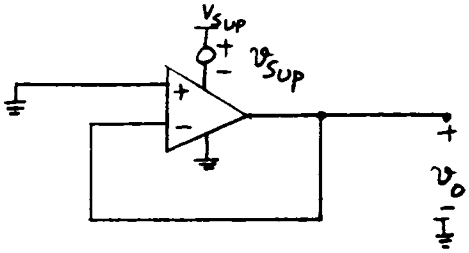
$$R_1 = \frac{R_2}{10} \leq 10 \text{ k}\Omega$$

One solution:

$R_1 = 10 \text{ k}\Omega \quad R_2 = 100 \text{ k}\Omega$

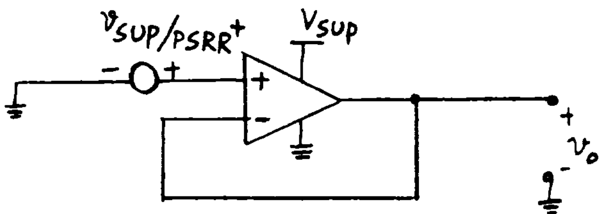
6.7

original connection :



$v_o = A^+ v_{sup}$

The same output can be obtained in the following configuration



From (6.51), $PSRR^+ = \frac{A_{dm}}{A^+}$

$$v_o = \frac{v_{sup}}{PSRR^+} A_{dm}$$

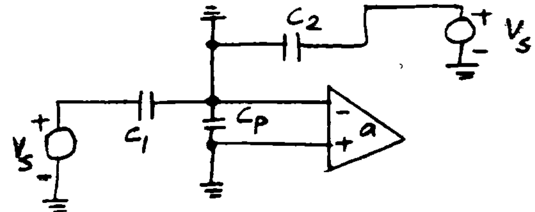
In the voltage follower configuration, $A_{dm} = 1$.

So, $v_o = \frac{v_{sup}}{PSRR^+} (1)$

Therefore, peak output $= \frac{v_{sup}}{PSRR^+} = \frac{20}{10}$ mV

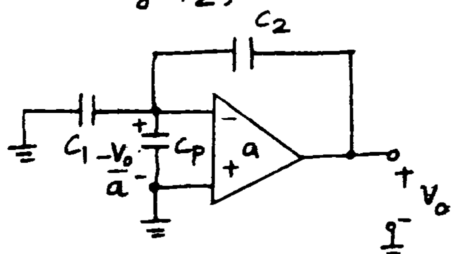
$= 2$ mV

During Φ_1,



$$Q_1 = V_s C_1 + V_s C_2$$

During Φ_2,



$$Q_2 = \left(0 + \frac{V_o}{a}\right) C_1 + \left(0 + \frac{V_o}{a}\right) C_p + \left(V_o + \frac{V_o}{a}\right) C_2$$

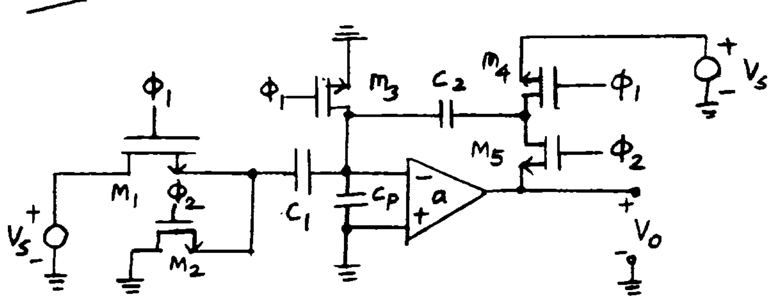
From charge conservation,

$Q_1 = Q_2$

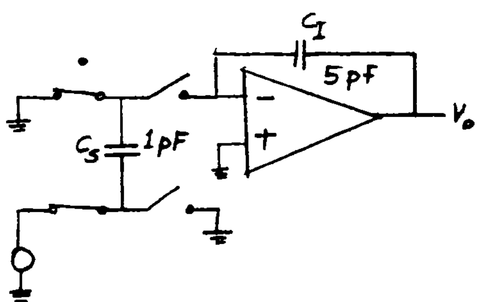
$$V_s (C_1 + C_2) = V_o \left(\frac{C_1}{a} + \frac{C_p}{a} + C_2 + \frac{C_2}{a} \right)$$

$$V_o = \frac{V_s (C_1 + C_2)}{C_2 + \frac{C_1 + C_p + C_2}{a}}$$

6.8



6.9



Each cycle on C_S

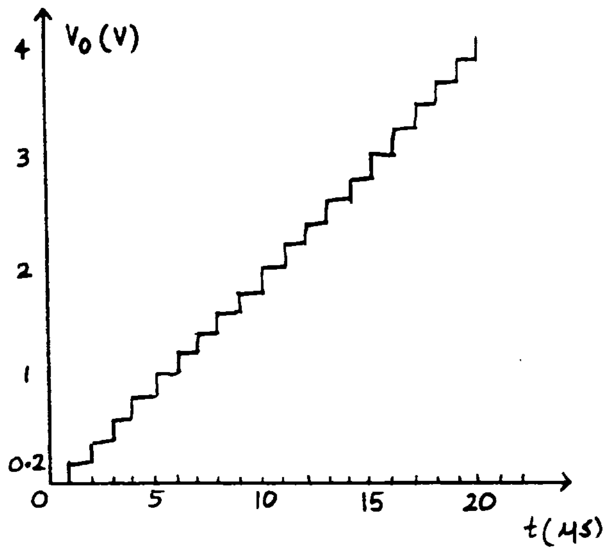
$Q = C_S V_S = 1\text{pF}(1\text{V}) = 1\text{pC}$

transfer to C_I

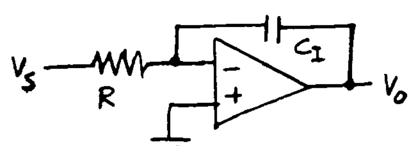
$Q = C_I V_o$

$1\text{pC} = 5\text{pF}\, V_o$

$0.2\text{ V} = V_o$ (per step)



(b) continuous time

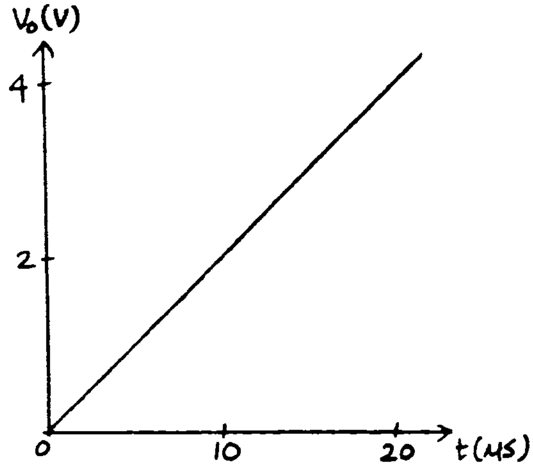


$R = \dfrac{1}{f C_S}$

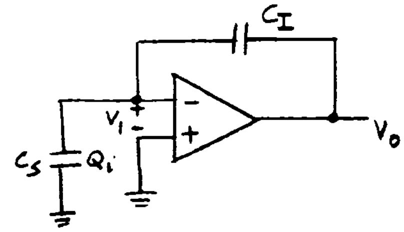
$$\frac{V_o}{V_S} = \frac{1}{R C_I s} = \frac{C_S}{C_I}\,\frac{f}{s}$$

$$V_o = f\,\frac{C_S}{C_I}\int V_S\,dt$$

$$= 10^6\,\frac{1}{5}\int 1\,dt$$



(c) finite gain



Initial charge on C_S capacitor

$Q_i = C_S V_S = 1\text{ pC}$

discharge C_S into C_I

$$\frac{V_o}{V_1} = -1000$$

final charge on $C_S = -V_1 C_S$

final charge on $C_I = (V_o - V_1) C_I$

charge conservation

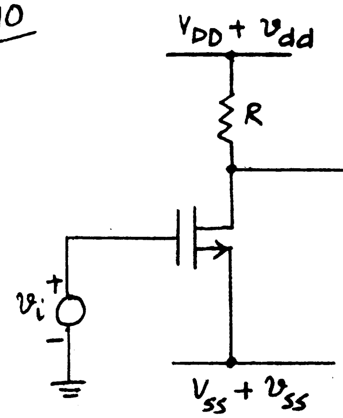
$(V_o - V_1) C_I - V_1 C_S = C_S (1\text{V})$

$$V_o + \frac{V_o}{1000} + \frac{V_o}{1000}(0.2) = 0.2$$

$$V_o = \frac{0.2\text{ V}}{1 + \frac{1.2}{1000}} \text{ per step}$$

↑ error term

6.10



$$\frac{v_o}{v_i} = -g_m (R \| r_o)$$

$$\frac{v_o}{v_{dd}} = \frac{r_o}{R + r_o}$$

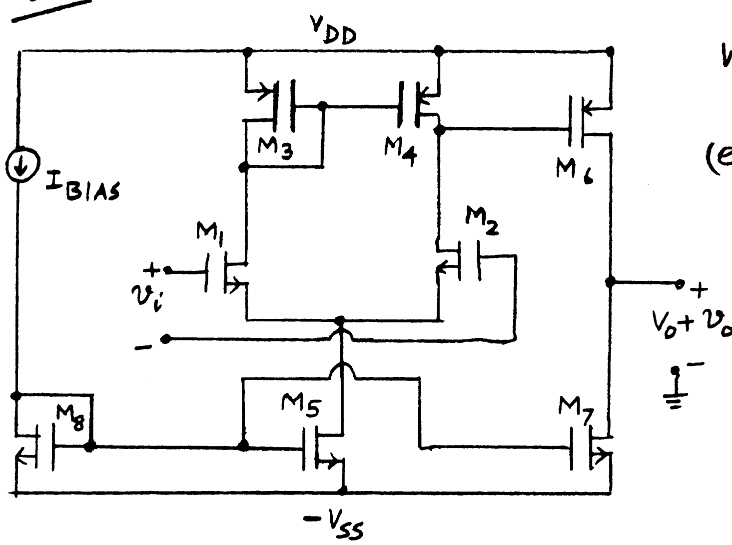
From (6.51), $PSRR^+ = \dfrac{\dfrac{r_o}{R+r_o}}{-g_m \dfrac{R r_o}{R + r_o}} = \dfrac{-1}{g_m R}$

$$\frac{v_o}{v_{ss}} = \left(g_m + \frac{1}{r_o}\right)(R \| r_o)$$

From (6.51), $PSRR^- = \dfrac{\left(g_m + \frac{1}{r_o}\right)(R \| r_o)}{-g_m (R \| r_o)}$

$$PSRR^- = -\left(1 + \frac{1}{g_m r_o}\right)$$

6.11



(a) $A_v = \dfrac{v_o}{v_i} = -g_{m_1}(r_{o2} \| r_{o4})\, g_{m_6}(r_{o6} \| r_{o7})$

same as (6.56)

$$A_v = \frac{-2}{V_{ov_1}} \frac{2}{|V_{ov_6}|} \left(\frac{V_{A2}|V_{A4}|}{V_{A2} + |V_{A4}|}\right)\left(\frac{|V_{A6}|\, V_{A7}}{|V_{A6}| + V_{A7}}\right)$$

(b) output swing

$$V_{ov_7} - V_{SS} \le V_o \le V_{DD} - |V_{ov_6}|$$

(c) If (6.66) is satisfied,

$$V_o = V_{DD} - V_{SD_6}$$
$$= V_{DD} - V_{SG_3}$$
$$= V_{DD} + V_{t_3} + V_{ov_3}$$

Note $V_{ov_3} < 0$,

Also $V_{t_3} < 0$ for enhancement mode

$$V_{os(sys)} = \frac{V_{DD} + V_{t_3} + V_{ov_3} - \frac{V_{DD} - V_{SS}}{2}}{A_v}$$

(d) CMRR

From (6.71),

$$CMRR \simeq (2 g_{m_1} r_{tail})\, g_{m_3}(r_{o2} \| r_{o4})$$

Where $r_{tail} = r_{o5}$

(e) CM Input range

To keep M_5 in active region,

$$V_{IC} > V_{ov_5} + V_{t_1} + V_{ov_1} - V_{SS}$$

To keep M_1 in active region,

$$V_{GD_1} < V_{t_1}$$

$$V_{IC} - (V_{DD} + V_{t_3} + V_{ov_3}) < V_{t_1}$$

$V_{IC} < V_{DD} + V_{t_3} + V_{t_1} + V_{ov_3}$

Note $V_{ov_3} < 0$

Also $V_{t_3} < 0$ for enhancement mode. So, the CM input range is,

$$V_{ov_5} + V_{t_1} + V_{ov_1} - V_{SS} < V_{IC} < V_{DD} + V_{t_3} + V_{t_1} + V_{ov_3}$$

(f) From an argument similar to that leading to (6.86),

$A^- \simeq 0.$

So, $PSRR^- \to \infty$ for low frequencies with perfect matching.

Also,

$$A^+ = \frac{v_o}{v_{dd}} = \frac{r_{o7}}{r_{o6} + r_{o7}} = \frac{V_{A_7}}{|V_{A_6}| + V_{A_7}}$$

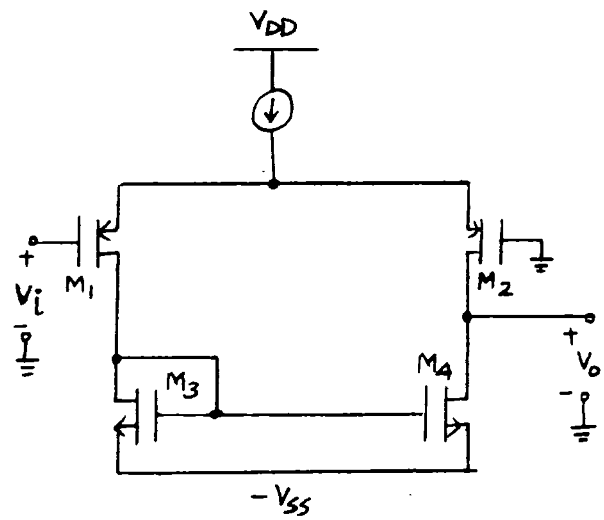
Then $PSRR^+ = \dfrac{A_{dm}}{A^+}$

$$= \frac{\frac{-2}{V_{ov_1}} \frac{2}{|V_{ov_6}|} \left(\frac{V_{A_2} |V_{A_4}|}{V_{A_2} + |V_{A_4}|} \right) \left(\frac{|V_{A_6}| V_{A_7}}{|V_{A_6}| + V_{A_7}} \right)}{\frac{V_{A_7}}{|V_{A_6}| + V_{A_7}}}$$

$$= \frac{-2}{V_{ov_1}} \frac{2}{|V_{ov_6}|} \left(\frac{V_{A_2} |V_{A_4}|}{V_{A_2} + |V_{A_4}|} \right) |V_{A_6}|$$

6.12

(a) For simplicity, replace M_5 in Fig (6.16) with an ideal current source. Although this change makes the common mode gain of the op amp zero, this change does not affect the characteristics of the circuit for differential mode inputs



In the circuit above, the gate of M_2 is grounded and the input is applied to only the gate of M_1. The resulting differential-mode input is the same as in Fig 6.16. The common mode input above may differ from that in Fig 6.16. Infact the common mode input in Fig 6.16 is not specified. However, the effect of a common mode input in Fig 6.16 is small as long as M_5 operates as a current source.

Also, a common-mode input in the drawing above has no effect on the output as long as all the transistors operate in the active region.

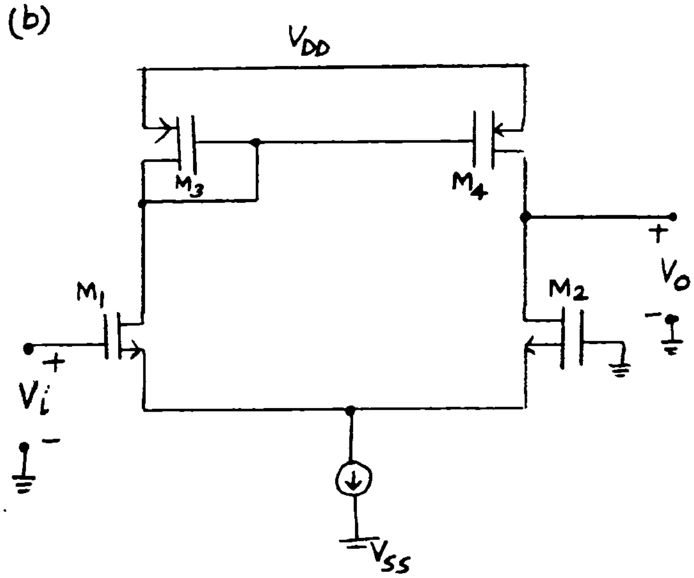
The first term in (6.69) predicts that if the only mismatch is $V_{t_1} > V_{t_2}$, $V_{OS} > 0$. Assume at first $V_{t_1} = V_{t_2}$. Then allow V_{t_1} to increase while $V_i = 0$. Since M_1 is a p-channel device, increasing V_{t_1} increases I_{D_3}, which decreases V_o. Since the gain from V_i to V_o is positive, V_i must be increased to increase V_o so that $V_{DS_4} = V_{DS_3}$. Therefore, $V_{OS} > 0$ in this case.

The second term in (6.69) predicts that if $V_{t_3} > V_{t_4}$, $V_{OS} > 0$ Assume at first $V_{t_3} = V_{t_4}$. Then allow V_{t_3} to increase while $V_i = 0$. Since $V_{GS_4} = V_{GS_3} = V_{t_3} + V_{ov_3}$, increasing V_{t_3} increases V_{GS_4}, which decreases V_o. Since the gain from V_i to V_o is positive, V_i must be increased to increase V_o so that $V_{DS_4} = V_{DS_3}$. Therefore, $V_{OS} > 0$ in this case.

The third term in (6.69) predicts that if $\left(\frac{W}{L}\right)_3 > \left(\frac{W}{L}\right)_4$, $V_{OS} < 0$ because $V_{ov(1-2)} < 0$ for p-channel input devices. Assume at first that $\left(\frac{W}{L}\right)_3 = \left(\frac{W}{L}\right)_4$. Then allow $\left(\frac{W}{L}\right)_3$ to increase when $V_i = 0$. This change decreases V_{ov_3}, which in turn decreases V_{GS_4} because $V_{GS_4} = V_{GS_3} = V_{t_3} + V_{ov_3}$. As a result, V_o increases when $\left(\frac{W}{L}\right)_3$ increases, and V_i must be decreased to decrease V_o. Therefore, $V_{OS} < 0$ in this case.

The last term in (6.69) predicts that if $\left(\frac{W}{L}\right)_1 > \left(\frac{W}{L}\right)_2$, $V_{OS} > 0$ because $V_{ov(1-2)} < 0$ for p-channel input devices. Assume at first that $\left(\frac{W}{L}\right)_1 = \left(\frac{W}{L}\right)_2$. Then allow $\left(\frac{W}{L}\right)_1$ to increase while $V_i = 0$. This change increases I_{D3} and decreases V_o. As a result, V_i must be increased to increase V_o. Therefore $V_{OS} > 0$ in this case.

(b)



<u>First term</u> : Increasing V_{t_1} while $V_i = 0$ decreases I_{D_1}, which decreases V_o. So V_i must be increased to increase V_o and force $V_{DS_3} = V_{DS_4}$. Therefore, $V_{OS} > 0$ in this case.

<u>Second term</u> : Increasing V_{t_3} while $V_i = 0$ decreases V_{SG_4} because $V_{SG_4} = V_{SG_3} = -V_{t_3} - V_{ov_3}$. So, this change decreases V_o. Therefore, V_i must be increased to increase V_o, and $V_{OS} > 0$ in this case.

<u>Third term</u> : Increasing $(W/L)_3$ while $V_i = 0$ decreases $|V_{ov_3}|$, decreasing V_{SG_4} and V_o. Therefore, V_i must be increased to increase V_o, and $V_{OS} > 0$ in this case.

<u>Last term</u> : Increasing $(W/L)_1$ while $V_i = 0$ increases I_{D_1}, in turn decreasing I_{D_2} because the tail current is constant. As a result V_o increases. Therefore, V_i must be decreased to decrease V_o, and $V_{OS} < 0$ in this case.

In practice, the polarity of the mismatches is not usually known. The main value of this problem is in developing a physical insight about the behaviour of a differential pair with a current mirror load.

6.13 From (6.69),

$$V_{os} = \Delta V_{t(3\text{-}4)} \frac{g_{m_3}}{g_{m_1}}$$

From (1.180) with $\left(\frac{W}{L}\right)_3 = \left(\frac{W}{L}\right)_1$ and $|I_{D_1}| = |I_{D_3}|$,

$$\frac{g_{m_3}}{g_{m_1}} = \sqrt{\frac{\mu_3}{\mu_1}}$$

μ_3 = mobility of M_3
μ_1 = mobility of M_1

(a) $V_{os} = \Delta V_{t(3\text{-}4)} \sqrt{\frac{450}{150}} = 10\,mV(\sqrt{3})$
$= 17.3$ mV

(b) $V_{os} = \Delta V_{t(3\text{-}4)} \sqrt{\frac{150}{450}} = 10\,mV\left(\frac{1}{\sqrt{3}}\right)$
$= 5.8$ mV

(c) The offset is smaller in (b) because the mobility of p-channel transistors is less than that of n-channel transistors.

6.14

With an n-channel input pair

(1) The input-referred offset voltage resulting from the mismatch between the thresholds of M_3 and M_4 is reduced.

(2) V_{DD} can be included in the common mode input range using only enhancement mode transistors

(3) $PSRR^-$ is improved.

(4) The W/L of the input transistors needed to obtain a given transconductance is reduced. As a result, the input capacitance is reduced.

(5) The input-referred thermal noise voltage is reduced (see chapter 11)

6.15

$200\,\mu A = |I_{D_8}| = |I_{D_5}| = |I_{D_7}| = I_{D_6}$

$100\,\mu A = I_{D_1} = I_{D_2} = I_{D_3} = I_{D_4}$

$$C_{ox} = \frac{\epsilon_{ox}}{t_{ox}} = \frac{3.9\,(8.85\times10^{-14}\,F/cm)}{80\,Å}$$

$$= 431\ nF/cm^2$$

$$\mu_n C_{ox} = 450\,\frac{cm^2}{V.s}\ 431\,\frac{nF}{cm^2}$$

$$= 194\ \mu A/V^2$$

$$k_n' = 194\ \mu A/V^2$$

$$k_p' = 64.7\ \mu A/V^2$$

$$\frac{v_o}{v_i} = -g_{m_2}(r_{o2}\,||\,r_{o4})\,g_{m_6}(r_{o6}\,||\,r_{o7})$$

$$\frac{1}{r_{o2}} = \frac{I_{D_2}}{L_{eff}}\,\frac{dX_d}{dV_{DS}} = \frac{100\,\mu A}{0.72\,\mu m}(0.04\,\mu) = 5.56\,\mu$$

$$r_{o2} = 180\,k\Omega = r_{o4}$$

$$r_{o6} = 90\,k\Omega = r_{o7}$$

$$L_{eff} = L - X_d - 2L_d$$

$$= 1 - 0.1 - 2(0.09)$$

$$= 0.72\,\mu m$$

$$g_{m_2} = \sqrt{2\,k_p'\,\frac{W}{L_{eff}}\,I_{D_2}}$$

$$= \sqrt{2\,(64.7\,\mu)\left(\frac{150}{0.72}\right)(100\,\mu)}$$

$$= 1640\ \mu A/V$$

$$g_{m_6} = \sqrt{2\,(194\,\mu)\left(\frac{100}{0.72}\right)(200\,\mu)}$$

$$= 3280\ \mu A/V$$

$$\frac{v_o}{v_i} = -(1.64m)(90K)(3.28m)(45K)$$

$$= -2.18\times10^4$$

common mode range:

From (6.75),

$$V_{IC} > V_{t_1} + V_{t_3} + V_{ov_3} - V_{SS}$$

$$V_{ov_3} = \sqrt{\frac{2(100)}{194\,(50/0.72)}} = 0.12\,V$$

$$V_{IC} > -0.8 + 0.6 + 0.12 - 1.5$$

$$V_{IC} > -1.58\,V$$

From (6.77),

$$V_{IC} < V_{t_1} + V_{ov_1} + V_{ov_5} + V_{DD}$$

$$V_{ov_5} = -\sqrt{\frac{2(200)}{64.7\,(150/0.72)}} = -0.17\,V$$

$$V_{ov_1} = -\sqrt{\frac{2(100)}{64.7\,(150/0.72)}} = -0.12\,V$$

$$V_{IC} < -0.8 - 0.12 - 0.17 + 1.5$$

$$V_{IC} < 0.41\,V$$

From (6.86),

$$\frac{v_o}{v_{dd}} \cong 0$$

From (6.87),

$$\frac{v_o}{v_{ss}} = \frac{r_{o7}}{r_{o6} + r_{o7}} = 0.5$$

```
TWO-STAGE CMOS AMPLIFIER
******
VDD 100  0  1.5
VSS 200  0  -1.5
M1    7  5    4   4   PMOS W=150U  L=1U
M2    8  6    4   4   PMOS W=150U  L=1U
M3    7  7    200 200 NMOS W=50U   L=1U
M4    8  7    200 200 NMOS W=50U   L=1U
M5    4  3    100 100 PMOS W=150U  L=1U
M6    9  8    200 200 NMOS W=100U  L=1U
M7    9  3    100 100 PMOS W=150U  L=1U
M8    3  3    100 100 PMOS W=150U  L=1U
IBIAS 3  200  200U
* THE DC OFFSET IS ADJUSTED BY TRIAL AND ERROR
* TO SET THE OUTPUT TO ZERO.
VI1   5  2  4.6U
VI2   6  2  0
VIC   2  0  0
*LEFF = LDRAWN - 2LD -XD = 1 - 2(0.09) - 0.1 = 0.72 UM
*LAMBDA=(DXD/DVDS)/LEFF = 0.04U/0.72U = 0.0555
.MODEL NMOS NMOS LEVEL=1 KP=194U  VTO=0.6  LAMBDA=0.0555
.MODEL PMOS PMOS LEVEL=1 KP=64.7U VTO=-0.8 LAMBDA=0.0555
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS VNTOL=1N ABSTOL=1F RELTOL=1U
.OP
.TF  V(9) VI1
.END

 ****  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
   NODE     =VOLTAGE       NODE     =VOLTAGE       NODE     =VOLTAGE
+0:2        =  0.         0:3        = 5.024E-01 0:4        = 9.357E-01
+0:5        = 4.600E-06 0:6        =  0.         0:7        =-7.609E-01
+0:8        =-7.602E-01 0:9        = 3.026E-04 0:100      = 1.500E+00
+0:200      =-1.500E+00

SUBCKT
ELEMENT  0:M1        0:M2        0:M3        0:M4
MODEL    0:PMOS      0:PMOS      0:NMOS      0:NMOS
 ID      -9.772E-05 -9.772E-05  9.772E-05  9.772E-05
 IBS       0.          0.          0.          0.
 IBD      1.697E-14  1.696E-14 -7.391E-15 -7.398E-15
 VGS     -9.357E-01 -9.357E-01  7.391E-01  7.391E-01
 VDS     -1.696E+00 -1.695E+00  7.391E-01  7.398E-01
 VBS       0.          0.          0.          0.
 VTH     -8.000E-01 -8.000E-01  6.000E-01  6.000E-01
 VDSAT   -1.357E-01 -1.357E-01  1.391E-01  1.391E-01
 BETA     1.062E-02  1.062E-02  1.010E-02  1.010E-02
 GAM EFF   0.          0.          0.          0.
 GM       1.441E-03  1.441E-03  1.405E-03  1.405E-03
 GDS      4.957E-06  4.957E-06  5.210E-06  5.210E-06
 GMB       0.          0.          0.          0.

SUBCKT
ELEMENT  0:M5        0:M6        0:M7        0:M8
MODEL    0:PMOS      0:NMOS      0:PMOS      0:PMOS
 ID      -1.954E-04  2.053E-04 -2.053E-04 -2.000E-04
 IBS       0.          0.          0.          0.
 IBD      5.643E-15 -1.500E-14  1.500E-14  9.976E-15
 VGS     -9.976E-01  7.398E-01 -9.976E-01 -9.976E-01
 VDS     -5.643E-01  1.500E+00 -1.499E+00 -9.976E-01
 VBS       0.          0.          0.          0.
 VTH     -8.000E-01  6.000E-01 -8.000E-01 -8.000E-01
 VDSAT   -1.976E-01  1.398E-01 -1.976E-01 -1.976E-01
 BETA     1.001E-02  2.102E-02  1.051E-02  1.024E-02
 GAM EFF   0.          0.          0.          0.
 GM       1.978E-03  2.937E-03  2.078E-03  2.024E-03
 GDS      1.052E-05  1.052E-05  1.052E-05  1.052E-05
 GMB       0.          0.          0.          0.

 ****     SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(9)/VI1                                   = -1.975E+04
INPUT RESISTANCE AT          VI1           =  1.000E+20
OUTPUT RESISTANCE AT V(9)                  =  4.754E+04
```

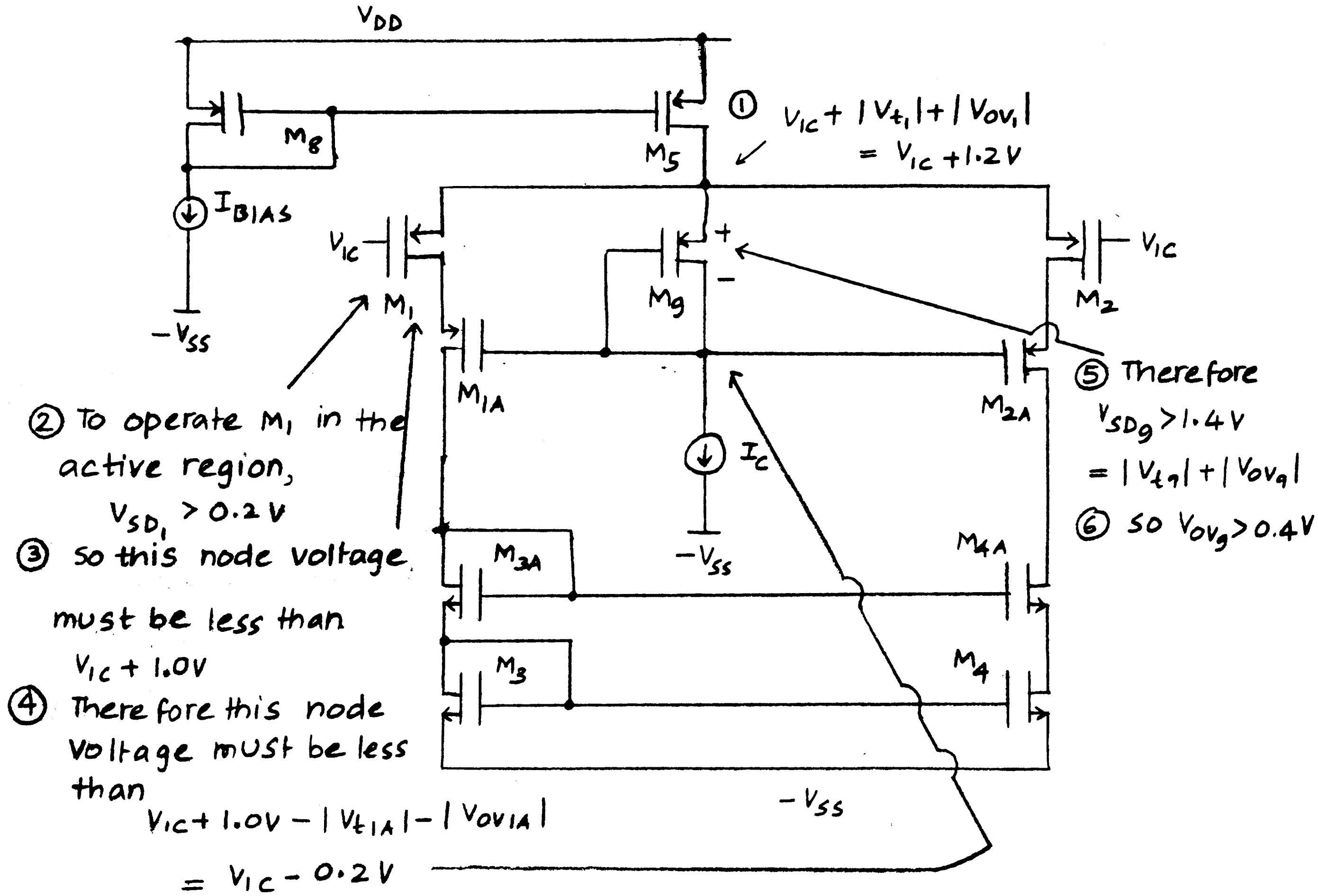
```
TWO-STAGE CMOS AMPLIFIER (MAXIMUM COMMON-MODE INPUT VOLTAGE)
******
VDD 100  0  1.5
VSS 200  0  -1.5
M1    7  5    4   4   PMOS W=150U  L=1U
M2    8  6    4   4   PMOS W=150U  L=1U
M3    7  7    200 200 NMOS W=50U   L=1U
M4    8  7    200 200 NMOS W=50U   L=1U
M5    4  3    100 100 PMOS W=150U  L=1U
M6    9  8    200 200 NMOS W=100U  L=1U
M7    9  3    100 100 PMOS W=150U  L=1U
M8    3  3    100 100 PMOS W=150U  L=1U
IBIAS 3  200  200U
* THE DC OFFSET IS ADJUSTED BY TRIAL AND ERROR
* TO SET THE OUTPUT TO ZERO.
VI1   5  2  13.7U
VI2   6  2  0
* THE MAXIMUM VALUE OF VIC IS ADJUSTED BY TRIAL AND ERROR
* UNTIL M5 BARELY OPERATES IN THE ACTIVE REGION
* (WHERE |VDS| > |VDSAT| FOR M5)
VIC   2  0  0.36
*LEFF = LDRAWN - 2LD -XD = 1 - 2(0.09) - 0.1 = 0.72 UM
*LAMBDA=(DXD/DVDS)/LEFF = 0.04U/0.72U = 0.0555
.MODEL NMOS NMOS LEVEL=1 KP=194U  VTO=0.6  LAMBDA=0.0555
.MODEL PMOS PMOS LEVEL=1 KP=64.7U VTO=-0.8 LAMBDA=0.0555
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS VNTOL=1N ABSTOL=1F RELTOL=1U
.OP
.TF  V(9) VI1
.END

 ****  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
   NODE     =VOLTAGE       NODE     =VOLTAGE       NODE     =VOLTAGE
+0:2        = 3.600E-01 0:3        = 5.024E-01 0:4        = 1.293E+00
+0:5        = 3.600E-01 0:6        = 3.600E-01 0:7        =-7.622E-01
+0:8        =-7.602E-01 0:9        = 1.329E-04 0:100      = 1.500E+00
+0:200      =-1.500E+00

**** MOSFETS
SUBCKT
ELEMENT  0:M1        0:M2        0:M3        0:M4
MODEL    0:PMOS      0:PMOS      0:NMOS      0:NMOS
 ID      -9.584E-05 -9.585E-05  9.584E-05  9.585E-05
 IBS       0.          0.          0.          0.
 IBD      2.055E-14  2.053E-14 -7.378E-15 -7.398E-15
 VGS     -9.331E-01 -9.332E-01  7.378E-01  7.378E-01
 VDS     -2.055E+00 -2.053E+00  7.378E-01  7.398E-01
 VBS       0.          0.          0.          0.
 VTH     -8.000E-01 -8.000E-01  6.000E-01  6.000E-01
 VDSAT   -1.331E-01 -1.332E-01  1.378E-01  1.378E-01
 BETA     1.081E-02  1.081E-02  1.010E-02  1.010E-02
 GAM EFF   0.          0.          0.          0.
 GM       1.440E-03  1.440E-03  1.391E-03  1.391E-03
 GDS      4.774E-06  4.775E-06  5.110E-06  5.110E-06
 GMB       0.          0.          0.          0.

SUBCKT
ELEMENT  0:M5        0:M6        0:M7        0:M8
MODEL    0:PMOS      0:NMOS      0:PMOS      0:PMOS
 ID      -1.917E-04  2.053E-04 -2.053E-04 -2.000E-04
 IBS       0.          0.          0.          0.
 IBD      2.068E-15 -1.500E-14  1.500E-14  9.976E-15
 VGS     -9.976E-01  7.398E-01 -9.976E-01 -9.976E-01
 VDS     -2.068E-01  1.500E+00 -1.499E+00 -9.976E-01
 VBS       0.          0.          0.          0.
 VTH     -8.000E-01  6.000E-01 -8.000E-01 -8.000E-01
 VDSAT   -1.976E-01  1.398E-01 -1.976E-01 -1.976E-01
 BETA     9.816E-03  2.102E-02  1.051E-02  1.024E-02
 GAM EFF   0.          0.          0.          0.
 GM       1.940E-03  2.937E-03  2.078E-03  2.024E-03
 GDS      1.052E-05  1.052E-05  1.052E-05  1.052E-05
 GMB       0.          0.          0.          0.

 ****     SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(9)/VI1                                   = -2.029E+04
INPUT RESISTANCE AT          VI1           =  1.000E+20
OUTPUT RESISTANCE AT V(9)                  =  4.753E+04
```

```
TWO-STAGE CMOS AMPLIFIER (MINIMUM COMMON-MODE INPUT VOLTAGE)
******
VDD 100  0  1.5
VSS 200  0  -1.5
M1    7  5     4   4    PMOS W=150U  L=1U
M2    8  6     4   4    PMOS W=150U  L=1U
M3    7  7     200 200  NMOS W=50U   L=1U
M4    8  7     200 200  NMOS W=50U   L=1U
M5    4  3     100 100  PMOS W=150U  L=1U
M6    9  8     200 200  NMOS W=100U  L=1U
M7    9  3     100 100  PMOS W=150U  L=1U
M8    3  3     100 100  PMOS W=150U  L=1U
IBIAS 3  200  200U
* THE DC OFFSET IS ADJUSTED BY TRIAL AND ERROR
* TO SET THE OUTPUT TO ZERO.
VI1   5  2  -39.7U
VI2   6  2  0
* THE MINIMUM VALUE OF VIC IS ADJUSTED BY TRIAL AND ERROR
* UNTIL M1 BARELY OPERATES IN THE ACTIVE REGION
* (WHERE |VDS| > |VDSAT| FOR M1)
VIC   2  0  -1.55
*LEFF = LDRAWN - 2LD -XD = 1 - 2(0.09) - 0.1 = 0.72 UM
*LAMBDA=(DXD/DVDS)/LEFF = 0.04U/0.72U = 0.0555
.MODEL NMOS NMOS LEVEL=1 KP=194U  VTO=0.6  LAMBDA=0.0555
.MODEL PMOS PMOS LEVEL=1 KP=64.7U VTO=-0.8 LAMBDA=0.0555
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS VNTOL=1N ABSTOL=1F RELTOL=1U
.OP
.TF   V(9) VI1
.END

 ****  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
  NODE       =VOLTAGE       NODE       =VOLTAGE       NODE       =VOLTAGE
+0:2        =-1.550E+00 0:3          = 5.024E-01 0:4          =-6.030E-01
+0:5        =-1.550E+00 0:6          =-1.550E+00 0:7          =-7.552E-01
+0:8        =-7.602E-01 0:9          = 6.068E-04 0:100        = 1.500E+00
+0:200      =-1.500E+00

**** MOSFETS
SUBCKT
ELEMENT  0:M1        0:M2        0:M3        0:M4
MODEL    0:PMOS      0:PMOS      0:NMOS      0:NMOS
 ID      -1.058E-04 -1.058E-04  1.058E-04  1.058E-04
 IBS       0.          0.          0.          0.
 IBD      1.523E-15  1.572E-15 -7.448E-15 -7.398E-15
 VGS     -9.471E-01 -9.470E-01  7.448E-01  7.448E-01
 VDS     -1.523E-01 -1.572E-01  7.448E-01  7.398E-01
 VBS       0.          0.          0.          0.
 VTH     -8.000E-01 -8.000E-01  6.000E-01  6.000E-01
 VDSAT   -1.471E-01 -1.470E-01  1.448E-01  1.448E-01
 BETA     9.787E-03  9.790E-03  1.010E-02  1.010E-02
 GAM EFF   0.          0.          0.          0.
 GM       1.439E-03  1.439E-03  1.462E-03  1.462E-03
 GDS      5.824E-06  5.821E-06  5.640E-06  5.640E-06
 GMB       0.          0.          0.          0.

SUBCKT
ELEMENT  0:M5        0:M6        0:M7        0:M8
MODEL    0:PMOS      0:NMOS      0:PMOS      0:PMOS
 ID      -2.116E-04  2.053E-04 -2.053E-04 -2.000E-04
 IBS       0.          0.          0.          0.
 IBD      2.103E-14 -1.501E-14  1.499E-14  9.976E-15
 VGS     -9.976E-01  7.398E-01 -9.976E-01 -9.976E-01
 VDS     -2.103E+00  1.500E+00 -1.499E+00 -9.976E-01
 VBS       0.          0.          0.          0.
 VTH     -8.000E-01  6.000E-01 -8.000E-01 -8.000E-01
 VDSAT   -1.976E-01  1.398E-01 -1.976E-01 -1.976E-01
 BETA     1.084E-02  2.102E-02  1.051E-02  1.024E-02
 GAM EFF   0.          0.          0.          0.
 GM       2.142E-03  2.937E-03  2.077E-03  2.024E-03
 GDS      1.052E-05  1.052E-05  1.052E-05  1.052E-05
 GMB       0.          0.          0.          0.

****       SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(9)/VI1                                    = -1.750E+04
INPUT RESISTANCE AT          VI1            =  1.000E+20
OUTPUT RESISTANCE AT V(9)                   =  4.754E+04
```

```
TWO-STAGE CMOS AMPLIFIER (GAIN FROM VDD)
******
VDD 100  0  1.5
VSS 200  0  -1.5
M1    7  5     4   4    PMOS W=150U  L=1U
M2    8  6     4   4    PMOS W=150U  L=1U
M3    7  7     200 200  NMOS W=50U   L=1U
M4    8  7     200 200  NMOS W=50U   L=1U
M5    4  3     100 100  PMOS W=150U  L=1U
M6    9  8     200 200  NMOS W=100U  L=1U
M7    9  3     100 100  PMOS W=150U  L=1U
M8    3  3     100 100  PMOS W=150U  L=1U
IBIAS 3  200  200U
* THE DC OFFSET IS ADJUSTED BY TRIAL AND ERROR
* TO SET THE OUTPUT TO ZERO.
VI1   5  2  4.6U
VI2   6  2  0
VIC   2  0  0
*LEFF = LDRAWN - 2LD -XD = 1 - 2(0.09) - 0.1 = 0.72 UM
*LAMBDA=(DXD/DVDS)/LEFF = 0.04U/0.72U = 0.0555
.MODEL NMOS NMOS LEVEL=1 KP=194U  VTO=0.6  LAMBDA=0.0555
.MODEL PMOS PMOS LEVEL=1 KP=64.7U VTO=-0.8 LAMBDA=0.0555
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS VNTOL=1N ABSTOL=1F RELTOL=1U
.OP
.TF   V(9) VDD
.END
 ****  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
  NODE       =VOLTAGE       NODE       =VOLTAGE       NODE       =VOLTAGE
+0:2        =  0.         0:3        = 5.024E-01 0:4          = 9.357E-01
+0:5        = 4.600E-06 0:6          =  0.         0:7        =-7.609E-01
+0:8        =-7.602E-01 0:9          = 3.026E-04 0:100        = 1.500E+00
+0:200      =-1.500E+00
****       SMALL-SIGNAL TRANSFER CHARACTERISTICS
V(9)/VDD                                    = -1.647E-02
INPUT RESISTANCE AT          VDD            =  4.723E+04
OUTPUT RESISTANCE AT V(9)                   =  4.754E+04
```

```
TWO-STAGE CMOS AMPLIFIER (GAIN FROM VSS)
******
VDD 100  0  1.5
VSS 200  0  -1.5
M1    7  5     4   4    PMOS W=150U  L=1U
M2    8  6     4   4    PMOS W=150U  L=1U
M3    7  7     200 200  NMOS W=50U   L=1U
M4    8  7     200 200  NMOS W=50U   L=1U
M5    4  3     100 100  PMOS W=150U  L=1U
M6    9  8     200 200  NMOS W=100U  L=1U
M7    9  3     100 100  PMOS W=150U  L=1U
M8    3  3     100 100  PMOS W=150U  L=1U
IBIAS 3  200  200U
* THE DC OFFSET IS ADJUSTED BY TRIAL AND ERROR
* TO SET THE OUTPUT TO ZERO.
VI1   5  2  4.6U
VI2   6  2  0
VIC   2  0  0
*LEFF = LDRAWN - 2LD -XD = 1 - 2(0.09) - 0.1 = 0.72 UM
*LAMBDA=(DXD/DVDS)/LEFF = 0.04U/0.72U = 0.0555
.MODEL NMOS NMOS LEVEL=1 KP=194U  VTO=0.6  LAMBDA=0.0555
.MODEL PMOS PMOS LEVEL=1 KP=64.7U VTO=-0.8 LAMBDA=0.0555
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS VNTOL=1N ABSTOL=1F RELTOL=1U
.OP
.TF   V(9) VSS
.END
 ****  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
  NODE       =VOLTAGE       NODE       =VOLTAGE       NODE       =VOLTAGE
+0:2        =  0.         0:3        = 5.024E-01 0:4          = 9.357E-01
+0:5        = 4.600E-06 0:6          =  0.         0:7        =-7.609E-01
+0:8        =-7.602E-01 0:9          = 3.026E-04 0:100        = 1.500E+00
+0:200      =-1.500E+00
****       SMALL-SIGNAL TRANSFER CHARACTERISTICS
V(9)/VSS                                    =  5.063E-01
INPUT RESISTANCE AT          VSS            =  1.865E+05
OUTPUT RESISTANCE AT V(9)                   =  4.754E+04
```

6.16



→ For all transistors except m_9, $|V_t| = 1V$ and $|V_{ov}| = 0.2V$

→ To operate M_5 in the active region,

$$V_{IC} < V_{DD} - |V_{t_1}| - |V_{ov_1}| - |V_{ov_5}|$$

$$V_{IC} < V_{DD} - 1.4V$$

→ To operate M_{1A} in the active region, $V_{SD(1A)} > |V_{ov_{1A}}| = 0.2V$

$$V_{S(1A)} = V_{IC} + 1V$$

$$V_{D(1A)} = -V_{SS} + V_{t_3} + V_{ov_3} + V_{t3A} + V_{ov3A}$$

$$= -V_{SS} + 2.4V$$

$$V_{SD(1A)} = V_{IC} + 1V - (-V_{SS} + 2.4V) > 0.2V$$

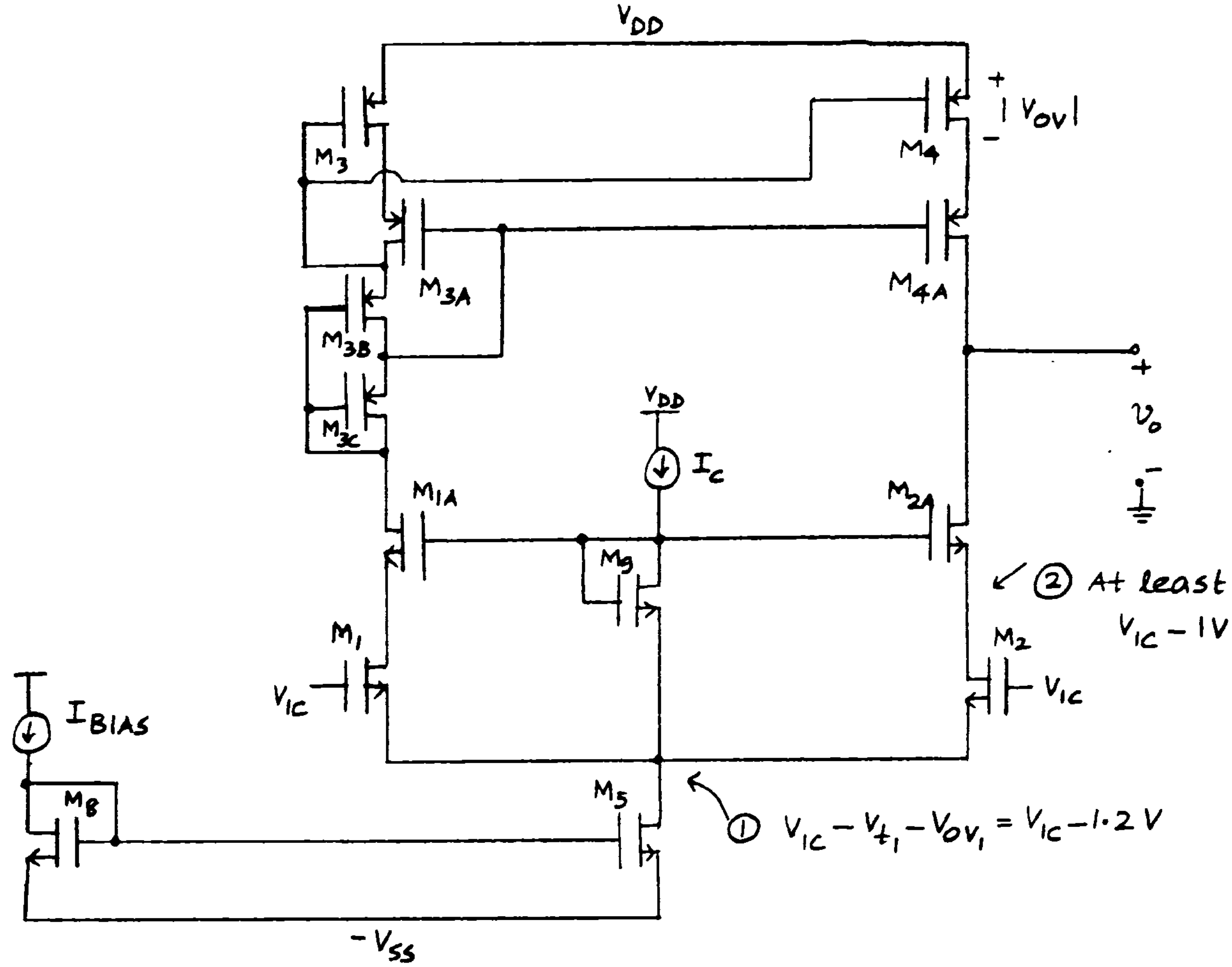
$$V_{IC} - 1.4 + V_{SS} > 0.2V$$

$$V_{IC} > -V_{SS} + 1.6V$$

To simultaneously satisfy both constraints on V_{IC}, the minimum supply difference $= V_{DD} - (-V_{SS}) = V_{DD} + V_{SS} = 3V$

This value can be reduced with smaller threshold and overdrive magnitudes.

6.17 Using a sooch-cascode current mirror,



Maximum swing :

$$V_o < V_{DD} - |V_{ov_4}| - |V_{ov_{4A}}| = V_{DD} - 0.4\,V$$

Minimum swing :

$$V_o > V_{IC} - 1V + V_{ov_{2A}} = V_{IC} - 0.8\,V$$

To keep M_5 in the active region,

$$V_{IC} > -V_{SS} + V_{t_1} + V_{ov_1} + V_{ov_5} = -V_{SS} + 1.4\,V$$

Minimum swing :

$$V_o > V_{IC} - 0.8 > -V_{SS} + 1.4 - 0.8 = -V_{SS} + 0.6\,V$$

For example, if $V_{DD} = V_{SS} = 1.5\,V$

$$-0.9\,V < V_o < 1.1\,V$$

6.18

To operate M_5 in the active region,

$V_{IC} < V_{DD} + V_{t_1} + V_{ov_1} + V_{ov_5}$

$V_{IC} < V_{DD} - 1\,V - 0.2\,V - 0.2\,V$

$V_{IC} < V_{DD} - 1.4\,V$

To operate M_1 in the active region,

$V_{GD_1} > V_{t_1}$

so a channel does not exist at the drain of M_1

$V_{GD_1} > V_{t_1}$

$V_{G_1} = V_{IC}$

$V_{D_1} = -V_{SS} + V_{ov_{11}}$

$V_{IC} - (-V_{SS} + V_{ov_{11}}) > V_{t_1}$

$V_{IC} > -V_{SS} + V_{ov_{11}} + V_{t_1}$

$V_{IC} > -V_{SS} + 0.2\,V - 1\,V$

$V_{IC} > -V_{SS} - 0.8\,V$

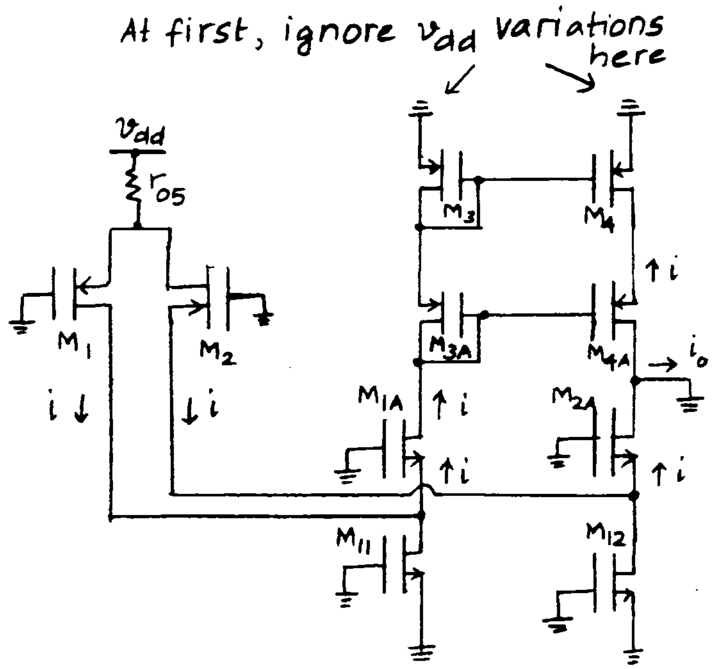
6.19

In the bias circuit,

$v_{gs(102)} = 0$ because $I_{BIAS} =$ constant

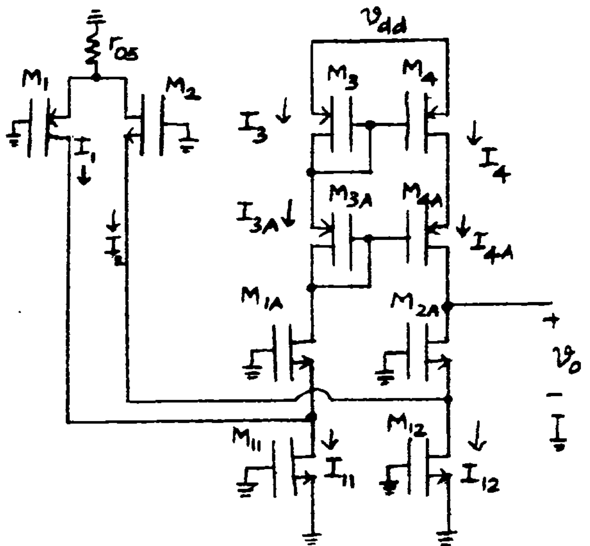
In other words, $V_{gs(102)} = V_{GS(102)}$ = constant. Therefore, v_{dd} variations also appear on V_{BIAS_1}. As a result, $v_{gs(5)} = 0$

consider v_{dd} variations through M_5 with $v_{gs(5)} = 0$. M_5 can be modeled simply as r_{o5} in the following small signal model



Here, the v_{dd} variation appears as a common-mode input to the differential pair, causing a common mode change in the drain currents of M_1 and M_2 (i). Since the drain currents of M_{11} and M_{12} are constant, the source currents of M_{1A} and M_{2A} are i (as labeled). Since the gate current of M_{1A} is zero, the small-signal current in the drain of M_{1A} is also i. This small-signal current is mirrored to the drain of M_{4A} by the cascode current mirror. Therefore, $i_o \simeq i - i = 0$

So, the gain from v_{dd} to the output is zero here. Now, consider v_{dd} variations on the sources of M_3 and M_4



$I_3 = I_{3A} \simeq$ constant because M_1 and M_{11} act as current sources. So, $v_{gs(3)} = v_{gs(3a)} = 0$

Since $v_{gs(4)} = v_{gs(3)}$, $v_{gs(4)} = 0$

Since $v_{ds(3)} = v_{ds(4)}$, $v_{gs(4a)} = v_{gs(3a)} = 0$

$I_{4A} = I_{3A}$ because $I_{11} = I_{12}$ and $I_1 = I_2$

Therefore, $v_{ds(4a)} = v_{ds(3a)} = v_{gs(3a)} = 0$ and v_{dd} variations appear at the output $\frac{v_o}{v_{dd}} = 1$

In the bias circuit,

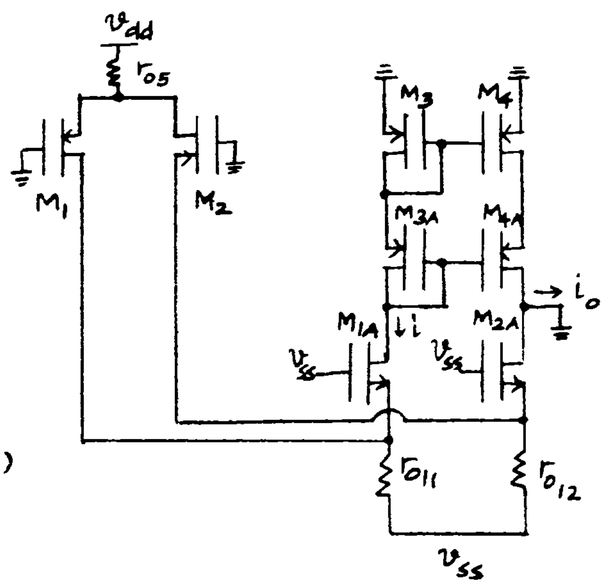
$I_{D(108)} \simeq$ constant because I_{BIAS} = constant and because $M_{101}, M_{102}, M_{108}$ and M_{109} form a cascode current mirror

Therefore, $v_{gs(107)} \simeq 0$

Similarly, $v_{gs(106)} \simeq 0$

Therefore, variations in $-V_{SS}$ also appear on V_{BIAS_2} and V_{BIAS_3}

Since $v_{gs(11)} = v_{gs(12)} = v_{gs(107)} \simeq 0$, M_{11} and M_{12} can be modeled simply as r_{o11} and r_{o12}



v_{ss} variations cause equal or common-mode variations in the drain currents of M_{1A} and M_{2A}, which cancel at the output because of the cascode current mirror

Therefore $\frac{v_o}{v_{ss}} = 0$

```
FOLDED-CASCODE MOS OP AMP
******
VDD    100    0      2.5
VSS    200    0      -2.5
M1     1      10     8    8    CMOSP W=200U L=1U
M2     2      0      8    8    CMOSP W=200U L=1U
M1A    5      12     1    200  CMOSN W=100U L=1U
M2A    6      12     2    200  CMOSN W=100U L=1U
M3     3      3      100  100  CMOSP W=200U L=1U
M4     4      3      100  100  CMOSP W=200U L=1U
M3A    5      5      3    100  CMOSP W=200U L=1U
M4A    6      5      4    100  CMOSP W=200U L=1U
M5     8      11     100  100  CMOSP W=200U L=1U
M11    1      13     200  200  CMOSN W=100U L=1U
M12    2      13     200  200  CMOSN W=100U L=1U
M101   101    101    11   100  CMOSP W=200U L=1U
M102   11     11     100  100  CMOSP W=200U L=1U
M103   103    11     100  100  CMOSP W=200U L=1U
M104   12     101    103  100  CMOSP W=200U L=1U
M105   12     12     106  200  CMOSN W=100U L=1U
M106   106    12     200  200  CMOSN W=20U  L=1U
M107   13     13     200  200  CMOSN W=100U L=1U
M108   13     101    109  100  CMOSP W=200U L=1U
M109   109    11     100  100  CMOSP W=200U L=1U
IB     101    200    100U
VI     10     0      0    AC  1
.MODEL CMOSN NMOS LEVEL=1 LAMBDA=100M VTO=0.7  KP=200U
.MODEL CMOSP PMOS LEVEL=1 LAMBDA=100M VTO=-0.7 KP=100U
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.TF V(6) VI
.END
```

```
 ****  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
  NODE      =VOLTAGE      NODE      =VOLTAGE      NODE      =VOLTAGE
+0:1       =-2.312E+00 0:2       =-2.312E+00 0:3        = 1.739E+00
+0:4       = 1.739E+00 0:5       = 9.779E-01 0:6        = 9.779E-01
+0:10      =  0.       0:11      = 1.703E+00 0:12       =-1.557E+00
+0:13      =-1.703E+00 0:100     = 2.500E+00 0:101      = 9.075E-01
+0:103     = 1.694E+00 0:106     =-2.354E+00 0:109      = 1.694E+00
+0:200     =-2.500E+00 0:8       = 7.645E-01
```

```
**** MOSFETS
SUBCKT
ELEMENT  0:M1        0:M2        0:M1A       0:M2A       0:M3
MODEL    0:CMOSP     0:CMOSP     0:CMOSN     0:CMOSN     0:CMOSP
 ID      -5.435E-05 -5.435E-05  4.009E-05  4.009E-05 -4.009E-05
 IBS       0.         0.        -1.871E-15 -1.871E-15   0.
 IBD      3.077E-14  3.077E-14 -3.478E-14 -3.478E-14  7.610E-15
 VGS     -7.645E-01 -7.645E-01  7.549E-01  7.549E-01 -7.610E-01
 VDS     -3.077E+00 -3.077E+00  3.290E+00  3.290E+00 -7.610E-01
 VBS       0.         0.        -1.871E-01 -1.871E-01   0.
 VTH     -7.000E-01 -7.000E-01  7.000E-01  7.000E-01 -7.000E-01
 VDSAT   -6.447E-02 -6.447E-02  5.492E-02  5.492E-02 -6.104E-02
 BETA     2.615E-02  2.615E-02  2.658E-02  2.658E-02  2.152E-02
 GAM EFF   0.         0.         0.         0.         0.
 GM       1.686E-03  1.686E-03  1.460E-03  1.460E-03  1.314E-03
 GDS      4.156E-06  4.156E-06  3.017E-06  3.017E-06  3.726E-06
 GMB       0.         0.         0.         0.         0.

SUBCKT
ELEMENT  0:M4        0:M3A       0:M4A       0:M5        0:M11
MODEL    0:CMOSP     0:CMOSP     0:CMOSP     0:CMOSP     0:CMOSN
 ID      -4.009E-05 -4.009E-05 -4.009E-05 -1.087E-04  9.444E-05
 IBS       0.        7.610E-15  7.610E-15   0.         0.
 IBD      7.610E-15  1.522E-14  1.522E-14  1.736E-14 -1.871E-15
 VGS     -7.610E-01 -7.610E-01 -7.610E-01 -7.962E-01  7.963E-01
 VDS     -7.610E-01 -7.610E-01 -7.610E-01 -1.735E+00  1.871E-01
 VBS       0.        7.610E-01  7.610E-01   0.         0.
 VTH     -7.000E-01 -7.000E-01 -7.000E-01 -7.000E-01  7.000E-01
 VDSAT   -6.104E-02 -6.104E-02 -6.104E-02 -9.624E-02  9.629E-02
 BETA     2.152E-02  2.152E-02  2.152E-02  2.347E-02  2.037E-02
 GAM EFF   0.         0.         0.         0.         0.
 GM       1.314E-03  1.314E-03  1.314E-03  2.259E-03  1.962E-03
 GDS      3.726E-06  3.726E-06  3.726E-06  9.262E-06  9.271E-06
 GMB       0.         0.         0.         0.         0.
```

```
SUBCKT
ELEMENT  0:M12       0:M101      0:M102      0:M103      0:M104
MODEL    0:CMOSN     0:CMOSP     0:CMOSP     0:CMOSP     0:CMOSP
 ID       9.444E-05 -1.000E-04 -1.000E-04 -1.001E-04 -1.001E-04
 IBS       0.        7.962E-15   0.          0.        8.056E-15
 IBD     -1.871E-15  1.592E-14  7.962E-15  8.056E-15  4.058E-14
 VGS      7.963E-01 -7.962E-01 -7.962E-01 -7.962E-01 -7.869E-01
 VDS      1.871E-01 -7.962E-01 -7.962E-01 -8.056E-01 -3.252E+00
 VBS       0.        7.962E-01   0.          0.        8.056E-01
 VTH      7.000E-01 -7.000E-01 -7.000E-01 -7.000E-01 -7.000E-01
 VDSAT    9.629E-02 -9.624E-02 -9.624E-02 -9.624E-02 -8.690E-02
 BETA     2.037E-02  2.159E-02  2.159E-02  2.161E-02  2.650E-02
 GAM EFF   0.         0.         0.         0.         0.
 GM       1.962E-03  2.078E-03  2.078E-03  2.080E-03  2.303E-03
 GDS      9.271E-06  9.262E-06  9.262E-06  9.262E-06  7.552E-06
 GMB       0.         0.         0.         0.         0.

SUBCKT
ELEMENT  0:M105      0:M106      0:M107      0:M108      0:M109
MODEL    0:CMOSN     0:CMOSN     0:CMOSN     0:CMOSP     0:CMOSP
 ID       1.001E-04  1.001E-04  1.001E-04 -1.001E-04 -1.001E-04
 IBS     -1.458E-15   0.          0.        8.060E-15   0.
 IBD     -9.421E-15 -1.458E-15 -7.963E-15  4.204E-14  8.060E-15
 VGS      7.963E-01  9.421E-01  7.963E-01 -7.864E-01 -7.962E-01
 VDS      7.963E-01  1.458E-01  7.963E-01 -3.397E+00 -8.060E-01
 VBS     -1.458E-01   0.          0.        8.060E-01   0.
 VTH      7.000E-01  7.000E-01  7.000E-01 -7.000E-01 -7.000E-01
 VDSAT    9.628E-02  1.458E-01  9.629E-02 -8.643E-02 -9.624E-02
 BETA     2.159E-02  4.058E-03  2.159E-02  2.680E-02  2.161E-02
 GAM EFF   0.         0.         0.         0.         0.
 GM       2.079E-03  5.916E-04  2.079E-03  2.316E-03  2.080E-03
 GDS      9.270E-06  4.006E-04  9.271E-06  7.471E-06  9.262E-06
 GMB       0.         0.         0.         0.         0.
```

```
****      SMALL-SIGNAL TRANSFER CHARACTERISTICS

      V(6)/VI                                   =  4.403E+04
      INPUT RESISTANCE AT         VI            =  1.000E+20
      OUTPUT RESISTANCE AT V(6)                 =  2.635E+07
```

```
FOLDED-CASCODE MOS OP AMP (GAIN FROM VDD)
******
VDD    100    0      2.5  AC  1
VSS    200    0      -2.5
M1     1      0      8    8    CMOSP W=200U L=1U
M2     2      0      8    8    CMOSP W=200U L=1U
M1A    5      12     1    200  CMOSN W=100U L=1U
M2A    6      12     2    200  CMOSN W=100U L=1U
M3     3      3      100  100  CMOSP W=200U L=1U
M4     4      3      100  100  CMOSP W=200U L=1U
M3A    5      5      3    100  CMOSP W=200U L=1U
M4A    6      5      4    100  CMOSP W=200U L=1U
M5     8      11     100  100  CMOSP W=200U L=1U
M11    1      13     200  200  CMOSN W=100U L=1U
M12    2      13     200  200  CMOSN W=100U L=1U
M101   101    101    11   100  CMOSP W=200U L=1U
M102   11     11     100  100  CMOSP W=200U L=1U
M103   103    11     100  100  CMOSP W=200U L=1U
M104   12     101    103  100  CMOSP W=200U L=1U
M105   12     12     106  200  CMOSN W=100U L=1U
M106   106    12     200  200  CMOSN W=20U  L=1U
M107   13     13     200  200  CMOSN W=100U L=1U
M108   13     101    109  100  CMOSP W=200U L=1U
M109   109    11     100  100  CMOSP W=200U L=1U
IB     101    200    100U
VI     10     0      0    AC  1
.MODEL CMOSN NMOS LEVEL=1 LAMBDA=100M VTO=0.7  KP=200U
.MODEL CMOSP PMOS LEVEL=1 LAMBDA=100M VTO=-0.7 KP=100U
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.TF V(6) VDD
.END
```

```
****  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
  NODE      =VOLTAGE      NODE      =VOLTAGE      NODE      =VOLTAGE
+0:1        =-2.312E+00 0:2         =-2.312E+00 0:3         = 1.739E+00
+0:4        = 1.739E+00 0:5         = 9.779E-01 0:6         = 9.779E-01
+0:10       =   0.      0:11        = 1.703E+00 0:12        =-1.557E+00
+0:13       =-1.703E+00 0:100       = 2.500E+00 0:101       = 9.075E-01
+0:103      = 1.694E+00 0:106       =-2.354E+00 0:109       = 1.694E+00
+0:200      =-2.500E+00 0:8         = 7.645E-01
****      SMALL-SIGNAL TRANSFER CHARACTERISTICS

     V(6)/VDD                                  =  1.006E+00
     INPUT RESISTANCE AT         VDD           =  4.710E+06
     OUTPUT RESISTANCE AT V(6)                 =  2.635E+07
```

```
FOLDED-CASCODE MOS OP AMP (GAIN FROM VSS)
******
VDD   100    0      2.5
VSS   200    0      -2.5  AC  1
M1    1      0      8      8    CMOSP W=200U L=1U
M2    2      0      8      8    CMOSP W=200U L=1U
M1A   5      12     1      200  CMOSN W=100U L=1U
M2A   6      12     2      200  CMOSN W=100U L=1U
M3    3      3      100    100  CMOSP W=200U L=1U
M4    4      3      100    100  CMOSP W=200U L=1U
M3A   5      5      3      100  CMOSP W=200U L=1U
M4A   6      5      4      100  CMOSP W=200U L=1U
M5    8      11     100    100  CMOSP W=200U L=1U
M11   1      13     200    200  CMOSN W=100U L=1U
M12   2      13     200    200  CMOSN W=100U L=1U
M101  101    101    11     100  CMOSP W=200U L=1U
M102  11     11     100    100  CMOSP W=200U L=1U
M103  103    11     100    100  CMOSP W=200U L=1U
M104  12     101    103    100  CMOSP W=200U L=1U
M105  12     12     106    200  CMOSN W=100U L=1U
M106  106    12     200    200  CMOSN W=20U  L=1U
M107  13     13     200    200  CMOSN W=100U L=1U
M108  13     101    109    100  CMOSP W=200U L=1U
M109  109    11     100    100  CMOSP W=200U L=1U
IB    101    200    100U
VI    10     0      0     AC  1
.MODEL CMOSN NMOS LEVEL=1 LAMBDA=100M VTO=0.7  KP=200U
.MODEL CMOSP PMOS LEVEL=1 LAMBDA=100M VTO=-0.7 KP=100U
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.TF V(6) VSS
.END
```

```
****  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
  NODE      =VOLTAGE      NODE      =VOLTAGE      NODE      =VOLTAGE
+0:1        =-2.312E+00 0:2         =-2.312E+00 0:3         = 1.739E+00
+0:4        = 1.739E+00 0:5         = 9.779E-01 0:6         = 9.779E-01
+0:10       =   0.      0:11        = 1.703E+00 0:12        =-1.557E+00
+0:13       =-1.703E+00 0:100       = 2.500E+00 0:101       = 9.075E-01
+0:103      = 1.694E+00 0:106       =-2.354E+00 0:109       = 1.694E+00
+0:200      =-2.500E+00 0:8         = 7.645E-01

****      SMALL-SIGNAL TRANSFER CHARACTERISTICS

     V(6)/VSS                                  =  5.429E-05
     INPUT RESISTANCE AT         VSS           =  6.493E+06
     OUTPUT RESISTANCE AT V(6)                 =  2.635E+07
```

6.20

For $I_{O(max)} = \pm 100\,\mu A$,

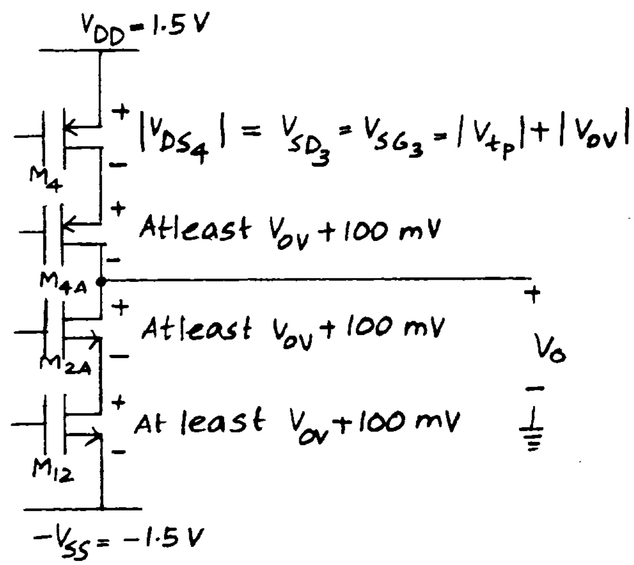
$I_{D_{11}} = I_{D_{12}} = 100\,\mu A$

Then half of $I_{D_{11}}$ should come from M_1 and the other half from from M_{1A}

so, $|I_{D_1}| = |I_{D_2}| = |I_{D_{1A}}| = I_{D_{2A}} = 50\,\mu A$

so, $|I_{D3A}| = |I_{D_3}| = |I_{D_4}| = |I_{D_{4A}}| = 50\,\mu A$

For the output swing requirement, concentrate on the output branch



$$V_{o(p-p)} = V_{DD} - (-V_{SS}) - |V_{tp}| - 4V_{ov} - 300\,mV$$

Requirement $V_{o(p-p)} > 1.5\,V$

$$1.5 < 1.5 - (-1.5) - 0.8 - 4V_{ov} - 0.3$$

$$-0.4 < -4V_{ov} \rightarrow V_{ov} < 0.1\,V$$

$$I = \frac{k'}{2}\frac{W}{L}V_{ov}^2 \Rightarrow \frac{W}{L} = \frac{2I}{k' V_{ov}^2}$$

$$\left(\frac{W}{L}\right)_{12} = \frac{2(100)}{194\,(0.1)^2} \simeq 100$$

$$\left(\frac{W}{L}\right)_{2A} = \frac{2(50)}{194\,(0.1)^2} \simeq 50$$

$$\left(\frac{W}{L}\right)_4 = \left(\frac{W}{L}\right)_{4A} = \frac{2(50)}{64.7(0.1)^2} \simeq 150$$

For the common-mode range requirement: To operate M_1 in the active region

$V_{GD_1} > V_{t_1} = -0.8\,V$

$V_{G1} = V_{IC}$

$V_{D_1} = -V_{SS} + V_{ov_{11}} + 0.1\,V$

$V_{IC} > -V_{SS} + V_{ov_{11}} + 0.1\,V + V_{t_1}$

$> 1.5 + 0.1 + 0.1 - 0.8 = -2.1\,V$

So, the common mode range includes $-V_{SS} = -1.5\,V$

To operate M_5 in the active region,

$V_{IC} < V_{DD} + V_{t_1} + V_{ov_1} + V_{ov_5}$

$V_{IC} < 1.5 - 0.8 + 2V_{ov}$

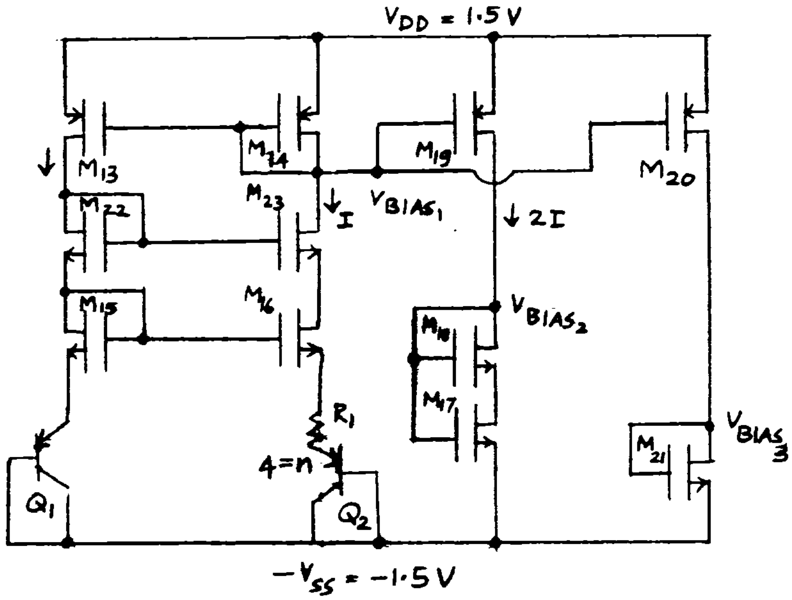
$0.5 < 0.7 + 2V_{ov}$

$V_{ov} = V_{ov_1} = V_{ov_5} > -0.1\,V$

$$\left(\frac{W}{L}\right)_1 = \frac{2(50)}{64.7(0.1)^2} \cong 150$$

$$\left(\frac{W}{L}\right)_5 = \frac{2(100)}{64.7(0.1)^2} \simeq 300$$

BIAS CIRCUIT:



$$I = \frac{V_T}{R_1}\ln(n) = 50\,\mu A \Rightarrow$$

$$R_1 = \frac{V_T \ln 4}{50\,\mu A} = 721\,\Omega$$

Check headroom requirements in the bias circuit. For the branch including M_{13}

$$V_{DD} - (|V_{ov_{13}}| + 0.1\,V) - V_{t_{22}} - V_{ov_{22}} - V_{t_{15}} - V_{ov_{15}} - 0.7 - (-V_{SS}) = 0$$

Let $|V_{ov_{13}}| = V_{ov_{22}} = V_{ov_{15}} = V_{ov}$

$V_{t_{22}} = V_{t_{15}} = 0.6\,V$

$1.5 - 0.1 - 0.6 - 0.6 - 0.7 - (-1.5) = 3V_{ov}$

$1 = 3V_{ov} \Rightarrow V_{ov} = 0.33\,V$

So, this branch operates with all transistors in the active region if $V_{ov} < 0.33\,V$

For the branch including M_{14},

$$V_{DD} - |V_{t14}| - |V_{ov_{14}}| - (V_{ov_{23}} + 0.1V) -$$
$$(V_{ov_{16}} + 0.1V) - V_T \ln 4 - 0.7V - (-V_{SS}) = 0$$

Let $|V_{ov_{14}}| = V_{ov_{23}} = V_{ov_{16}} = V_{ov}$

$V_T \ln 4 = 36\,mV$ (neglect); $V_{t_{14}} = -0.8V$

$$1.5 - 0.8 - 0.1 - 0.1 - 0.7 - (-1.5) = 3V_{ov}$$
$$1.3 = 3\,V_{ov}$$
$$V_{ov} = 0.43\,V$$

So, this branch operates with all transistors in the active region if $V_{ov} < 0.43\,V$

So, this design will use the previously computed value of $V_{ov} = 0.1\,V$

$$\left(\frac{W}{L}\right)_{13} = \left(\frac{W}{L}\right)_{14} = \frac{2(50)}{64.7\,(0.1)^2} \simeq 150$$

$$\left(\frac{W}{L}\right)_{22} = \left(\frac{W}{L}\right)_{23} = \left(\frac{W}{L}\right)_{15} = \left(\frac{W}{L}\right)_{16} = \frac{2(50)}{194\,(0.1)^2} \simeq 50$$

$$\left(\frac{W}{L}\right)_{19} = \left(\frac{W}{L}\right)_{20} = 2\left(\frac{W}{L}\right)_{14} = 300$$

$$\left(\frac{W}{L}\right)_{18} = \left(\frac{W}{L}\right)_{21} = \frac{2(100)}{194\,(0.1)^2} \simeq 100$$

M_{18} forces M_{17} to operate in the triode region.

From (4.73), $\left(\frac{W}{L}\right)_{17} = \frac{1}{3}\left(\frac{W}{L}\right)_{18}$ sets $V_{DS_{17}} = V_{ov} = 0.1V$

To increase $V_{DS_{17}}$ to $V_{ov} + 0.1V = 0.2V$, reduce $\left(\frac{W}{L}\right)_7$ to about $\frac{1}{5}\left(\frac{W}{L}\right)_{18} = 20$

This choice is confirmed in simulation. It biases M_{11} & M_{12} so that $V_{DS_{11}} = V_{DS_{12}} \simeq 0.2\,V$

```
FOLDED CASCODE OP AMP
******
VDD   100  0    1.5
VSS   200  0    -1.5
M1    17   9    8   8    PMOS W=150U L=1U
M2    18   10   8   8    PMOS W=150U L=1U
M1A   15   2    17  200  NMOS W=50U  L=1U
M2A   16   2    18  200  NMOS W=50U  L=1U
M3    13   13   100 100  PMOS W=150U L=1U
M4    14   13   100 100  PMOS W=150U L=1U
M3A   15   15   13  13   PMOS W=150U L=1U
M4A   16   15   14  14   PMOS W=150U L=1U
M5    8    1    100 100  PMOS W=300U L=1U
M11   17   3    200 200  NMOS W=100U L=1U
M12   18   3    200 200  NMOS W=100U L=1U
M13   20   1    100 100  PMOS W=150U L=1U
M14   1    1    100 100  PMOS W=150U L=1U
M15   4    4    5   200  NMOS W=50U  L=1U
M16   21   4    6   200  NMOS W=50U  L=1U
M17   12   2    200 200  NMOS W=10U  L=1U
M18   2    2    12  200  NMOS W=100U L=1U
M19   2    1    100 100  PMOS W=300U L=1U
M20   3    1    100 100  PMOS W=300U L=1U
M21   3    3    200 200  NMOS W=100U L=1U
M22   20   20   4   200  NMOS W=50U  L=1U
M23   1    20   21  200  NMOS W=50U  L=1U
Q1    200  200  5   PNP
Q2    200  200  7   PNP 4
R1    6    7    721
.MODEL NMOS NMOS LEVEL=1 KP=194U  VTO=0.6  LAMBDA=0.024 GAMMA=0.25
.MODEL PMOS PMOS LEVEL=1 KP=64.7U VTO=-0.8 LAMBDA=0.048 GAMMA=0.25
.MODEL PNP  PNP  BF=50   IS=2E-15
VI1  9    0    0
VI2  10   0    0
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.TF   V(16) VI1
.END
 ****  OPERATING POINT INFORMATION    TNOM=  27.000 TEMP=  27.000
   NODE     =VOLTAGE      NODE      =VOLTAGE      NODE      =VOLTAGE
+0:1        = 6.016E-01 0:2        =-5.479E-01 0:3         =-7.971E-01
+0:4        =-1.005E-01 0:5        =-8.820E-01 0:6         =-8.823E-01
+0:7        =-9.176E-01 0:8        = 8.950E-01 0:9         =   0.
+0:10       =   0.      0:12       =-1.282E+00 0:13        = 5.960E-01
+0:14       = 5.960E-01 0:15       =-3.081E-01 0:16        =-3.081E-01
+0:17       =-1.285E+00 0:18       =-1.285E+00 0:20        = 7.586E-01
+0:21       =-1.010E-01 0:100      = 1.500E+00 0:200       =-1.500E+00
**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT  0:Q1        0:Q2
MODEL    0:PNP       0:PNP
 IB      -9.542E-07 -9.612E-07
 IC      -4.771E-05 -4.806E-05
 VBE     -6.180E-01 -5.824E-01
 VCE     -6.180E-01 -5.824E-01
 VBC        0.         0.
 VS       1.500E+00  1.500E+00
 POWER    3.008E-05  2.855E-05
 BETAD    5.000E+01  5.000E+01
 GM       1.845E-03  1.858E-03
 RPI      2.710E+04  2.690E+04
 RX         0.         0.
 RO       1.293E+13  3.233E+12
 BETAAC   5.000E+01  5.000E+01
**** MOSFETS
SUBCKT
ELEMENT  0:M1       0:M2       0:M1A      0:M2A      0:M3
MODEL    0:PMOS     0:PMOS     0:NMOS     0:NMOS     0:PMOS
 ID      -4.836E-05 -4.836E-05  5.479E-05  5.479E-05 -5.479E-05
 IBS        0.         0.      -2.150E-15 -2.150E-15    0.
 IBD      2.180E-14  2.180E-14 -1.192E-14 -1.192E-14  9.040E-15
 VGS     -8.950E-01 -8.950E-01  7.371E-01  7.371E-01 -9.040E-01
 VDS     -2.180E+00 -2.180E+00  9.769E-01  9.769E-01 -9.040E-01
 VBS        0.         0.      -2.150E-01 -2.150E-01    0.
 VTH     -8.000E-01 -8.000E-01  6.320E-01  6.320E-01 -8.000E-01
 VDSAT   -9.498E-02 -9.498E-02  1.051E-01  1.051E-01 -1.040E-01
 BETA     1.072E-02  1.072E-02  9.927E-03  9.927E-03  1.013E-02
 GAM EFF  2.500E-01  2.500E-01  2.500E-01  2.500E-01  2.500E-01
 GM       1.018E-03  1.018E-03  1.043E-03  1.043E-03  1.053E-03
 GDS      2.101E-06  2.101E-06  1.285E-06  1.285E-06  2.521E-06
 GMB      1.643E-04  1.643E-04  1.444E-04  1.444E-04  1.700E-04

SUBCKT
ELEMENT  0:M4       0:M3A      0:M4A      0:M5       0:M11
MODEL    0:PMOS     0:PMOS     0:PMOS     0:PMOS     0:NMOS
 ID      -5.479E-05 -5.479E-05 -5.479E-05 -9.672E-05  1.032E-04
 IBS        0.         0.         0.         0.         0.
 IBD      9.040E-15  9.040E-15  9.040E-15  6.050E-15 -2.150E-15
 VGS     -9.040E-01 -9.040E-01 -9.040E-01 -8.984E-01  7.029E-01
 VDS     -9.040E-01 -9.040E-01 -9.040E-01 -6.050E-01  2.150E-01
 VBS        0.         0.         0.         0.         0.
 VTH     -8.000E-01 -8.000E-01 -8.000E-01 -8.000E-01  6.000E-01
 VDSAT   -1.040E-01 -1.040E-01 -1.040E-01 -9.841E-02  1.029E-01
 BETA     1.013E-02  1.013E-02  1.013E-02  1.997E-02  1.950E-02
 GAM EFF  2.500E-01  2.500E-01  2.500E-01  2.500E-01  2.500E-01
 GM       1.053E-03  1.053E-03  1.053E-03  1.966E-03  2.006E-03
 GDS      2.521E-06  2.521E-06  2.521E-06  4.511E-06  2.463E-06
 GMB      1.700E-04  1.700E-04  1.700E-04  3.172E-04  3.237E-04

SUBCKT
ELEMENT  0:M12      0:M13      0:M14      0:M15      0:M16
MODEL    0:NMOS     0:PMOS     0:PMOS     0:NMOS     0:NMOS
 ID       1.032E-04 -4.867E-05 -4.902E-05  4.867E-05  4.902E-05
 IBS        0.         0.         0.      -6.180E-15 -6.177E-15
 IBD     -2.150E-15  7.414E-15  8.984E-15 -1.400E-14 -1.399E-14
 VGS      7.029E-01 -8.984E-01 -8.984E-01  7.815E-01  7.818E-01
 VDS      2.150E-01 -7.414E-01 -8.984E-01  7.815E-01  7.813E-01
 VBS        0.         0.         0.      -6.180E-01 -6.177E-01
 VTH      6.000E-01 -8.000E-01 -8.000E-01  6.823E-01  6.822E-01
 VDSAT    1.029E-01 -9.841E-02 -9.841E-02  9.925E-02  9.961E-02
 BETA     1.950E-02  1.005E-02  1.012E-02  9.882E-03  9.882E-03
 GAM EFF  2.500E-01  2.500E-01  2.500E-01  2.500E-01  2.500E-01
 GM       2.006E-03  9.891E-04  9.963E-04  9.807E-04  9.843E-04
 GDS      2.463E-06  2.256E-06  2.256E-06  1.146E-06  1.155E-06
 GMB      3.237E-04  1.596E-04  1.608E-04  1.111E-04  1.115E-04

SUBCKT
ELEMENT  0:M17      0:M18      0:M19      0:M20      0:M21
MODEL    0:NMOS     0:NMOS     0:PMOS     0:PMOS     0:NMOS
 ID       1.032E-04  1.032E-04 -1.032E-04 -1.044E-04  1.044E-04
 IBS        0.      -2.175E-15    0.         0.         0.
 IBD     -2.175E-15 -9.521E-15  2.048E-14  2.297E-14 -7.029E-15
 VGS      9.521E-01  7.347E-01 -8.984E-01 -8.984E-01  7.029E-01
 VDS      2.175E-01  7.347E-01 -2.047E+00 -2.297E+00  7.029E-01
 VBS        0.      -2.175E-01    0.         0.         0.
 VTH      6.000E-01  6.324E-01 -8.000E-01 -8.000E-01  6.000E-01
 VDSAT    2.175E-01  1.023E-01 -9.841E-02 -9.841E-02  1.029E-01
 BETA     1.950E-03  1.974E-02  2.132E-02  2.155E-02  1.973E-02
 GAM EFF  2.500E-01  2.500E-01  2.500E-01  2.500E-01  2.500E-01
 GM       4.241E-04  2.019E-03  2.098E-03  2.121E-03  2.029E-03
 GDS      2.650E-04  2.435E-06  4.511E-06  4.511E-06  2.463E-06
 GMB      6.844E-05  2.791E-04  3.385E-04  3.422E-04  3.274E-04

SUBCKT
ELEMENT  0:M22      0:M23
MODEL    0:NMOS     0:NMOS
 ID       4.867E-05  4.902E-05
 IBS     -1.400E-14 -1.399E-14
 IBD     -2.259E-14 -2.102E-14
 VGS      8.590E-01  8.595E-01
 VDS      8.590E-01  7.025E-01
 VBS     -1.399E+00 -1.399E+00
 VTH      7.599E-01  7.598E-01
 VDSAT    9.915E-02  9.970E-02
 BETA     9.900E-03  9.864E-03
 GAM EFF  2.500E-01  2.500E-01
 GM       9.816E-04  9.834E-04
 GDS      1.144E-06  1.157E-06
 GMB      8.677E-05  8.694E-05

****      SMALL-SIGNAL TRANSFER CHARACTERISTICS

     V(16)/VI1                                    =  9.290E+04
     INPUT RESISTANCE AT          VI1             =  1.000E+20
     OUTPUT RESISTANCE AT V(16)                   =  9.159E+07
```

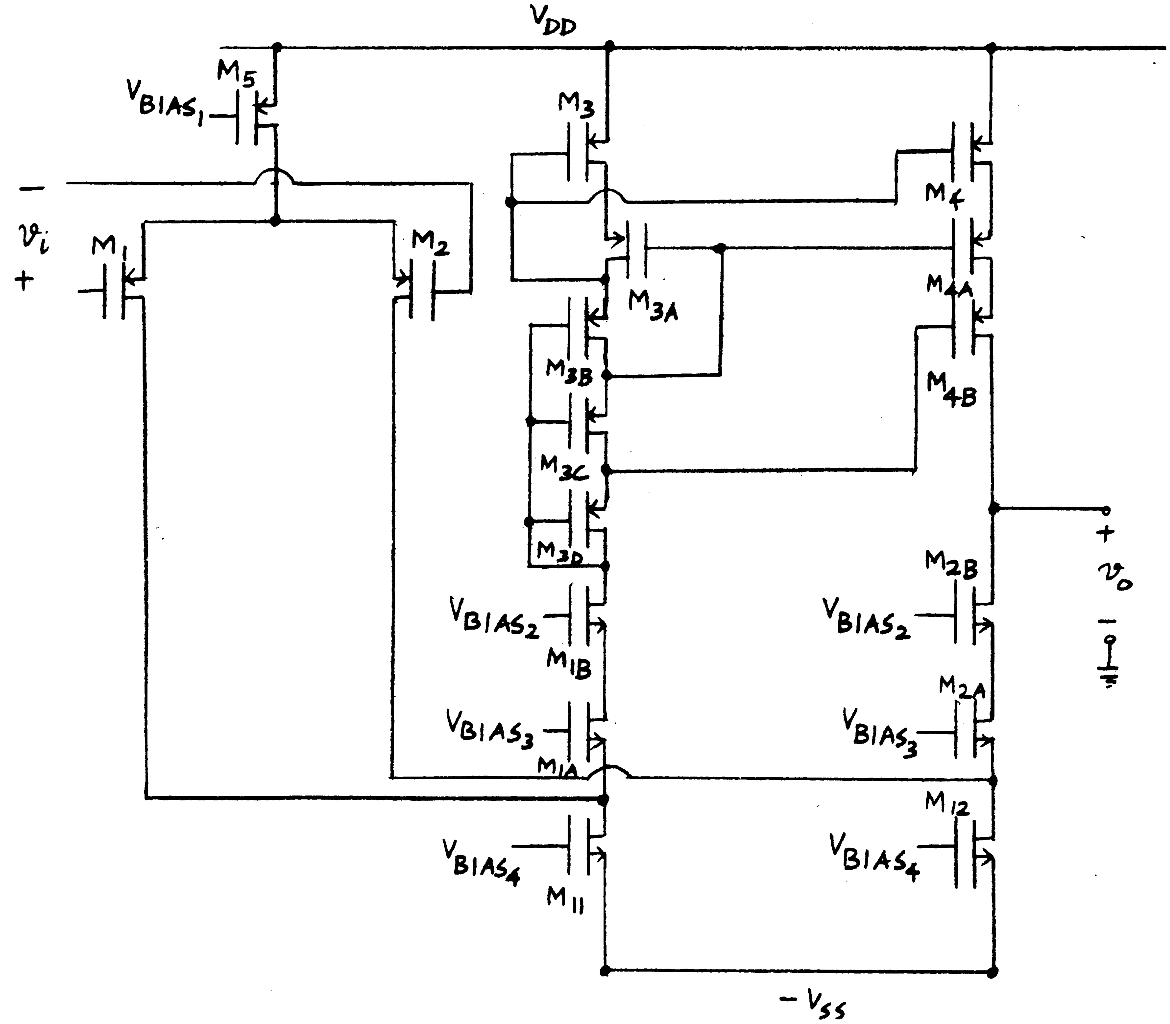
```
FOLDED CASCODE OP AMP (CONNECTED AS VOLTAGE FOLLOWER)
* CONNECT THE OP AMP AS A VOLTAGE FOLLOWER TO SEE THE COMMON-MODE
* INPUT RANGE.  THIS CONNECTION ALSO SHOWS THE OUTPUT SWING.
******
VDD   100  0    1.5
VSS   200  0    -1.5
M1    17   9    8    8    PMOS W=150U L=1U
M2    18   16   8    8    PMOS W=150U L=1U
M1A   15   2    17   200  NMOS W=50U  L=1U
M2A   16   2    18   200  NMOS W=50U  L=1U
M3    13   13   100  100  PMOS W=150U L=1U
M4    14   13   100  100  PMOS W=150U L=1U
M3A   15   15   13   13   PMOS W=150U L=1U
M4A   16   15   14   14   PMOS W=150U L=1U
M5    8    1    100  100  PMOS W=300U L=1U
M11   17   3    200  200  NMOS W=100U L=1U
M12   18   3    200  200  NMOS W=100U L=1U
M13   20   1    100  100  PMOS W=150U L=1U
M14   1    1    100  100  PMOS W=150U L=1U
M15   4    4    5    200  NMOS W=50U  L=1U
M16   21   4    6    200  NMOS W=50U  L=1U
M17   12   2    200  200  NMOS W=10U  L=1U
M18   2    2    12   200  NMOS W=100U L=1U
M19   2    1    100  100  PMOS W=300U L=1U
M20   3    1    100  100  PMOS W=300U L=1U
M21   3    3    200  200  NMOS W=100U L=1U
M22   20   20   4    200  NMOS W=50U  L=1U
M23   1    20   21   200  NMOS W=50U  L=1U
Q1    200  200  5    PNP
Q2    200  200  7    PNP 4
R1    6    7    721
.MODEL NMOS NMOS LEVEL=1 KP=194U  VTO=0.6  LAMBDA=0.024 GAMMA=0.25
.MODEL PMOS PMOS LEVEL=1 KP=64.7U VTO=-0.8 LAMBDA=0.048 GAMMA=0.25
.MODEL PNP  PNP  BF=50   IS=2E-15
VI1  9   0   0
VI2  10  0   0
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.TF   V(16) VI1
.DC   VI1   -1.7 1.5 0.1
.PLOT DC    V(16)
.END
```

```
******  DC TRANSFER CURVES      TNOM=  27.000 TEMP=  27.000
   VOLT      V(16)
(A        )   -2.000E+00    -1.000E-00     0.         1.000E-00    2.000E+00
                   +             +             +            +            +
-1.700E+00 -1.50E+00-+------A------+------+------+------+------+------+------+-
-1.600E+00 -1.49E+00 +      A      +      +      +      +      +      +      +
-1.500E+00 -1.45E+00 +      +A     +      +      +      +      +      +      +
-1.400E+00 -1.39E+00 +      +A     +      +      +      +      +      +      +
-1.300E+00 -1.30E+00 +      +  A   +      +      +      +      +      +      +
-1.200E+00 -1.20E+00 +      +   A  +      +      +      +      +      +      +
-1.100E+00 -1.10E+00 +      +     A+      +      +      +      +      +      +
-1.000E+00 -1.00E-00 +      +      A      +      +      +      +      +      +
-9.000E-01 -9.00E-01 +      +      +A     +      +      +      +      +      +
-8.000E-01 -8.00E-01 +      +      +  A   +      +      +      +      +      +
-7.000E-01 -7.00E-01-+------+------+---A--+------+------+------+------+------+-
-6.000E-01 -6.00E-01 +      +      +     A+      +      +      +      +      +
-5.000E-01 -5.00E-01 +      +      +      A      +      +      +      +      +
-4.000E-01 -4.00E-01 +      +      +      +A     +      +      +      +      +
-3.000E-01 -3.00E-01 +      +      +      +  A   +      +      +      +      +
-2.000E-01 -2.00E-01 +      +      +      +   A  +      +      +      +      +
-1.000E-01 -1.00E-01 +      +      +      +     A+      +      +      +      +
  0.       -3.33E-06 +      +      +      +      A      +      +      +      +
 1.000E-01  1.00E-01 +      +      +      +      +A     +      +      +      +
 2.000E-01  2.00E-01 +      +      +      +      +  A   +      +      +      +
 3.000E-01  3.00E-01-+------+------+------+------+---A--+------+------+------+-
 4.000E-01  4.00E-01 +      +      +      +      +     A+      +      +      +
 5.000E-01  5.00E-01 +      +      +      +      +      A      +      +      +
 6.000E-01  6.00E-01 +      +      +      +      +      +A     +      +      +
 7.000E-01  6.88E-01 +      +      +      +      +      +  A   +      +      +
 8.000E-01  6.88E-01 +      +      +      +      +      +  A   +      +      +
 9.000E-01  6.88E-01 +      +      +      +      +      +  A   +      +      +
 1.000E+00  6.88E-01 +      +      +      +      +      +  A   +      +      +
 1.100E+00  6.88E-01 +      +      +      +      +      +  A   +      +      +
 1.200E+00  6.88E-01 +      +      +      +      +      +  A   +      +      +
 1.300E+00  6.88E-01-+------+------+------+------+------+--A---+------+------+-
 1.400E+00  6.88E-01 +      +      +      +      +      +  A   +      +      +
 1.500E+00  6.88E-01 +      +      +      +      +      +  A   +      +      +
                   +             +             +            +            +
```

```
****  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
  NODE       =VOLTAGE        NODE      =VOLTAGE       NODE      =VOLTAGE
+0:1         = 6.016E-01 0:2           =-5.479E-01 0:3          =-7.971E-01
+0:4         =-1.005E-01 0:5           =-8.820E-01 0:6          =-8.823E-01
+0:7         =-9.176E-01 0:8           = 8.950E-01 0:9          =   0.
+0:10        =   0.      0:12          =-1.282E+00 0:13         = 5.960E-01
+0:14        = 5.967E-01 0:15          =-3.081E-01 0:16         =-3.327E-06
+0:17        =-1.285E+00 0:18          =-1.284E+00 0:20         = 7.586E-01
+0:21        =-1.010E-01 0:100         = 1.500E+00 0:200        =-1.500E+00
```

```
****     SMALL-SIGNAL TRANSFER CHARACTERISTICS

     V(16)/VI1                                 =  1.000E-00
     INPUT RESISTANCE AT          VI1          =  1.000E+20
     OUTPUT RESISTANCE AT V(16)                =  9.858E+02
```

6.21



From Table (2·4), $\mu_n = 3\mu_p$.
Therefore, to produce overdrives with equal magnitudes for identical drain current magnitudes, n-channel transistors require $\left(\frac{W}{L}\right)$ 3 times smaller than corresponding p-channel transistors.

Let $|I_{D_1}| = |I_{D_2}| = I$

Then $|I_{D_5}| = I_{D_{11}} = I_{D_{12}} = 2I$

All other transistors have $|I_D| = I$

For equal overdrive magnitudes,

$$\left(\frac{W}{L}\right)_5 = 2\left(\frac{W}{L}\right)_1$$

$$\left(\frac{W}{L}\right)_{11} = \left(\frac{W}{L}\right)_{12} = \frac{2}{3}\left(\frac{W}{L}\right)_1$$

$$\left(\frac{W}{L}\right)_{3D} = \left(\frac{W}{L}\right)_{3A} = \left(\frac{W}{L}\right)_3 = \left(\frac{W}{L}\right)_4 = \left(\frac{W}{L}\right)_{4A} = \left(\frac{W}{L}\right)_{4B} = \left(\frac{W}{L}\right)_1$$

M_3, M_{3A}, M_{3B}, M_{3C}, M_{3D}, M_4, M_{4A} and M_{4B} form a double-cascode sooch current mirror

From (4.73),

$$\left(\frac{W}{L}\right)_{3C} = \frac{1}{3}\left(\frac{W}{L}\right)_{3D} = \frac{1}{3}\left(\frac{W}{L}\right)_1$$

From Problem (4.8),

$$\left(\frac{W}{L}\right)_{3B} = \frac{1}{5}\left(\frac{W}{L}\right)_{3D} = \frac{1}{5}\left(\frac{W}{L}\right)_1$$

to maximize output swing.

6.22

M_4, M_{4A}, M_{2A} and M_{12} should all operate in the active region for a peak to peak output swing of 2.5V

$$V_{DD} - (-V_{SS}) - V_{O(P-P)} = 1.65 - (-1.65) - 2.5 = 0.8\,V$$

Divide this amount equally among M_4, M_{4A}, M_{2A} and M_{12} to get $|V_{DS(min)}| = 0.2\,V$

To set $|V_{DS(min)}| = |V_{ov}| + 0.1\,V$

choose $|V_{ov}| = 0.1\,V$

Since all transistors are biased with equal $|V_{ov}|$, set $|V_{ov}| = 0.1\,V$ for all the transistors

since $I_{BIAS} = 25\,\mu A$

assume

$$I_{D101} = I_{D102} = I_{D103} = I_{D104}$$
$$= |I_{D105}| = |I_{D106}| = |I_{D107}| = |I_{D108}|$$
$$= I_{D109} = I_{D110}$$
$$= |I_{D111}| = |I_{D112}|$$
$$= I_{D113} = I_{D114} = 25\,\mu A$$

Since $I_{D25} = |I_{D35}| = 200\,\mu A$

$$I_{D21} = I_{D22} = |I_{D23}| = |I_{D24}| = 100\,\mu A$$

$$|I_{D31}| = |I_{D32}| = I_{D33} = I_{D34} = 100\,\mu A$$

Since $|I_{D5}| = 200\,\mu A$

$$|I_{D1}| = |I_{D2}| = 100\,\mu A$$

Since $I_{D11} = I_{D12} = 200\,\mu A$

$$I_{D1A} = I_{D2A} = |I_{D3A}| = |I_{D3}| = |I_{D4}| = I_{D4A} = 100\,\mu A$$

Since $|I_D| = \frac{k'}{2}\frac{W}{L}V_{ov}^2$

$$\frac{W}{L} = \frac{2|I_D|}{k' V_{ov}^2}$$

In the bias circuit,

$$\left(\frac{W}{L}\right)_{101} = \left(\frac{W}{L}\right)_{102} = \left(\frac{W}{L}\right)_{103} = \left(\frac{W}{L}\right)_{104} = \left(\frac{W}{L}\right)_{109} = \left(\frac{W}{L}\right)_{110} = \left(\frac{W}{L}\right)_{113}$$
$$= \frac{2(25)}{194(0.1)^2} \simeq 25$$

In the A_1 amplifiers,

$$\left(\frac{W}{L}\right)_{25} = \frac{2(200)}{194(0.1)^2} \simeq 200$$

$$\left(\frac{W}{L}\right)_{21} = \left(\frac{W}{L}\right)_{22} = \frac{2(100)}{194(0.1)^2} \simeq 100$$

$$\left(\frac{W}{L}\right)_{23} = \left(\frac{W}{L}\right)_{24} = \frac{2(100)}{64.7(0.1)^2} \simeq 300$$

In the A_2 amplifiers,

$$\left(\frac{W}{L}\right)_{35} = \frac{2(200)}{64.7(0.1)^2} \simeq 600$$

$$\left(\frac{W}{L}\right)_{31} = \left(\frac{W}{L}\right)_{32} = \frac{2(100)}{64.7\,(0.1)^2} \simeq 300$$

$$\left(\frac{W}{L}\right)_{33} = \left(\frac{W}{L}\right)_{34} = \frac{2(100)}{194\,(0.1)^2} \simeq 100$$

In the main op-amp,

$$\left(\frac{W}{L}\right)_{5} = \frac{2(200)}{64.7\,(0.1)^2} \simeq 600$$

$$\left(\frac{W}{L}\right)_{1} = \left(\frac{W}{L}\right)_{2} = \frac{2(100)}{64.7\,(0.1)^2} \simeq 300$$

$$\left(\frac{W}{L}\right)_{11} = \left(\frac{W}{L}\right)_{12} = \frac{2(200)}{194\,(0.1)^2} \simeq 200$$

$$\left(\frac{W}{L}\right)_{1A} = \left(\frac{W}{L}\right)_{2A} = \frac{2(100)}{194\,(0.1)^2} \simeq 100$$

$$\left(\frac{W}{L}\right)_{3A} = \left(\frac{W}{L}\right)_{3} = \left(\frac{W}{L}\right)_{4} = \left(\frac{W}{L}\right)_{4A} = \frac{2(100)}{64.7\,(0.1)^2} \simeq 300$$

From SPICE,

$\left(\frac{W}{L}\right)_{106} = 5$ to set $|V_{DS_{106}}| \simeq 0.1$ V

$\left(\frac{W}{L}\right)_{114} = 2.5$ to set $V_{DS_{114}} \simeq 0.1$ V

$\frac{v_o}{v_i} \simeq 35 \times 10^6$ with

$$\lambda_n = \frac{0.02}{1-2(0.09)} = 0.024\ V^{-1}$$

$$|\lambda_p| = \frac{0.04}{1-2(0.09)} = 0.049\ V^{-1}$$

and $|V_{to}| = 0.7$ V

With $V_{ton} = 0.6$ V and $V_{top} = -0.8$ V

$$\frac{v_o}{v_i} = 35 \times 10^4$$

The gain falls in this case because M_{22} in the A_1 amplifiers operates in the triode region. This happens because $V_{GD_{22}} \simeq |V_{tp}| + |V_{ovp}| > V_{t22}$ as explained in section 6.7. Therefore, increasing $|V_{to}|$ for p-channel transistors and reducing V_{to} for n-channel transistors both push M_{22} closer to the triode region.

```
ACTIVE FOLDED CASCODE OP AMP
******
VDD    100   0     1.65
VSS    200   0     -1.65
* OP AMP
M1     11    1     5     100 CMOSP W=300U L=1U
M2     12    2     5     100 CMOSP W=300U L=1U
M1A    40    61    11    200 CMOSN W=100U L=1U
M2A    10    62    12    200 CMOSN W=100U L=1U
M3     3     40    100   100 CMOSP W=300U L=1U
M4     4     40    100   100 CMOSP W=300U L=1U
M3A    40    63    3     100 CMOSP W=300U L=1U
M4A    10    64    4     100 CMOSP W=300U L=1U
M5     5     51    100   100 CMOSP W=600U L=1U
M11    11    54    200   200 CMOSN W=200U L=1U
M12    12    54    200   200 CMOSN W=200U L=1U
* AUXILIARY AMPLIFIER SUBCIRCUITS
.SUBCKT AMP1 (21 22 24 26 100 200)
*E1     24    0     21    22  100
M21    23    21    25    200 CMOSN W=100U L=1U
M22    24    22    25    200 CMOSN W=100U L=1U
M23    23    23    100   100 CMOSP W=300U L=1U
M24    24    23    100   100 CMOSP W=300U L=1U
M25    25    26    200   200 CMOSN W=200U L=1U
.ENDS AMP1
.SUBCKT AMP2 (31 32 34 36 100 200)
*E2     34    0     31    32  100
M31    33    31    35    100 CMOSP W=300U L=1U
M32    34    32    35    100 CMOSP W=300U L=1U
M33    33    33    200   200 CMOSN W=100U L=1U
M34    34    33    200   200 CMOSN W=100U L=1U
M35    35    36    100   100 CMOSP W=600U L=1U
.ENDS AMP2
* AUXILIARY AMPLIFIERS
X1     52    3     63    54  100   200   AMP1
X2     52    4     64    54  100   200   AMP1
X3     53    11    61    51  100   200   AMP2
X4     53    12    62    51  100   200   AMP2
* BIAS GENERATOR
IBIAS  100   101   25U
M101   101   101   54    200 CMOSN W=25U  L=1U
M102   54    54    200   200 CMOSN W=25U  L=1U
M103   103   54    200   200 CMOSN W=25U  L=1U
M104   105   101   103   200 CMOSN W=25U  L=1U
M105   105   105   52    100 CMOSP W=25U  L=1U
M106   52    105   100   100 CMOSP W=5U   L=1U
M107   51    51    100   100 CMOSP W=75U  L=1U
M108   108   108   51    100 CMOSP W=75U  L=1U
M109   108   101   110   200 CMOSN W=25U  L=1U
M110   110   54    200   200 CMOSN W=25U  L=1U
M111   111   51    100   100 CMOSP W=75U  L=1U
M112   113   108   111   100 CMOSP W=75U  L=1U
M113   113   113   53    200 CMOSN W=25U  L=1U
M114   53    113   200   200 CMOSN W=2.5U L=1U
CL     10    0     4P
.MODEL CMOSN NMOS LEVEL=1
+ TOX=0.8E-08 VTO=0.7 KP=194U LD=0.09U LAMBDA=0.024 GAMMA=0.25
.MODEL CMOSP PMOS LEVEL=1
+ TOX=0.8E-08 VTO=-0.7 KP=64.7U LD=0.09U LAMBDA=0.049 GAMMA=0.25
VIP    1     0 0 AC 1
VIN    2     0 0
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.TF V(10) VIP
.END
```

```
 ****  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
   NODE      =VOLTAGE       NODE      =VOLTAGE       NODE      =VOLTAGE
+0:1        =   0.        0:2       =   0.        0:3        = 1.437E+00
+0:4        = 1.437E+00 0:5         = 8.854E-01 0:10         = 8.598E-01
+0:11       =-1.456E+00 0:12        =-1.456E+00 0:40         = 8.598E-01
+0:51       = 8.598E-01 0:52        = 1.436E+00 0:53         =-1.456E+00
+0:54       =-8.589E-01 0:61        =-6.396E-01 0:62         =-6.396E-01
+0:63       = 6.165E-01 0:64        = 6.165E-01 0:100        = 1.650E+00
+0:101      = 3.327E-02 0:103       =-8.584E-01 0:105        = 5.492E-01
+0:108      =-3.128E-02 0:110       =-8.590E-01 0:111        = 8.587E-01
+0:113      =-6.360E-01 0:200       =-1.650E+00 1:23         = 8.587E-01
+1:25       = 4.287E-01 2:23        = 8.587E-01 2:25         = 4.287E-01
+3:33       =-8.563E-01 3:35        =-4.457E-01 4:33         =-8.563E-01
+4:35       =-4.457E-01
```

```
**** MOSFETS
SUBCKT
ELEMENT  0:M1       0:M2       0:M1A      0:M2A      0:M3
MODEL    0:CMOSP    0:CMOSP    0:CMOSN    0:CMOSN    0:CMOSP
 ID      -9.988E-05 -9.988E-05  9.730E-05  9.730E-05 -9.730E-05
 IBS      7.646E-15  7.646E-15 -1.931E-15 -1.931E-15   0.
 IBD      3.107E-14  3.107E-14 -2.510E-14 -2.510E-14  2.124E-15
 VGS     -8.854E-01 -8.854E-01  8.173E-01  8.173E-01 -7.902E-01
 VDS     -2.342E+00 -2.342E+00  2.316E+00  2.316E+00 -2.124E-01
 VBS      7.646E-01  7.646E-01 -1.931E-01 -1.931E-01   0.
 VTH     -7.984E-01 -7.984E-01  7.290E-01  7.290E-01 -7.000E-01
 VDSAT   -8.701E-02 -8.701E-02  8.827E-02  8.827E-02 -9.020E-02
 BETA     2.639E-02  2.639E-02  2.497E-02  2.497E-02  2.392E-02
 GAM EFF  2.500E-01  2.500E-01  2.500E-01  2.500E-01  2.500E-01
 GM       2.296E-03  2.296E-03  2.205E-03  2.205E-03  2.157E-03
 GDS      4.390E-06  4.390E-06  2.212E-06  2.212E-06  4.719E-06
 GMB      2.457E-04  2.457E-04  3.094E-04  3.094E-04  3.482E-04
SUBCKT
ELEMENT  0:M4       0:M3A      0:M4A      0:M5       0:M11
MODEL    0:CMOSP    0:CMOSP    0:CMOSP    0:CMOSP    0:CMOSN
 ID      -9.730E-05 -9.730E-05 -9.730E-05 -1.998E-04  1.972E-04
 IBS       0.        2.124E-15  2.124E-15   0.         0.
 IBD      2.124E-15  7.902E-15  7.902E-15  7.646E-15 -1.931E-15
 VGS     -7.902E-01 -8.211E-01 -8.211E-01 -7.902E-01  7.911E-01
 VDS     -2.124E-01 -5.778E-01 -5.778E-01 -7.646E-01  1.931E-01
 VBS       0.        2.124E-01  2.124E-01   0.         0.
 VTH     -7.000E-01 -7.317E-01 -7.317E-01 -7.000E-01  7.000E-01
 VDSAT   -9.020E-02 -8.942E-02 -8.942E-02 -9.019E-02  9.108E-02
 BETA     2.392E-02  2.434E-02  2.434E-02  4.912E-02  4.754E-02
 GAM EFF  2.500E-01  2.500E-01  2.500E-01  2.500E-01  2.500E-01
 GM       2.157E-03  2.176E-03  2.176E-03  4.430E-03  4.330E-03
 GDS      4.719E-06  4.637E-06  4.637E-06  9.435E-06  4.711E-06
 GMB      3.482E-04  3.018E-04  3.018E-04  7.148E-04  6.987E-04
SUBCKT
ELEMENT  0:M12      0:M101     0:M102     0:M103     0:M104
MODEL    0:CMOSN    0:CMOSN    0:CMOSN    0:CMOSN    0:CMOSN
 ID       1.972E-04  2.500E-05  2.500E-05  2.500E-05  2.500E-05
 IBS       0.       -7.911E-15   0.         0.       -7.916E-15
 IBD     -1.931E-15 -1.683E-14 -7.911E-15 -7.916E-15 -2.199E-14
 VGS      7.911E-01  8.922E-01  7.911E-01  7.911E-01  8.917E-01
 VDS      1.931E-01  8.922E-01  7.911E-01  7.916E-01  1.407E+00
 VBS       0.       -7.911E-01   0.         0.       -7.916E-01
 VTH      7.000E-01  8.012E-01  7.000E-01  7.000E-01  8.013E-01
 VDSAT    9.108E-02  9.097E-02  9.108E-02  9.108E-02  9.043E-02
 BETA     4.754E-02  6.041E-03  6.027E-03  6.027E-03  6.114E-03
 GAM EFF  2.500E-01  2.500E-01  2.500E-01  2.500E-01  2.500E-01
 GM       4.330E-03  5.496E-04  5.490E-04  5.490E-04  5.529E-04
 GDS      4.711E-06  5.874E-07  5.888E-07  5.888E-07  5.804E-07
 GMB      6.987E-04  5.825E-05  8.859E-05  8.859E-05  5.859E-05
SUBCKT
ELEMENT  0:M105     0:M106     0:M107     0:M108     0:M109
MODEL    0:CMOSP    0:CMOSP    0:CMOSP    0:CMOSP    0:CMOSN
 ID      -2.500E-05 -2.500E-05 -2.500E-05 -2.500E-05  2.500E-05
 IBS      2.132E-15   0.         0.        7.902E-15 -7.910E-15
 IBD      1.101E-14  2.132E-15  7.902E-15  1.681E-14 -1.619E-14
 VGS     -8.876E-01 -1.100E+00 -7.902E-01 -8.911E-01  8.922E-01
 VDS     -8.876E-01 -2.132E-01 -7.902E-01 -8.911E-01  8.277E-01
 VBS      2.132E-01   0.         0.        7.902E-01 -7.910E-01
 VTH     -7.318E-01 -7.000E-01 -7.000E-01 -8.011E-01  8.012E-01
 VDSAT   -1.559E-01 -2.132E-01 -9.019E-02 -8.998E-02  9.104E-02
 BETA     2.058E-03  3.986E-04  6.147E-03  6.176E-03  6.032E-03
 GAM EFF  2.500E-01  2.500E-01  2.500E-01  2.500E-01  2.500E-01
 GM       3.208E-04  8.497E-05  5.544E-04  5.557E-04  5.492E-04
 GDS      1.174E-06  7.601E-05  1.179E-06  1.174E-06  5.883E-07
 GMB      4.447E-05  1.371E-05  8.946E-05  5.891E-05  5.821E-05
SUBCKT
ELEMENT  0:M110     0:M111     0:M112     0:M113     0:M114
MODEL    0:CMOSN    0:CMOSP    0:CMOSP    0:CMOSN    0:CMOSN
 ID       2.500E-05 -2.500E-05 -2.500E-05  2.500E-05  2.500E-05
 IBS       0.         0.        7.913E-15 -1.938E-15   0.
 IBD     -7.910E-15  7.913E-15  2.286E-14 -1.014E-14 -1.938E-15
 VGS      7.911E-01 -7.902E-01 -8.900E-01  8.201E-01  1.014E+00
 VDS      7.910E-01 -7.913E-01 -1.494E+00  8.201E-01  1.938E-01
 VBS       0.         0.        7.913E-01 -1.938E-01   0.
 VTH      7.000E-01 -7.000E-01 -8.012E-01  7.291E-01  7.000E-01
 VDSAT    9.108E-02 -9.019E-02 -8.873E-02  9.105E-02  1.938E-01
 BETA     6.027E-03  6.147E-03  6.351E-03  6.031E-03  5.942E-04
 GAM EFF  2.500E-01  2.500E-01  2.500E-01  2.500E-01  2.500E-01
 GM       5.489E-04  5.544E-04  5.635E-04  5.492E-04  1.152E-04
 GDS      5.888E-07  1.179E-06  1.141E-06  5.884E-07  7.199E-05
 GMB      8.859E-05  8.947E-05  5.972E-05  7.704E-05  1.859E-05
```

```
SUBCKT   X1         X1         X1         X1         X1
ELEMENT  1:M21      1:M22      1:M23      1:M24      1:M25
MODEL    0:CMOSN    0:CMOSN    0:CMOSP    0:CMOSP    0:CMOSN
 ID       1.024E-04  1.036E-04 -1.024E-04 -1.036E-04  2.061E-04
 IBS     -2.079E-14 -2.079E-14  0.         0.         0.
 IBD     -2.509E-14 -2.267E-14  7.913E-15  1.033E-14 -2.079E-14
 VGS      1.008E+00  1.008E+00 -7.913E-01 -7.913E-01  7.911E-01
 VDS      4.300E-01  1.878E-01 -7.913E-01 -1.033E+00  2.078E+00
 VBS     -2.078E+00 -2.078E+00  0.         0.         0.
 VTH      9.155E-01  9.155E-01 -7.000E-01 -7.000E-01  7.000E-01
 VDSAT    9.259E-02  9.338E-02 -9.129E-02 -9.129E-02  9.108E-02
 BETA     2.390E-02  2.377E-02  2.459E-02  2.487E-02  4.968E-02
 GAM EFF  2.500E-01  2.500E-01  2.500E-01  2.500E-01  2.500E-01
 GM       2.213E-03  2.219E-03  2.245E-03  2.270E-03  4.525E-03
 GDS      2.434E-06  2.476E-06  4.833E-06  4.833E-06  4.711E-06
 GMB      1.690E-04  1.695E-04  3.622E-04  3.664E-04  7.302E-04

SUBCKT   X2         X2         X2         X2         X2
ELEMENT  2:M21      2:M22      2:M23      2:M24      2:M25
MODEL    0:CMOSN    0:CMOSN    0:CMOSP    0:CMOSP    0:CMOSN
 ID       1.024E-04  1.036E-04 -1.024E-04 -1.036E-04  2.061E-04
 IBS     -2.079E-14 -2.079E-14  0.         0.         0.
 IBD     -2.509E-14 -2.267E-14  7.913E-15  1.033E-14 -2.079E-14
 VGS      1.008E+00  1.008E+00 -7.913E-01 -7.913E-01  7.911E-01
 VDS      4.300E-01  1.878E-01 -7.913E-01 -1.033E+00  2.078E+00
 VBS     -2.078E+00 -2.078E+00  0.         0.         0.
 VTH      9.155E-01  9.155E-01 -7.000E-01 -7.000E-01  7.000E-01
 VDSAT    9.259E-02  9.338E-02 -9.129E-02 -9.129E-02  9.108E-02
 BETA     2.390E-02  2.377E-02  2.459E-02  2.487E-02  4.968E-02
 GAM EFF  2.500E-01  2.500E-01  2.500E-01  2.500E-01  2.500E-01
 GM       2.213E-03  2.219E-03  2.245E-03  2.270E-03  4.525E-03
 GDS      2.434E-06  2.476E-06  4.833E-06  4.833E-06  4.711E-06
 GMB      1.690E-04  1.695E-04  3.622E-04  3.664E-04  7.302E-04

SUBCKT   X3         X3         X3         X3         X3
ELEMENT  3:M31      3:M32      3:M33      3:M34      3:M35
MODEL    0:CMOSP    0:CMOSP    0:CMOSN    0:CMOSN    0:CMOSP
 ID      -1.059E-04 -1.064E-04  1.059E-04  1.064E-04 -2.123E-04
 IBS      2.096E-14  2.096E-14  0.         0.         0.
 IBD      2.506E-14  2.290E-14 -7.937E-15 -1.010E-14  2.096E-14
 VGS     -1.010E+00 -1.011E+00  7.937E-01  7.937E-01 -7.902E-01
 VDS     -4.106E-01 -1.939E-01  7.937E-01  1.010E+00 -2.095E+00
 VBS      2.095E+00  2.095E+00  0.         0.         0.
 VTH     -9.168E-01 -9.168E-01  7.000E-01  7.000E-01 -7.000E-01
 VDSAT   -9.365E-02 -9.438E-02  9.372E-02  9.372E-02 -9.019E-02
 BETA     2.415E-02  2.390E-02  2.411E-02  2.423E-02  5.220E-02
 GAM EFF  2.500E-01  2.500E-01  2.500E-01  2.500E-01  2.500E-01
 GM       2.261E-03  2.255E-03  2.260E-03  2.271E-03  4.708E-03
 GDS      5.086E-06  5.166E-06  2.494E-06  2.494E-06  9.435E-06
 GMB      1.722E-04  1.717E-04  3.646E-04  3.665E-04  7.598E-04

SUBCKT   X4         X4         X4         X4         X4
ELEMENT  4:M31      4:M32      4:M33      4:M34      4:M35
MODEL    0:CMOSP    0:CMOSP    0:CMOSN    0:CMOSN    0:CMOSP
 ID      -1.059E-04 -1.064E-04  1.059E-04  1.064E-04 -2.123E-04
 IBS      2.096E-14  2.096E-14  0.         0.         0.
 IBD      2.506E-14  2.290E-14 -7.937E-15 -1.010E-14  2.096E-14
 VGS     -1.010E+00 -1.011E+00  7.937E-01  7.937E-01 -7.902E-01
 VDS     -4.106E-01 -1.939E-01  7.937E-01  1.010E+00 -2.095E+00
 VBS      2.095E+00  2.095E+00  0.         0.         0.
 VTH     -9.168E-01 -9.168E-01  7.000E-01  7.000E-01 -7.000E-01
 VDSAT   -9.365E-02 -9.438E-02  9.372E-02  9.372E-02 -9.019E-02
 BETA     2.415E-02  2.390E-02  2.411E-02  2.423E-02  5.220E-02
 GAM EFF  2.500E-01  2.500E-01  2.500E-01  2.500E-01  2.500E-01
 GM       2.261E-03  2.255E-03  2.260E-03  2.271E-03  4.708E-03
 GDS      5.086E-06  5.166E-06  2.494E-06  2.494E-06  9.435E-06
 GMB      1.722E-04  1.717E-04  3.646E-04  3.665E-04  7.598E-04

****     SMALL-SIGNAL TRANSFER CHARACTERISTICS

     V(10)/VIP                                =  3.488E+07
     INPUT RESISTANCE AT          VIP         =  1.000E+20
     OUTPUT RESISTANCE AT V(10)               =  1.519E+10
```

```
ACTIVE FOLDED CASCODE OP AMP (NEW ZERO-BIAS THRESHOLDS)
******
VDD    100    0     1.65
VSS    200    0    -1.65
* OP AMP
M1     11     1      5      100 CMOSP W=300U L=1U
M2     12     2      5      100 CMOSP W=300U L=1U
M1A    40     61     11     200 CMOSN W=100U L=1U
M2A    10     62     12     200 CMOSN W=100U L=1U
M3     3      40     100    100 CMOSP W=300U L=1U
M4     4      40     100    100 CMOSP W=300U L=1U
M3A    40     63     3      100 CMOSP W=300U L=1U
M4A    10     64     4      100 CMOSP W=300U L=1U
M5     5      51     100    100 CMOSP W=600U L=1U
M11    11     54     200    200 CMOSN W=200U L=1U
M12    12     54     200    200 CMOSN W=200U L=1U
* AUXILIARY AMPLIFIER SUBCIRCUITS
.SUBCKT AMP1 (21 22 24 26 100 200)
*E1     24     0      21     22  100
M21    23     21     25     200 CMOSN W=100U L=1U
M22    24     22     25     200 CMOSN W=100U L=1U
M23    23     23     100    100 CMOSP W=300U L=1U
M24    24     23     100    100 CMOSP W=300U L=1U
M25    25     26     200    200 CMOSN W=200U L=1U
.ENDS AMP1
.SUBCKT AMP2 (31 32 34 36 100 200)
*E2     34     0      31     32  100
M31    33     31     35     100 CMOSP W=300U L=1U
M32    34     32     35     100 CMOSP W=300U L=1U
M33    33     33     200    200 CMOSN W=100U L=1U
M34    34     33     200    200 CMOSN W=100U L=1U
M35    35     36     100    100 CMOSP W=600U L=1U
.ENDS AMP2
* AUXILIARY AMPLIFIERS
X1     52     3      63     54  100   200    AMP1
X2     52     4      64     54  100   200    AMP1
X3     53     11     61     51  100   200    AMP2
X4     53     12     62     51  100   200    AMP2
* BIAS GENERATOR
IBIAS  100    101    25U
M101   101    101    54     200 CMOSN W=25U  L=1U
M102   54     54     200    200 CMOSN W=25U  L=1U
M103   103    54     200    200 CMOSN W=25U  L=1U
M104   105    101    103    200 CMOSN W=25U  L=1U
M105   105    105    52     100 CMOSP W=25U  L=1U
M106   52     105    100    100 CMOSP W=5U   L=1U
M107   51     51     100    100 CMOSP W=75U  L=1U
M108   108    108    51     100 CMOSP W=75U  L=1U
M109   108    101    110    200 CMOSN W=25U  L=1U
M110   110    54     200    200 CMOSN W=25U  L=1U
M111   111    51     100    100 CMOSP W=75U  L=1U
M112   113    108    111    100 CMOSP W=75U  L=1U
M113   113    113    53     200 CMOSN W=25U  L=1U
M114   53     113    200    200 CMOSN W=2.5U L=1U
CL     10     0      4P
.MODEL CMOSN NMOS LEVEL=1
+ TOX=0.8E-08 VTO=0.6 KP=194U LD=0.09U LAMBDA=0.024 GAMMA=0.25
.MODEL CMOSP PMOS LEVEL=1
+ TOX=0.8E-08 VTO=-0.8 KP=64.7U LD=0.09U LAMBDA=0.049 GAMMA=0.25
VIP      1         0 0 AC 1
VIN      2         0 0
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.TF V(10) VIP
.END
```

```
 ****  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
   NODE       =VOLTAGE     NODE      =VOLTAGE     NODE      =VOLTAGE
 +0:1         =   0.       0:2       =   0.       0:3       = 1.476E+00
 +0:4         = 1.476E+00  0:5       = 9.751E-01  0:10      = 7.591E-01
 +0:11        =-1.457E+00  0:12      =-1.457E+00  0:40      = 7.591E-01
 +0:51        = 7.600E-01  0:52      = 1.436E+00  0:53      =-1.456E+00
 +0:54        =-9.588E-01  0:61      =-7.390E-01  0:62      =-7.390E-01
 +0:63        = 5.600E-01  0:64      = 5.600E-01  0:100     = 1.650E+00
 +0:101       =-1.773E-01  0:103     =-9.582E-01  0:105     = 4.494E-01
 +0:108       =-2.412E-01  0:110     =-9.589E-01  0:111     = 7.591E-01
 +0:113       =-7.360E-01  0:200     =-1.650E+00  1:23      = 7.587E-01
 +1:25        = 5.211E-01  2:23      = 7.587E-01  2:25      = 5.211E-01
 +3:33        =-9.566E-01  3:35      =-3.537E-01  4:33      =-9.566E-01
 +4:35        =-3.537E-01
```

**** MOSFETS

SUBCKT					
ELEMENT	0:M1	0:M2	0:M1A	0:M2A	0:M3
MODEL	0:CMOSP	0:CMOSP	0:CMOSN	0:CMOSN	0:CMOSP
ID	-9.899E-05	-9.899E-05	9.866E-05	9.866E-05	-9.866E-05
IBS	6.749E-15	6.749E-15	-1.930E-15	-1.930E-15	0.
IBD	3.107E-14	3.107E-14	-2.409E-14	-2.409E-14	1.740E-15
VGS	-9.751E-01	-9.751E-01	7.180E-01	7.180E-01	-8.909E-01
VDS	-2.432E+00	-2.432E+00	2.216E+00	2.216E+00	-1.740E-01
VBS	6.749E-01	6.749E-01	-1.930E-01	-1.930E-01	0.
VTH	-8.886E-01	-8.886E-01	6.290E-01	6.290E-01	-8.000E-01
VDSAT	-8.645E-02	-8.645E-02	8.899E-02	8.899E-02	-9.091E-02
BETA	2.649E-02	2.649E-02	2.492E-02	2.492E-02	2.387E-02
GAM EFF	2.500E-01	2.500E-01	2.500E-01	2.500E-01	2.500E-01
GM	2.290E-03	2.290E-03	2.217E-03	2.217E-03	2.170E-03
GDS	4.334E-06	4.334E-06	2.248E-06	2.248E-06	4.793E-06
GMB	2.535E-04	2.535E-04	3.112E-04	3.112E-04	3.502E-04

SUBCKT					
ELEMENT	0:M4	0:M3A	0:M4A	0:M5	0:M11
MODEL	0:CMOSP	0:CMOSP	0:CMOSP	0:CMOSP	0:CMOSN
ID	-9.866E-05	-9.866E-05	-9.866E-05	-1.980E-04	1.976E-04
IBS	0.	1.740E-15	1.740E-15	0.	0.
IBD	1.740E-15	8.909E-15	8.909E-15	6.749E-15	-1.930E-15
VGS	-8.909E-01	-9.160E-01	-9.160E-01	-8.900E-01	6.912E-01
VDS	-1.740E-01	-7.169E-01	-7.169E-01	-6.749E-01	1.930E-01
VBS	0.	1.740E-01	1.740E-01	0.	0.
VTH	-8.000E-01	-8.263E-01	-8.263E-01	-8.000E-01	6.000E-01
VDSAT	-9.091E-02	-8.974E-02	-8.974E-02	-8.998E-02	9.119E-02
BETA	2.387E-02	2.450E-02	2.450E-02	4.891E-02	4.754E-02
GAM EFF	2.500E-01	2.500E-01	2.500E-01	2.500E-01	2.500E-01
GM	2.170E-03	2.199E-03	2.199E-03	4.401E-03	4.335E-03
GDS	4.793E-06	4.670E-06	4.670E-06	9.390E-06	4.722E-06
GMB	3.502E-04	3.124E-04	3.124E-04	7.101E-04	6.995E-04

SUBCKT					
ELEMENT	0:M12	0:M101	0:M102	0:M103	0:M104
MODEL	0:CMOSN	0:CMOSN	0:CMOSN	0:CMOSN	0:CMOSN
ID	1.976E-04	2.500E-05	2.500E-05	2.500E-05	2.500E-05
IBS	0.	-6.912E-15	0.	0.	-6.918E-15
IBD	-1.930E-15	-1.473E-14	-6.912E-15	-6.918E-15	-2.099E-14
VGS	6.912E-01	7.815E-01	6.912E-01	6.912E-01	7.809E-01
VDS	1.930E-01	7.815E-01	6.912E-01	6.918E-01	1.407E+00
VBS	0.	-6.912E-01	0.	0.	-6.918E-01
VTH	6.000E-01	6.904E-01	6.000E-01	6.000E-01	6.905E-01
VDSAT	9.119E-02	9.109E-02	9.119E-02	9.119E-02	9.043E-02
BETA	4.754E-02	6.026E-03	6.013E-03	6.013E-03	6.114E-03
GAM EFF	2.500E-01	2.500E-01	2.500E-01	2.500E-01	2.500E-01
GM	4.335E-03	5.489E-04	5.483E-04	5.483E-04	5.529E-04
GDS	4.722E-06	5.890E-07	5.902E-07	5.902E-07	5.804E-07
GMB	6.995E-04	6.038E-05	8.848E-05	8.848E-05	6.081E-05

SUBCKT					
ELEMENT	0:M105	0:M106	0:M107	0:M108	0:M109
MODEL	0:CMOSP	0:CMOSP	0:CMOSP	0:CMOSP	0:CMOSN
ID	-2.500E-05	-2.500E-05	-2.500E-05	-2.500E-05	2.500E-05
IBS	2.133E-15	0.	0.	8.900E-15	-6.911E-15
IBD	1.201E-14	2.133E-15	8.900E-15	1.891E-14	-1.409E-14
VGS	-9.873E-01	-1.200E+00	-8.900E-01	-1.001E+00	7.816E-01
VDS	-9.873E-01	-2.133E-01	-8.900E-01	-1.001E+00	7.176E-01
VBS	2.133E-01	0.	0.	8.900E-01	-6.911E-01
VTH	-8.318E-01	-8.000E-01	-8.000E-01	-9.115E-01	6.904E-01
VDSAT	-1.555E-01	-2.133E-01	-8.998E-02	-8.974E-02	9.116E-02
BETA	2.068E-03	3.986E-04	6.176E-03	6.208E-03	6.017E-03
GAM EFF	2.500E-01	2.500E-01	2.500E-01	2.500E-01	2.500E-01
GM	3.216E-04	8.504E-05	5.557E-04	5.571E-04	5.485E-04
GDS	1.168E-06	7.588E-05	1.174E-06	1.168E-06	5.898E-07
GMB	4.457E-05	1.372E-05	8.967E-05	5.705E-05	6.034E-05

SUBCKT					
ELEMENT	0:M110	0:M111	0:M112	0:M113	0:M114
MODEL	0:CMOSN	0:CMOSP	0:CMOSP	0:CMOSN	0:CMOSN
ID	2.500E-05	-2.500E-05	-2.500E-05	2.500E-05	2.500E-05
IBS	0.	0.	8.909E-15	-1.938E-15	0.
IBD	-6.911E-15	8.909E-15	2.386E-14	-9.140E-15	-1.938E-15
VGS	6.912E-01	-8.900E-01	-1.000E+00	7.202E-01	9.140E-01
VDS	6.911E-01	-8.909E-01	-1.495E+00	7.202E-01	1.938E-01
VBS	0.	0.	8.909E-01	-1.938E-01	0.
VTH	6.000E-01	-8.000E-01	-9.116E-01	6.291E-01	6.000E-01
VDSAT	9.119E-02	-8.998E-02	-8.873E-02	9.116E-02	1.938E-01
BETA	6.013E-03	6.176E-03	6.351E-03	6.017E-03	5.942E-04
GAM EFF	2.500E-01	2.500E-01	2.500E-01	2.500E-01	2.500E-01
GM	5.483E-04	5.557E-04	5.635E-04	5.485E-04	1.151E-04
GDS	5.902E-07	1.174E-06	1.141E-06	5.898E-07	7.205E-05
GMB	8.848E-05	8.968E-05	5.769E-05	7.696E-05	1.858E-05

SUBCKT	X1	X1	X1	X1	X1
ELEMENT	1:M21	1:M22	1:M23	1:M24	1:M25
MODEL	0:CMOSN	0:CMOSN	0:CMOSP	0:CMOSP	0:CMOSN
ID	1.030E-04	1.040E-04	-1.030E-04	-1.040E-04	2.070E-04
IBS	-2.171E-14	-2.171E-14	0.	0.	0.
IBD	-2.409E-14	-2.210E-14	8.913E-15	1.090E-14	-2.171E-14
VGS	9.156E-01	9.549E-01	-8.913E-01	-8.913E-01	6.912E-01
VDS	2.376E-01	3.887E-02	-8.913E-01	-1.090E+00	2.171E+00
VBS	-2.171E+00	-2.171E+00	0.	0.	0.
VTH	8.225E-01	8.225E-01	-8.000E-01	-8.000E-01	6.000E-01
VDSAT	9.305E-02	3.887E-02	-9.132E-02	-9.132E-02	9.119E-02
BETA	2.379E-02	2.368E-02	2.470E-02	2.494E-02	4.978E-02
GAM EFF	2.500E-01	2.500E-01	2.500E-01	2.500E-01	2.500E-01
GM	2.214E-03	9.205E-04	2.256E-03	2.277E-03	4.540E-03
GDS	2.458E-06	2.217E-03	4.836E-06	4.836E-06	4.722E-06
GMB	1.663E-04	6.912E-05	3.641E-04	3.675E-04	7.326E-04

SUBCKT	X2	X2	X2	X2	X2
ELEMENT	2:M21	2:M22	2:M23	2:M24	2:M25
MODEL	0:CMOSN	0:CMOSN	0:CMOSP	0:CMOSP	0:CMOSN
ID	1.030E-04	1.040E-04	-1.030E-04	-1.040E-04	2.070E-04
IBS	-2.171E-14	-2.171E-14	0.	0.	0.
IBD	-2.409E-14	-2.210E-14	8.913E-15	1.090E-14	-2.171E-14
VGS	9.156E-01	9.549E-01	-8.913E-01	-8.913E-01	6.912E-01
VDS	2.376E-01	3.887E-02	-8.913E-01	-1.090E+00	2.171E+00
VBS	-2.171E+00	-2.171E+00	0.	0.	0.
VTH	8.225E-01	8.225E-01	-8.000E-01	-8.000E-01	6.000E-01
VDSAT	9.305E-02	3.887E-02	-9.132E-02	-9.132E-02	9.119E-02
BETA	2.379E-02	2.368E-02	2.470E-02	2.494E-02	4.978E-02
GAM EFF	2.500E-01	2.500E-01	2.500E-01	2.500E-01	2.500E-01
GM	2.214E-03	9.205E-04	2.256E-03	2.277E-03	4.540E-03
GDS	2.458E-06	2.217E-03	4.836E-06	4.836E-06	4.722E-06
GMB	1.663E-04	6.912E-05	3.641E-04	3.675E-04	7.326E-04

SUBCKT	X3	X3	X3	X3	X3
ELEMENT	3:M31	3:M32	3:M33	3:M34	3:M35
MODEL	0:CMOSP	0:CMOSP	0:CMOSN	0:CMOSN	0:CMOSP
ID	-1.050E-04	-1.055E-04	1.050E-04	1.055E-04	-2.105E-04
IBS	2.004E-14	2.004E-14	0.	0.	0.
IBD	2.607E-14	2.389E-14	-6.934E-15	-9.110E-15	2.004E-14
VGS	-1.102E+00	-1.103E+00	6.934E-01	6.934E-01	-8.900E-01
VDS	-6.029E-01	-3.853E-01	6.934E-01	9.110E-01	-2.003E+00
VBS	2.003E+00	2.003E+00	0.	0.	0.
VTH	-1.009E+00	-1.009E+00	6.000E-01	6.000E-01	-8.000E-01
VDSAT	-9.281E-02	-9.353E-02	9.342E-02	9.342E-02	-8.998E-02
BETA	2.437E-02	2.412E-02	2.405E-02	2.418E-02	5.199E-02
GAM EFF	2.500E-01	2.500E-01	2.500E-01	2.500E-01	2.500E-01
GM	2.262E-03	2.256E-03	2.247E-03	2.259E-03	4.678E-03
GDS	4.995E-06	5.074E-06	2.478E-06	2.478E-06	9.390E-06
GMB	1.752E-04	1.748E-04	3.626E-04	3.645E-04	7.549E-04

SUBCKT	X4	X4	X4	X4	X4
ELEMENT	4:M31	4:M32	4:M33	4:M34	4:M35
MODEL	0:CMOSP	0:CMOSP	0:CMOSN	0:CMOSN	0:CMOSP
ID	-1.050E-04	-1.055E-04	1.050E-04	1.055E-04	-2.105E-04
IBS	2.004E-14	2.004E-14	0.	0.	0.
IBD	2.607E-14	2.389E-14	-6.934E-15	-9.110E-15	2.004E-14
VGS	-1.102E+00	-1.103E+00	6.934E-01	6.934E-01	-8.900E-01
VDS	-6.029E-01	-3.853E-01	6.934E-01	9.110E-01	-2.003E+00
VBS	2.003E+00	2.003E+00	0.	0.	0.
VTH	-1.009E+00	-1.009E+00	6.000E-01	6.000E-01	-8.000E-01
VDSAT	-9.281E-02	-9.353E-02	9.342E-02	9.342E-02	-8.998E-02
BETA	2.437E-02	2.412E-02	2.405E-02	2.418E-02	5.199E-02
GAM EFF	2.500E-01	2.500E-01	2.500E-01	2.500E-01	2.500E-01
GM	2.262E-03	2.256E-03	2.247E-03	2.259E-03	4.678E-03
GDS	4.995E-06	5.074E-06	2.478E-06	2.478E-06	9.390E-06
GMB	1.752E-04	1.748E-04	3.626E-04	3.645E-04	7.549E-04

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(10)/VIP		= 3.492E+05
INPUT RESISTANCE AT	VIP	= 1.000E+20
OUTPUT RESISTANCE AT V(10)		= 1.525E+08

6.23

The limiting branch includes M_{107}, M_{108}, M_{109}, and M_{110} because $|V_{DS}|$ for three of these four transistors includes a $|V_t|$

$$|V_{DS_{107}}| = |V_{t\,107}| + |V_{ov_{107}}|$$

$$|V_{DS\,108}| = |V_{t\,108}| + |V_{ov_{108}}|$$

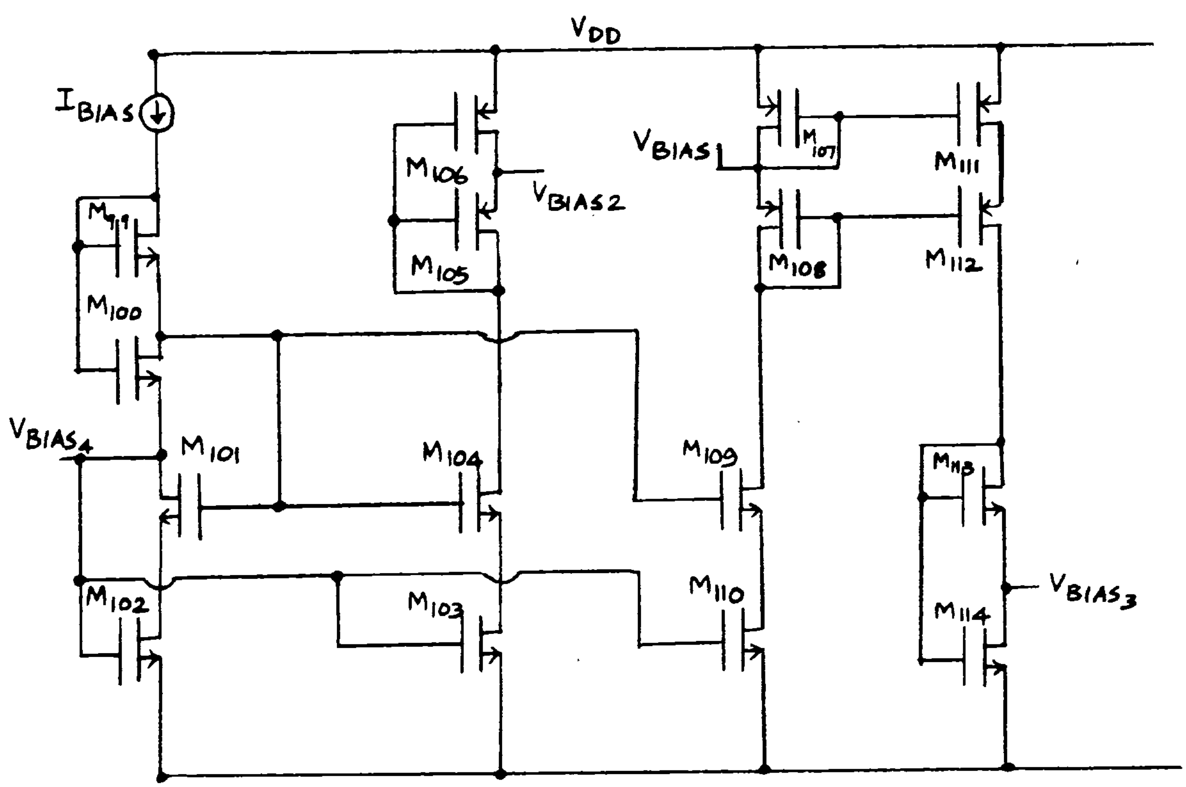
$$V_{DS_{110}} = V_{t_{102}} + V_{ov_{102}} \text{ if } V_{GS_{101}} = V_{GS_{109}}$$

No other branch includes more than two $|V_t|$ terms.

Since $|V_{DS}|$ of M_{107}, M_{108}, and M_{110} are set to a $|V_t|$ above $|V_{ov}|$, these transistors stay in the active region as $|V_{ov}|$ is increased. Therefore, M_{109} enters the triode region first because its drain-source voltage is determined by the power-supply voltages and the drain-source voltages of M_{107}, M_{108}, and M_{110} as follows

$$V_{DS_{109}} = V_{DD} - (-V_{SS}) - |V_{t_{107}}| - |V_{ov_{107}}| - |V_{t\,108}| - |V_{ov_{108}}| - V_{t_{102}} - V_{ov_{102}}$$

To increase the allowed $|V_{ov}|$, use a sooch cascode



If $\left(\frac{W}{L}\right)_{100}$ is adjusted so that

$V_{DS_{100}} = V_{OV_{110}} + 0.1\ V$

Then, $V_{DS_{110}} = V_{OV_{110}} + 0.1\ V$

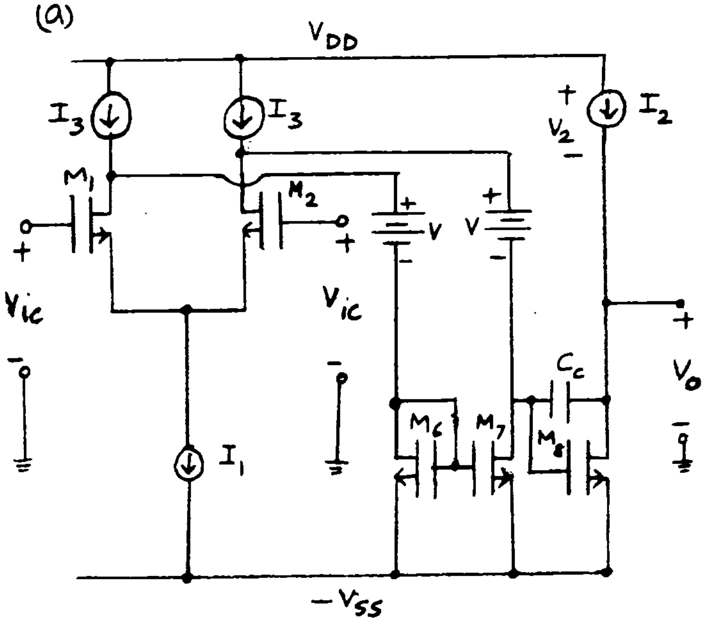
instead of

$V_{DS_{110}} = V_{t_{102}} + V_{OV_{102}}$ in the previous circuit. Assuming $V_{OV_{110}} = V_{OV_{102}}$, the sooch cascode reduces $V_{DS_{110}}$ if $V_{t_{102}} > 0.1\ V$

In turn, this increases $V_{DS_{109}}$ for a fixed $|V_{OV}|$, which means that a larger $|V_{OV}|$ is required to push M_{109} into the triode region. The key disadvantage of the new circuit is that it reduces the voltage across the I_{BIAS} generator.

6.24

(a)



CM input range:

To keep the transistor that forms I_1 in the active region,

$$V_{ic} > -V_{SS} + V_{OV_n} + V_{OV_1} + V_{t_1}$$

$$V_{IC} > -V_{SS} + V_{t_1} + 2V_{OV_n}$$

To keep M_1 in the active region,

$$V_{GD_1} < V_{t_1}$$

$$V_{G_1} = V_{IC}$$

$$V_{D_1} = -V_{SS} + V_{t_3} + V_{OV_3} + V$$

$$= -V_{SS} + V_{t_3} + V_{OV_n} + V$$

$$V_{G_1} - V_{D_1} < V_{t_1}$$

$$V_{IC} < V_{D_1} + V_{t_1}$$

$$< -V_{SS} + V_{t_3} + V_{OV_n} + V + V_{t_1}$$

So the CM input range is:

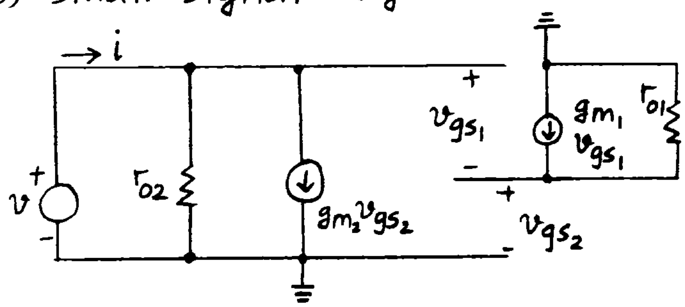
$$-V_{SS} + V_{t_1} + 2V_{OV_n} < V_{IC} < -V_{SS} + V_{t_3} + V_{OV_n} + V + V_{t_1}$$

output swing:

$$-V_{SS} + V_{OV_n} < V_o < V_{DD} - |V_{OV_P}|$$

because $V_{DS_8} > V_{OV_n}$ is required to operate M_8 in the active region and $V_2 > |V_{OV_P}|$ is required to operate the transistor forming I_2 in the active region.

(b) small-signal diagram :



$$R_i = \frac{v}{i}$$

$$i = \frac{v}{r_{o2}} + g_{m_2} v_{gs_2}$$

Since M_1 is a source-follower $v_{gs_2} \cong v$

$$i \simeq v\left(\frac{1}{r_{o2}} + g_{m_2}\right)$$

$$\frac{v}{i} \simeq \frac{1}{g_{m_2} + \frac{1}{r_{o2}}} \simeq \frac{1}{g_{m_2}} < 1\,k\Omega$$

$$g_{m_2} = \sqrt{2\,(100\,\mu A)(194\,\mu A/V^2)\left(W/L\right)_2}$$

$$1000\,\frac{\mu A}{V} = \frac{1}{1\,k\Omega} < \sqrt{2(100\,\mu A)\left(194\,\frac{\mu A}{V^2}\right)\left(\frac{W}{L}\right)_2}$$

$$\left(\frac{W}{L}\right)_2 > 25.8$$

$$V_{GS_2} = V_{t_2} + V_{ov_2}$$

$$= 0.6 + \sqrt{\frac{2(100)}{194(26)}} = 0.8\ V$$

$$V_{GS_1} + V_{GS_2} = V$$

$$V_{GS_1} = V - V_{GS_2} = 1.5 - 0.8 = 0.7\ V$$

$$= \underbrace{V_t}_{0.6\,V} + V_{ov_1}$$

SO, $V_{ov_1} = 0.7 - 0.6 = 0.1\ V$; $I_{D_1} = \frac{k'}{2}\left(\frac{W}{L}\right)_1 V_{ov_1}^2$

$$\left(\frac{W}{L}\right)_1 = \frac{2\,I_{D_1}}{k'\,V_{ov_1}^2} = \frac{2(100)}{194\,(0.1)^2} \simeq 100$$

```
MOS FLOATING LEVEL SHIFT
******
VDD     100    0     1.65
VSS     200    0     -1.65
M1      100      3         4       4   CMOSN W=100U L=1U
M2      3        4         5       200 CMOSN W=26U  L=1U
VM2     5        200       0
IB      4        200       100U
VI      3        200       1.5
.MODEL CMOSN NMOS LEVEL=1 VTO=0.6 KP=194U
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.DC VI 0 2 0.1
.PLOT DC I(VM2)
.TF V(3) VI
.END

 ******  DC TRANSFER CURVES      TNOM=  27.000 TEMP=  27.000
    VOLT       I(VM2)
(A        )      0.          5.000E-04    1.000E-03    1.500E-C3   2.000E-03
                      +           +            +            +           +
  0.        -2.02E-28-A------+------+------+------+------+------+------+------+-
1.000E-01  1.00E-13 A       +      +      +      +      +      +      +      +
2.000E-01  2.00E-13 A       +      +      +      +      +      +      +      +
3.000E-01  3.00E-13 A       +      +      +      +      +      +      +      +
4.000E-01  4.00E-13 A       +      +      +      +      +      +      +      +
5.000E-01  5.00E-13 A       +      +      +      +      +      +      +      +
6.000E-01  6.00E-13 A       +      +      +      +      +      +      +      +
7.000E-01  7.00E-13 A       +      +      +      +      +      +      .      +
8.000E-01  8.00E-13 A       +      +      +      +      +      +      +      +
9.000E-01  9.00E-13 A       +      +      +      +      +      +      .      +
1.000E+00  1.00E-12-A------+------+------+------+------+------+------+------+-
1.100E+00  1.10E-12 A       +      +      +      +      +      +      +      +
1.200E+00  1.20E-12 A       +      +      +      +      +      +      +      +
1.300E+00  1.30E-12 A       +      +      +      +      +      +      +      +
1.400E+00  2.45E-05 +A      +      +      +      +      +      +      +      +
1.500E+00  9.93E-05 +  A    +      +      +      +      +      +      +      +
1.600E+00  2.25E-04 +     A+      +      +      +      +      +      +      +
1.700E+00  4.00E-04 +       +  A   +      +      +      +      +      +      +
1.800E+00  6.27E-04 +       +      +  A   +      +      +      +      +      +
1.900E+00  9.03E-04 +       +      +      +  A   +      +      +      +      +
2.000E+00  1.23E-03-+------+------+------+------+-----A+------+------+------+-
                    +             +             +             +             +
 ****  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
   NODE      =VOLTAGE       NODE      =VOLTAGE       NODE      =VOLTAGE
+0:3         =-1.500E-01 0:4         =-8.515E-01 0:5          =-1.650E+00
+0:100       = 1.650E+00 0:200       =-1.650E+00

SUBCKT
ELEMENT  0:M1        0:M2
MODEL    0:CMOSN     0:CMOSN
 ID        1.000E-04  9.934E-05
 IBS         0.         0.
 IBD      -2.502E-14 -1.500E-14
 VGS       7.015E-01  7.985E-01
 VDS       2.501E+00  1.500E+00
 VBS         0.         0.
 VTH       6.000E-01  6.000E-01
 VDSAT     1.015E-01  1.985E-01
 BETA      1.940E-02  5.044E-03
 GAM EFF     0.         0.
 GM        1.970E-03  1.001E-03
 GDS         0.         0.
 GMB         0.         0.

****      SMALL-SIGNAL TRANSFER CHARACTERISTICS

     V(3)/VI                                    =  1.000E+00
     INPUT RESISTANCE AT          VI            =  9.989E+02
     OUTPUT RESISTANCE AT V(3)                  =    0.
```

6.25

$$I_{REF} = \frac{V_{CC} - V_{EE} - 2V_{BE}}{39\ k\Omega} = 0.48\ mA$$

$$V_T \ln \frac{I_{REF}}{I_1} = (5\ k\Omega)\, I_1$$

By trial, $I_1 = 17\ \mu A$ and thus

$$I_{C_1} = I_{C_2} = 8.5\ \mu A$$

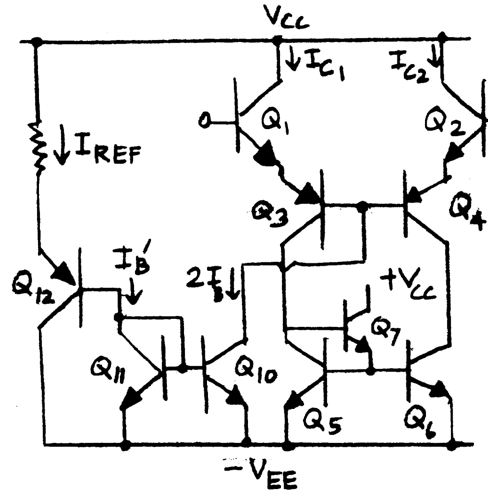
The change is a decrease of $1\ \mu A$

```
741 INPUT STAGE, VCC = 10 V (INFINITE VAF)
******
VCC    100    0     10
* USE A VOLTAGE-CONTROLLED VOLTAGE SOURCE TO SET VEE = -1(VCC)
EVEE   200    0     100   0     -1
Q1     7      8     10    NPN
Q2     7      9     11    NPN
Q3     12     6     10    PNP
Q4     16     6     11    PNP
Q5     12     13    14    NPN
Q6     16     13    15    NPN
Q7     100    12    13    NPN
Q8     7      7     100   PNP
Q9     6      7     100   PNP
Q10    6      4     5     NPN
Q11    4      4     200   NPN
Q12    3      3     100   PNP
R1     14     200   1K
R2     15     200   1K
R3     13     200   50K
R5     3      4     39K
R4     5      200   5K
VI1    8      0     0
VI2    9      0     0
.MODEL NPN   NPN  BF=250  IS=5E-15
.MODEL PNP   PNP  BF=50   IS=2E-15
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.DC VCC 10 15 5
.PRINT DC I(Q1) I(Q2)
.END
 ******  DC TRANSFER CHARACTERISTIC     TNOM=  27.000 TEMP=  27.000
       VOLT      CURRENT      CURRENT
                   Q1           Q2
  1.0000E+01    8.724E-06    8.709E-06
  1.5000E+01    9.597E-06    9.582E-06
 ****  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
   NODE      =VOLTAGE      NODE     =VOLTAGE       NODE     =VOLTAGE
+0:3        = 9.322E+00 0:4        =-9.346E+00 0:5        =-9.914E+00
+0:6        =-1.124E+00 0:7        = 9.409E+00 0:8        =  0.
+0:9        =  0.       0:10       =-5.504E-01 0:11       =-5.503E-01
+0:12       =-8.884E+00 0:13       =-9.441E+00 0:14       =-9.991E+00
+0:15       =-9.991E+00 0:16       =-6.970E-01 0:100      = 1.000E+01
+0:200      =-1.000E+01
**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT  0:Q1        0:Q2        0:Q3        0:Q4
MODEL    0:NPN       0:NPN       0:PNP       0:PNP
 IB       3.489E-08   3.484E-08  -1.717E-07  -2.017E-07
 IC       8.724E-06   8.709E-06  -8.587E-06  -8.542E-06
 VBE      5.504E-01   5.503E-01  -5.737E-01  -5.737E-01
 VCE      9.959E+00   9.959E+00  -8.334E+00  -1.467E-01
SUBCKT
ELEMENT  0:Q5        0:Q6        0:Q7        0:Q8
MODEL    0:NPN       0:NPN       0:NPN       0:PNP
 IB       3.417E-08   3.417E-08   4.477E-08  -3.352E-07
 IC       8.542E-06   8.542E-06   1.119E-05  -1.676E-05
 VBE      5.498E-01   5.498E-01   5.568E-01  -5.910E-01
 VCE      1.106E+00   9.294E+00   1.944E+01  -5.910E-01
SUBCKT
ELEMENT  0:Q9        0:Q10       0:Q11       0:Q12
MODEL    0:PNP       0:NPN       0:NPN       0:PNP
 IB      -3.352E-07   6.854E-08   1.907E-06  -9.386E-06
 IC      -1.676E-05   1.714E-05   4.767E-04  -4.693E-04
 VBE     -5.910E-01   5.678E-01   6.539E-01  -6.772E-01
 VCE     -1.112E+01   8.789E+00   6.539E-01  -6.772E-01
```

```
741 INPUT STAGE, VCC = 10 V (FINITE VAF)
******
VCC    100    0     10
* USE A VOLTAGE-CONTROLLED VOLTAGE SOURCE TO SET VEE = -1(VCC)
EVEE   200    0     100   0     -1
Q1     7      8     10    NPN
Q2     7      9     11    NPN
Q3     12     6     10    PNP
Q4     16     6     11    PNP
Q5     12     13    14    NPN
Q6     16     13    15    NPN
Q7     100    12    13    NPN
Q8     7      7     100   PNP
Q9     6      7     100   PNP
Q10    6      4     5     NPN
Q11    4      4     200   NPN
Q12    3      3     100   PNP
R1     14     200   1K
R2     15     200   1K
R3     13     200   50K
R5     3      4     39K
R4     5      200   5K
VI1    8      0     0
VI2    9      0     0
.MODEL NPN   NPN  BF=250  IS=5E-15   VAF=130
.MODEL PNP   PNP  BF=50   IS=2E-15   VAF=50
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.DC VCC 10 15 5
.PRINT DC I(Q1) I(Q2)
.END
 ******  DC TRANSFER CHARACTERISTIC     TNOM=  27.000 TEMP=  27.000
       VOLT      CURRENT      CURRENT
                   Q1           Q2
  1.0000E+01    7.370E-06    7.348E-06
  1.5000E+01    7.554E-06    7.534E-06
 ****  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
   NODE      =VOLTAGE      NODE     =VOLTAGE       NODE     =VOLTAGE
+0:3        = 9.322E+00 0:4        =-9.346E+00 0:5        =-9.912E+00
+0:6        =-1.109E+00 0:7        = 9.413E+00 0:8        =  0.
+0:9        =  0.       0:10       =-5.442E-01 0:11       =-5.441E-01
+0:12       =-8.894E+00 0:13       =-9.447E+00 0:14       =-9.992E+00
+0:15       =-9.992E+00 0:16       =-8.534E+00 0:100      = 1.000E+01
+0:200      =-1.000E+01
**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT  0:Q1        0:Q2        0:Q3        0:Q4
MODEL    0:NPN       0:NPN       0:PNP       0:PNP
 IB       2.749E-08   2.741E-08  -1.258E-07  -1.262E-07
 IC       7.370E-06   7.348E-06  -7.272E-06  -7.249E-06
 VBE      5.442E-01   5.441E-01  -5.656E-01  -5.657E-01
 VCE      9.957E+00   9.957E+00  -8.350E+00  -7.990E+00
SUBCKT
ELEMENT  0:Q5        0:Q6        0:Q7        0:Q8
MODEL    0:NPN       0:NPN       0:NPN       0:PNP
 IB       2.881E-08   2.879E-08   3.867E-08  -2.830E-07
 IC       7.233E-06   7.249E-06   1.107E-05  -1.415E-05
 VBE      5.454E-01   5.454E-01   5.530E-01  -5.866E-01
 VCE      1.098E+00   1.458E+00   1.944E+01  -5.866E-01
SUBCKT
ELEMENT  0:Q9        0:Q10       0:Q11       0:Q12
MODEL    0:PNP       0:NPN       0:NPN       0:PNP
 IB      -2.830E-07   6.539E-08   1.907E-06  -9.386E-06
 IC      -1.713E-05   1.738E-05   4.767E-04  -4.693E-04
 VBE     -5.866E-01   5.666E-01   6.539E-01  -6.772E-01
 VCE     -1.111E+01   8.802E+00   6.539E-01  -6.772E-01
```

6.26

(a)

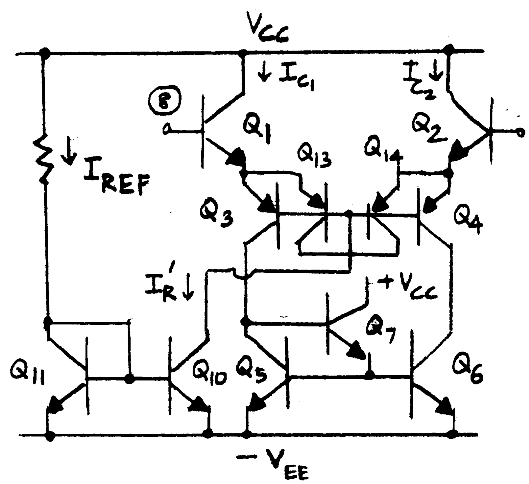


$I_{C_1} = I_{C_2} = 10\ \mu A \qquad \beta_{pnp} = 50$

$I_B = \dfrac{I_{C_1}}{1+\beta_{pnp}} \qquad \therefore\ 2I_B = 0.39\ \mu A \simeq I_B'$

$\therefore\ I_{REF} = (1+\beta_{pnp})\, I_B' = 20\ \mu A$

(b)



$I_{C_1} = I_{C_2} = 10\ \mu A$

$I_{E_3} = I_{E_{13}} = I_{E_{14}} = I_{E_4} \simeq \dfrac{I_{C_1}}{2} = 5\ \mu A$

$I_R' = 2|I_{C_3}| + 4|I_{B_{13}}|$

$= 2\left(\dfrac{5\ \mu A}{1+50}\right)\cdot 50 + 4\cdot\left(\dfrac{5\ \mu A}{1+50}\right)$

$= 10.2\ \mu A = I_{REF}$

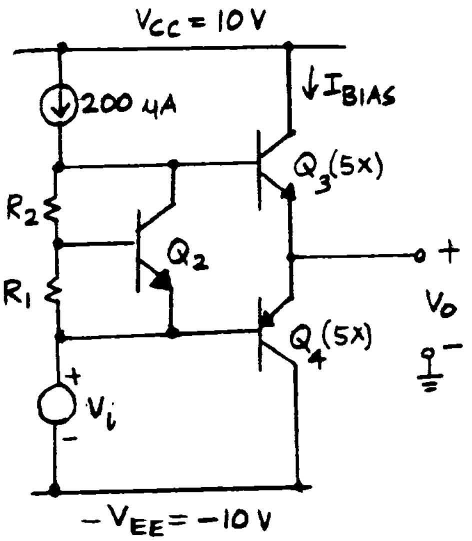
```
741 INPUT BIAS SCHEME (A)
******
VCC     100    0     15
VEE     200    0     -15
IREF    100      3         20U
Q1      100      8         10      NPN
Q2      100      9         11      NPN
Q3      12       6         10      PNP
Q4      16       6         11      PNP
Q5      12       13        200     NPN
Q6      16       13        200     NPN
Q7      100      12        13      NPN
Q10     6        4         200     NPN
Q11     4        4         200     NPN
Q12     200      4         3       PNP

* WITH VIC = -12.6 V,
* VCE10 = VIC - VBE1 - |VBE3| - (-VEE)
*       = -12.6 - 0.6 - 0.6 + 15 = 1.2 V
* THIS IS ENOUGH TO OPERATE Q10 IN THE FORWARD-ACTIVE REGION.
VI1     8        0         -12.6
VI2     9        0         -12.6 AC    1

.MODEL NPN    NPN  BF=250 IS=5E-15
.MODEL PNP    PNP  BF=50  IS=2E-15
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP

* VOUT IS USED TO MEASURE THE AC SHORT CIRCUIT OUTPUT
* CURRENT TO FIND GM.
* THE DC VALUE OF VOUT WAS GIVEN IN THE PROBLEM STATEMENT.
VOUT    16       200       1.6

.AC DEC 1 1 10
.PRINT AC IM(VOUT) IP(VOUT)

* THE TRANSCONDUCTANCE CAN ALSO BE MEASURED BY ELIMINATING
* THE VOLTAGE SOURCE CONNECTED AT THE OUTPUT AND THE
* AC ANALYSIS ABOVE, FINDING THE VOLTAGE GAIN AND OUTPUT
* RESISTANCE WITH A .TF STATEMENT AS SHOWN BELOW,
* AND CALCULATING GM = (VOLTAGE GAIN)/(OUTPUT RESISTANCE)
* THE RESULT IS GM = 1.736E4/9.237E7 = 188E-6 A/V
*.TF V(16) VI2
.END

 ****  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
   NODE      =VOLTAGE        NODE      =VOLTAGE        NODE      =VOLTAGE
+0:3         =-1.393E+01 0:4          =-1.453E+01 0:6          =-1.373E+01
+0:8         =-1.260E+01 0:9          =-1.260E+01 0:10         =-1.315E+01
+0:11        =-1.315E+01 0:12         =-1.401E+01 0:13         =-1.444E+01
+0:16        =-1.340E+01 0:100        = 1.500E+01 0:200        =-1.500E+01

**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT  0:Q1        0:Q2        0:Q3        0:Q4        0:Q5
MODEL    0:NPN       0:NPN       0:PNP       0:PNP       0:NPN
 IB       3.945E-08   3.945E-08 -1.942E-07 -1.949E-07   3.883E-08
 IC       9.863E-06   9.863E-06 -9.708E-06 -9.707E-06   9.708E-06
 VBE      5.536E-01   5.536E-01 -5.769E-01 -5.769E-01   5.532E-01
 VCE      2.815E+01   2.815E+01 -8.651E-01 -2.464E-01   9.813E-01
 VBC     -2.760E+01  -2.760E+01  2.883E-01 -3.304E-01  -4.282E-01
 VS      -1.500E+01  -1.500E+01  1.373E+01  1.373E+01   1.401E+01
 POWER    2.777E-04   2.777E-04  8.511E-06  2.505E-06   9.548E-06
 BETAD    2.500E+02   2.500E+02  5.000E+01  4.981E+01   2.500E+02
 GM       3.813E-04   3.813E-04  3.754E-04  3.753E-04   3.753E-04
 RPI      6.555E+05   6.556E+05  1.332E+05  1.332E+05   6.660E+05
 RX        0.          0.          0.          0.          0.
 RO       5.520E+15   5.520E+15  1.441E+14  3.661E+07   8.563E+13
 BETAAC   2.500E+02   2.500E+02  5.000E+01  4.999E+01   2.500E+02
```

```
SUBCKT
ELEMENT  0:Q6        0:Q7        0:Q10       0:Q11       0:Q12
MODEL    0:NPN       0:NPN       0:NPN       0:NPN       0:PNP
 IB       3.883E-08   3.094E-10   1.556E-09   1.556E-09  -3.922E-07
 IC       9.708E-06   7.735E-08   3.890E-07   3.890E-07  -1.961E-05
 VBE      5.532E-01   4.282E-01   4.699E-01   4.699E-01  -5.950E-01
 VCE      1.600E+00   2.944E+01   1.269E+00   4.699E-01  -1.065E+00
 VBC     -1.046E+00  -2.901E+01  -7.996E-01   0.          4.699E-01
 VS       1.340E+01  -1.500E+01   1.373E+01   1.453E+01   1.453E+01
 POWER    1.555E-05   2.278E-06   4.947E-07   1.836E-07   2.112E-05
 BETAD    2.500E+02   2.500E+02   2.500E+02   2.500E+02   5.000E+01
 GM       3.753E-04   2.991E-06   1.504E-05   1.504E-05   7.581E-04
 RPI      6.660E+05   8.359E+07   1.662E+07   1.662E+07   6.595E+04
 RX       0.          0.          0.          0.          0.
 RO       2.093E+14   5.803E+15   1.599E+14   5.172E+12   2.349E+14
 BETAAC   2.500E+02   2.500E+02   2.500E+02   2.500E+02   5.000E+01

****** AC ANALYSIS               TNOM=  27.000 TEMP=  27.000
     FREQ       I MAG       I PHASE
                VOUT        VOUT
 1.0000E+00    1.877E-04   4.174E-23
 1.0000E+01    1.877E-04   4.174E-22
```

```
741 INPUT BIAS SCHEME (B)
******
VCC    100    0     15
VEE    200    0     -15
IREF   100    4          10.2U
Q1     100    8          10      NPN
Q2     100    9          11      NPN
Q3     12     6          10      PNP
Q4     16     6          11      PNP
Q5     12     13         200     NPN
Q6     16     13         200     NPN
Q7     100    12         13      NPN
Q10    6      4          200     NPN
Q11    4      4          200     NPN
* REMOVE Q12 FROM THE CIRCUIT.
*  IT WAS ONLY NEEDED FOR PART (A).
Q12    200    200    200    PNP
Q13    6      6      10     PNP
Q14    6      6      11     PNP

* WITH VIC = -12.6 V,
* VCE10 = VIC - VBE1 - |VBE3| - (-VEE)
        = -12.6 - 0.6 - 0.6 + 15 = 1.2 V
* THIS IS ENOUGH TO OPERATE Q10 IN THE FORWARD-ACTIVE REGION.
VI1    8     0     -12.6
VI2    9     0     -12.6 AC    1

.MODEL NPN   NPN  BF=250 IS=5E-15
.MODEL PNP   PNP  BF=50  IS=2E-15
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP

* VOUT IS USED TO MEASURE THE AC SHORT CIRCUIT OUTPUT
* CURRENT TO FIND GM.
* THE DC VALUE OF VOUT WAS GIVEN IN THE PROBLEM STATEMENT.
VOUT   16     200     1.6

.AC DEC 1 1 10
.PRINT AC IM(VOUT) IP(VOUT)

* THE TRANSCONDUCTANCE CAN ALSO BE MEASURED BY ELIMINATING
* THE VOLTAGE SOURCE CONNECTED AT THE OUTPUT AND THE
* AC ANALYSIS ABOVE, FINDING THE VOLTAGE GAIN AND OUTPUT
* RESISTANCE WITH A .TF STATEMENT AS SHOWN BELOW,
* AND CALCULATING GM = (VOLTAGE GAIN)/(OUTPUT RESISTANCE)
* THE RESULT IS GM = 1.942E4/2.065E8 = 94E-6 A/V
* THE TRANSCONDUCTANCE IS REDUCED HERE COMPARED
* TO THE TRANSCONDUCTANCE IN PART (A) BECAUSE
* THE COLLECTOR CURRENT OF Q13 AND Q14 HERE FLOWS
* IN Q10 AND DOES NOT CONTRIBUTE TO THE STAGE OUTPUT.
*.TF V(16) VI2
.END
```

```
****  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
  NODE     =VOLTAGE       NODE   =VOLTAGE       NODE    =VOLTAGE
+0:3       =   0.         0:4    =-1.444E+01    0:6     =-1.371E+01
+0:8       =-1.260E+01    0:9    =-1.260E+01    0:10    =-1.315E+01
+0:11      =-1.315E+01    0:12   =-1.405E+01    0:13    =-1.446E+01
+0:16      =-1.340E+01    0:100  = 1.500E+01    0:200   =-1.500E+01

**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT  0:Q1        0:Q2        0:Q3        0:Q4        0:Q5
MODEL    0:NPN       0:NPN       0:PNP       0:PNP       0:NPN
 IB       3.954E-08   3.954E-08  -9.729E-08  -9.765E-08   1.946E-08
 IC       9.884E-06   9.884E-06  -4.865E-06  -4.864E-06   4.865E-06
 VBE      5.536E-01   5.536E-01  -5.590E-01  -5.590E-01   5.353E-01
 VCE      2.815E+01   2.815E+01  -9.008E-01  -2.464E-01   9.456E-01
 VBC     -2.760E+01  -2.760E+01   3.418E-01  -3.126E-01  -4.103E-01
 VS      -1.500E+01  -1.500E+01   1.371E+01   1.371E+01   1.405E+01
 POWER    2.783E-04   2.783E-04   4.437E-06   1.253E-06   4.610E-06
 BETAD    2.500E+02   2.500E+02   5.000E+01   4.981E+01   2.500E+02
 GM       3.822E-04   3.822E-04   1.881E-04   1.881E-04   1.881E-04
 RPI      6.541E+05   6.541E+05   2.658E+05   2.658E+05   1.329E+06
 RX       0.          0.          0.          0.          0.
 RO       5.520E+15   5.520E+15   1.709E+14   7.290E+07   8.205E+13
 BETAAC   2.500E+02   2.500E+02   5.000E+01   4.999E+01   2.500E+02

SUBCKT
ELEMENT  0:Q6        0:Q7        0:Q10       0:Q11       0:Q12
MODEL    0:NPN       0:NPN       0:NPN       0:NPN       0:PNP
 IB       1.946E-08   1.550E-10   4.048E-08   4.048E-08   0.
 IC       4.865E-06   3.876E-08   1.012E-05   1.012E-05   0.
 VBE      5.353E-01   4.103E-01   5.542E-01   5.542E-01   0.
 VCE      1.600E+00   2.946E+01   1.287E+00   5.542E-01   0.
 VBC     -1.064E+00  -2.905E+01  -7.332E-01   0.          0.
 VS       1.340E+01  -1.500E+01   1.371E+01   1.444E+01   1.500E+01
 POWER    7.794E-06   1.142E-06   1.305E-05   5.631E-06   0.
 BETAD    2.500E+02   2.500E+02   2.500E+02   2.500E+02   0.
 GM       1.881E-04   1.499E-06   3.912E-04   3.912E-04   0.
 RPI      1.329E+06   1.668E+08   6.390E+05   6.390E+05   6.466E+14
 RX       0.          0.          0.          0.          0.
 RO       2.129E+14   5.810E+15   1.466E+14   5.172E+12   1.293E+13
 BETAAC   2.500E+02   2.500E+02   2.500E+02   2.500E+02   0.

SUBCKT
ELEMENT  0:Q13       0:Q14
MODEL    0:PNP       0:PNP
 IB      -9.729E-08  -9.730E-08
 IC      -4.865E-06  -4.865E-06
 VBE     -5.590E-01  -5.590E-01
 VCE     -5.590E-01  -5.590E-01
 VBC      0.          0.
 VS       1.371E+01   1.371E+01
 POWER    2.774E-06   2.774E-06
 BETAD    5.000E+01   5.000E+01
 GM       1.881E-04   1.881E-04
 RPI      2.658E+05   2.658E+05
 RX       0.          0.
 RO       1.293E+13   1.293E+13
 BETAAC   5.000E+01   5.000E+01

****** AC ANALYSIS               TNOM=  27.000 TEMP=  27.000
     FREQ       I MAG       I PHASE
                VOUT        VOUT
 1.0000E+00    9.405E-05   8.873E-23
 1.0000E+01    9.405E-05   8.873E-22
```

6.27



Neglect current flow through R_1 and R_2 from 200 μA source.

$\therefore I_{C_2} = 200\,\mu A$, $V_{BE_2} = V_T \ln \frac{I_{C2}}{I_{S_2}}$

$$V_{BE_4} + V_{BE_3} = V_{BE_2} + \frac{V_{BE2}}{R_1} \times R_2$$

$$= \frac{V_T}{R_1}(R_1 + R_2) \ln \frac{I_{C2}}{I_{S_2}}$$

$$= V_T \ln\left(\frac{I_{C_3}|I_{C4}|}{I_{S_3} I_{S4}}\right)$$

Areas of Q_3, Q_4 are 5 times of Q_1 and Q_2. Therefore,

$I_{S_1} = I_{S_2} = 10^{-15} A = I_S$

$I_{S_3} = I_{S_4} = 5 \times 10^{-15} A = 5 I_S$

$$V_T \ln\left(\frac{I_{BIAS}^2}{25 I_S^2}\right) = V_T\left(1 + \frac{R_2}{R_1}\right) \ln\left(\frac{I_{C2}}{I_S}\right)$$

$$\therefore I_{BIAS} = 5 I_S \left(\frac{I_{C2}}{I_S}\right)^{\frac{1}{2}(1+\frac{R_2}{R_1})}$$

$$= 5 (I_{C_2})^{\frac{1}{2}(1+\frac{R_2}{R_1})} (I_S)^{\frac{1}{2}(1-\frac{R_2}{R_1})} \rightarrow (1)$$

$$\frac{R_2}{R_1} = \frac{2 \ln\left(\frac{I_{BIAS}}{5 I_S}\right)}{\ln\left(\frac{I_{C2}}{I_S}\right)} - 1$$

$I_{BIAS} = 50\,\mu A$, $I_S = 10^{-15} A$, $I_{C_2} = 200\,\mu A$

$\therefore \frac{R_2}{R_1} = 0.77$

From (1), If we choose $\frac{R_2}{R_1} = 1$

then $I_{BIAS} = 5 (I_{C_2})^{\frac{1}{2}(1 + R_2/R_1)}$

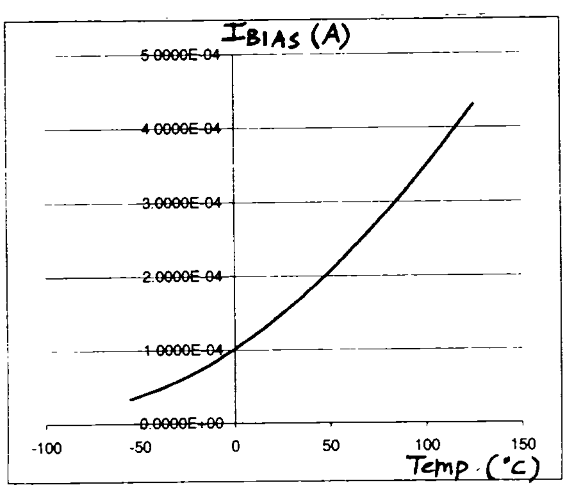
$= 1000\,\mu A = 1\,mA$

and I_{BIAS} is independent of temperature. In general, if $\frac{R_2}{R_1} \neq 1$ then I_{BIAS} is dependent on temperature because I_S depends on temperature.

```
741 OUTPUT-STAGE BIAS SCHEME
* BF=LARGE TO CHECK HAND CALCULATIONS
******
VCC   100   0    10
VEE   200   0    -10
IREF  100     3      200U
Q2    3       4      5      NPN
Q3    100     3      6      NPN  5
Q4    200     5      6      PNP  5
R1    4       5      100K
R2    3       4      77K
VI    5       200    9.404
.MODEL NPN   NPN  BF=10000 IS=1E-15
.MODEL PNP   PNP  BF=10000 IS=1E-15
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.END

 **** OPERATING POINT INFORMATION     TNOM=  27.000 TEMP=  27.000
   NODE      =VOLTAGE      NODE      =VOLTAGE      NODE      =VOLTAGE
+0:3         = 5.952E-01 0:4         = 7.614E-02 0:5         =-5.960E-01
+0:6         =-4.124E-04 0:100       = 1.000E+01 0:200       =-1.000E+01
**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT  0:Q2        0:Q3        0:Q4
MODEL    0:NPN       0:NPN       0:PNP
 IB       1.933E-08  5.008E-09 -5.008E-09
 IC       1.933E-04  5.008E-05 -5.008E-05
 VBE      6.721E-01  5.956E-01 -5.956E-01
 VCE      1.191E+00  1.000E+01 -9.999E+00
 BETAD    1.000E+04  1.000E+04  1.000E+04

741 OUTPUT-STAGE BIAS SCHEME
* SET BF TO NORMAL VALUES AND RUN TEMPERATURE SWEEP
******
VCC   100   0    10
VEE   200   0    -10
IREF  100     3      200U
Q2    3       4      5      NPN
Q3    100     3      6      NPN  5
Q4    200     5      6      PNP  5
R1    4       5      100K
R2    3       4      77K
VI    5       200    9.404
.MODEL NPN   NPN  BF=250   IS=1E-15
.MODEL PNP   PNP  BF=50    IS=1E-15
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.TEMP -55 -35 -15 5 25 45 65 85 105 125
.END

 **** OPERATING POINT INFORMATION     TNOM=  27.000 TEMP= -55.000
   NODE      =VOLTAGE      NODE      =VOLTAGE      NODE      =VOLTAGE
+0:3         = 8.957E-01 0:4         = 2.135E-01 0:5         =-5.960E-01
+0:6         = 1.497E-01 0:100       = 1.000E+01 0:200       =-1.000E+01
**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT  0:Q2        0:Q3        0:Q4
MODEL    0:NPN       0:NPN       0:PNP
 IB       7.640E-07  1.301E-07 -6.403E-07
 IC       1.910E-04  3.253E-05 -3.202E-05
 VBE      8.095E-01  7.460E-01 -7.457E-01
 VCE      1.491E+00  9.850E+00 -1.015E+01
 BETAD    2.500E+02  2.500E+02  5.000E+01

 **** OPERATING POINT INFORMATION     TNOM=  27.000 TEMP= -35.000
   NODE      =VOLTAGE      NODE      =VOLTAGE      NODE      =VOLTAGE
+0:3         = 8.375E-01 0:4         = 1.806E-01 0:5         =-5.960E-01
+0:6         = 1.206E-01 0:100       = 1.000E+01 0:200       =-1.000E+01
**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT  0:Q2        0:Q3        0:Q4
MODEL    0:NPN       0:NPN       0:PNP
 IB       7.650E-07  2.086E-07 -1.027E-06
 IC       1.913E-04  5.215E-05 -5.134E-05
 VBE      7.766E-01  7.169E-01 -7.166E-01
 VCE      1.433E+00  9.879E+00 -1.012E+01
 BETAD    2.500E+02  2.500E+02  5.000E+01

 **** OPERATING POINT INFORMATION     TNOM=  27.000 TEMP= -15.000
   NODE      =VOLTAGE      NODE      =VOLTAGE      NODE      =VOLTAGE
+0:3         = 7.786E-01 0:4         = 1.473E-01 0:5         =-5.960E-01
+0:6         = 9.110E-02 0:100       = 1.000E+01 0:200       =-1.000E+01

**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT  0:Q2        0:Q3        0:Q4
MODEL    0:NPN       0:NPN       0:PNP
 IB       7.660E-07  3.116E-07 -1.533E-06
 IC       1.915E-04  7.790E-05 -7.667E-05
 VBE      7.433E-01  6.875E-01 -6.871E-01
 VCE      1.374E+00  9.908E+00 -1.009E+01
 BETAD    2.500E+02  2.500E+02  5.000E+01

 **** OPERATING POINT INFORMATION     TNOM=  27.000 TEMP=   5.000
   NODE      =VOLTAGE      NODE      =VOLTAGE      NODE      =VOLTAGE
+0:3         = 7.189E-01 0:4         = 1.135E-01 0:5         =-5.960E-01
+0:6         = 6.125E-02 0:100       = 1.000E+01 0:200       =-1.000E+01

**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT  0:Q2        0:Q3        0:Q4
MODEL    0:NPN       0:NPN       0:PNP
 IB       7.668E-07  4.401E-07 -2.166E-06
 IC       1.917E-04  1.100E-04 -1.083E-04
 VBE      7.095E-01  6.576E-01 -6.573E-01
 VCE      1.314E+00  9.938E+00 -1.006E+01
 BETAD    2.500E+02  2.500E+02  5.000E+01

 **** OPERATING POINT INFORMATION     TNOM=  27.000 TEMP=  25.000
   NODE      =VOLTAGE      NODE      =VOLTAGE      NODE      =VOLTAGE
+0:3         = 6.585E-01 0:4         = 7.939E-02 0:5         =-5.960E-01
+0:6         = 3.107E-02 0:100       = 1.000E+01 0:200       =-1.000E+01

**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT  0:Q2        0:Q3        0:Q4
MODEL    0:NPN       0:NPN       0:PNP
 IB       7.675E-07  5.944E-07 -2.925E-06
 IC       1.919E-04  1.486E-04 -1.463E-04
 VBE      6.754E-01  6.275E-01 -6.271E-01
 VCE      1.254E+00  9.968E+00 -1.003E+01
 BETAD    2.500E+02  2.500E+02  5.000E+01

 **** OPERATING POINT INFORMATION     TNOM=  27.000 TEMP=  45.000
   NODE      =VOLTAGE      NODE      =VOLTAGE      NODE      =VOLTAGE
+0:3         = 5.976E-01 0:4         = 4.492E-02 0:5         =-5.960E-01
+0:6         = 5.725E-04 0:100       = 1.000E+01 0:200       =-1.000E+01

**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT  0:Q2        0:Q3        0:Q4
MODEL    0:NPN       0:NPN       0:PNP
 IB       7.682E-07  7.741E-07 -3.810E-06
 IC       1.920E-04  1.935E-04 -1.905E-04
 VBE      6.409E-01  5.970E-01 -5.966E-01
 VCE      1.193E+00  9.999E+00 -1.000E+01
 BETAD    2.500E+02  2.500E+02  5.000E+01

 **** OPERATING POINT INFORMATION     TNOM=  27.000 TEMP=  65.000
   NODE      =VOLTAGE      NODE      =VOLTAGE      NODE      =VOLTAGE
+0:3         = 5.360E-01 0:4         = 1.012E-02 0:5         =-5.960E-01
+0:6         =-3.021E-02 0:100       = 1.000E+01 0:200       =-1.000E+01

**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT  0:Q2        0:Q3        0:Q4
MODEL    0:NPN       0:NPN       0:PNP
 IB       7.688E-07  9.782E-07 -4.814E-06
 IC       1.922E-04  2.446E-04 -2.407E-04
 VBE      6.061E-01  5.662E-01 -5.658E-01
 VCE      1.132E+00  1.003E+01 -9.969E+00
 BETAD    2.500E+02  2.500E+02  5.000E+01
```

```
**** OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  85.000
  NODE      =VOLTAGE       NODE      =VOLTAGE       NODE      =VOLTAGE
+0:3        = 4.739E-01 0:4          =-2.498E-02 0:5          =-5.960E-01
+0:6        =-6.127E-02 0:100        = 1.000E+01 0:200        =-1.000E+01
**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT  0:Q2         0:Q3         0:Q4
MODEL    0:NPN        0:NPN        0:PNP
 IB      7.693E-07  1.205E-06 -5.933E-06
 IC      1.923E-04  3.014E-04 -2.966E-04
 VBE     5.710E-01  5.352E-01 -5.347E-01
 VCE     1.069E+00  1.006E+01 -9.938E+00
 BETAD   2.500E+02  2.500E+02  5.000E+01

**** OPERATING POINT INFORMATION      TNOM=  27.000 TEMP= 105.000
  NODE      =VOLTAGE       NODE      =VOLTAGE       NODE      =VOLTAGE
+0:3        = 4.113E-01 0:4          =-6.037E-02 0:5          =-5.960E-01
+0:6        =-9.259E-02 0:100        = 1.000E+01 0:200        =-1.000E+01
**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT  0:Q2         0:Q3         0:Q4
MODEL    0:NPN        0:NPN        0:PNP
 IB      7.697E-07  1.454E-06 -7.158E-06
 IC      1.924E-04  3.636E-04 -3.579E-04
 VBE     5.356E-01  5.039E-01 -5.034E-01
 VCE     1.007E+00  1.009E+01 -9.907E+00
 BETAD   2.500E+02  2.500E+02  5.000E+01

**** OPERATING POINT INFORMATION      TNOM=  27.000 TEMP= 125.000
  NODE      =VOLTAGE       NODE      =VOLTAGE       NODE      =VOLTAGE
+0:3        = 3.482E-01 0:4          =-9.604E-02 0:5          =-5.960E-01
+0:6        =-1.242E-01 0:100        = 1.000E+01 0:200        =-1.000E+01
**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT  0:Q2         0:Q3         0:Q4
MODEL    0:NPN        0:NPN        0:PNP
 IB      7.699E-07  1.723E-06 -8.480E-06
 IC      1.925E-04  4.308E-04 -4.240E-04
 VBE     5.000E-01  4.724E-01 -4.718E-01
 VCE     9.442E-01  1.012E+01 -9.875E+00
 BETAD   2.500E+02  2.500E+02  5.000E+01
```

TEMP (DEG C)	IC3 = IBIAS (A)	TEMP	IC3 = IBIAS (A)
-55	3.253E-05	45	1.935E-04
-35	5.215E-05	65	2.446E-04
-15	7.790E-05	85	3.014E-04
5	1.100E-04	105	3.636E-04
25	1.486E-04	125	4.308E-04



6-28

If the bias current level of 741 input stage is doubled, then from (6.134), $G_{m_1} = \dfrac{1}{2.7\,K\Omega}$

From (6.138),

$$R_{o1} = R_{OUT}|_{Q_4} \,\|\, R_{OUT}|_{Q_6}$$

$$= 2\, r_{o4} \,\|\, r_{o6}(1 + g_{m_6}(1K\Omega))$$

Using $\eta_{npn} = 2\times10^{-4}$, $\eta_{pnp} = 5\times10^{-4}$ and $|I_C| = 19\,\mu A$, we have

$$r_{o4} = \frac{1}{\eta g_m} = \frac{10^4}{5}\,\frac{26}{19\times10^{-3}} = 2.74\ M\Omega$$

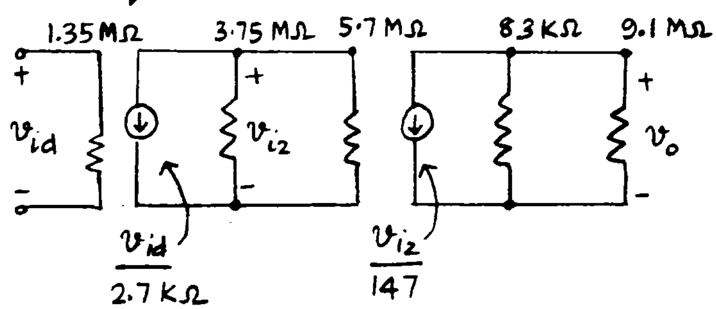
$$r_{o6} = \frac{10^4}{2}\,\frac{26}{19\times10^{-3}} = 6.84\ M\Omega$$

$$g_{m_6} \times 1K\Omega = 0.73$$

$$\therefore\ R_{o1} = (5.48)\,\|\,(6.84\times1.73)\ M\Omega$$

$$= 3.75\ M\Omega$$

741 equivalent



$3.75 \,\|\, 5.7 \quad 2.26\ M\Omega\ ;\ 83K \,\|\, 9.1M \simeq 82K\Omega$

$$A_v = \frac{2260}{2.7}\cdot\frac{82}{0.147} = 838\times558$$

$$= 468{,}000$$

6.29

If the 100Ω emitter resistor of Q_{17} is removed, then in (6.142) we have,

$$R_{eq_1} = r_{\pi_{17}} \pm \frac{\beta}{g_m} = 250 \times \frac{26}{0.55} = 11.8\ k\Omega$$

$$R_{i_2} = r_{\pi_{16}} + (1+\beta_o)(r_{\pi_{17}} \parallel 50\ k\Omega)$$

$$= 406\ k\Omega + 251 \times 9.55\ k\Omega$$

$$= 2.8\ M\Omega$$

From (6.146)

$$G_{m_2} \simeq g_{m_{17}} = \frac{0.55}{26} = \frac{1}{47.3\Omega}$$

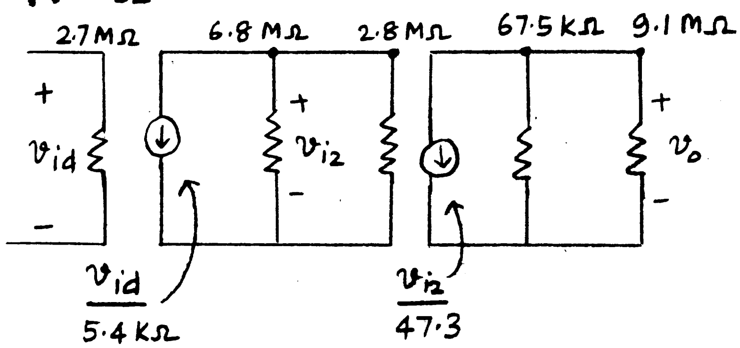
From (6.147)

$$R_{o2} = r_{o13_B} \parallel r_{o17}$$

$$r_{o13_B} = \frac{1}{\eta g_m} = \frac{10^4}{5}\frac{26}{0.55} = 94.5\ k\Omega$$

$$r_{o17} = \frac{1}{\eta g_m} = \frac{10^4}{2}\frac{26}{0.55} = 236\ k\Omega$$

$$\therefore R_{o2} = 67.5\ k\Omega$$



$$6.8 \parallel 2.8 = 1.98\ M\Omega$$

$$67.5k \parallel 9.1M = 67k$$

$$A_v = \frac{1980}{5.4} \times \frac{67}{0.047}$$

$$= 523{,}000$$

6.30

Minimum CM input voltage:

The circuit ceases to function correctly when Q_3 and Q_4 saturate.

Q_3 and Q_4 operate in the F.A.R. when,

$$V_{EC_3} > V_{CE(sat)}$$

$$V_{E_3} = V_{IC} - V_{BE_1}$$

$$V_{C_3} = -V_{EE} + V_{BE_5} + V_{BE_7} + \underbrace{I_{C_5}(1K)}_{\text{neglect}}$$

$$V_{EC_3} = V_{IC} - V_{BE_1} - (-V_{EE}) - V_{BE_5} - V_{BE_7} > V_{CE(sat)}$$

$$V_{IC} > -V_{EE} + V_{BE_1} + V_{BE_5} + V_{BE_7} + V_{CE(sat)}$$

Maximum CM input voltage:

Q_1 and Q_2 operate in the F.A.R. when

$$V_{CE_1} > V_{CE(sat)}$$

$$V_{C_1} = V_{CC} - |V_{BE_8}|$$

$$V_{E_1} = V_{IC} - V_{BE_1}$$

$$V_{CE_1} = V_{CC} - |V_{BE_8}| - V_{IC} + V_{BE_1} > V_{CE(sat)}$$

Assume $V_{BE_1} = |V_{BE_8}|$

Then $V_{IC} < V_{CC} - V_{CE(sat)}$

```
741 AS A VOLTAGE FOLLOWER
******
* POWER SUPPLIES
VCC    100   0     15
VEE    200   0     -15

* INPUT STAGE
Q1     7     8         10     NPN
Q2     7     9         11     NPN
Q3     12    6         10     PNP
Q4     16    6         11     PNP
Q5     12    13        14     NPN
Q6     16    13        15     NPN
Q7     100   12        13     NPN
Q8     7     7         100    PNP
Q9     6     7         100    PNP
Q10    6     4         5      NPN
Q11    4     4         200    NPN
Q12    3     3         100    PNP
R1     14    200       1K
R2     15    200       1K
R3     13    200       50K
R5     3     4         39K
R4     5     200       5K

* DARLINGTON GAIN STAGE
Q13B   19    3         100    PNPB
Q16    100   16        17     NPN
Q17    19    17        18     NPN
R8     18    200       100
R9     17    200       50K

* OUTPUT STAGE
Q13A   20    3         100    PNPA
Q14    100   20        25     NPN  3
Q18    20    21        22     NPN
Q19    20    20        21     NPN
Q20    200   22        23     PNP  3
Q23    200   19        22     PNP
R6     25    9         27
R7     23    9         22
R10    21    22        40K

VI1    8         0         0
.MODEL NPN   NPN  BF=250  IS=5E-15    VAF=130
.MODEL PNP   PNP  BF=50   IS=2E-15    VAF=50
.MODEL PNPA  PNP  BF=50   IS=0.5E-15  VAF=50
.MODEL PNPB  PNP  BF=50   IS=1.5E-15  VAF=50
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.DC VI1 -15 15 0.5

* ASSUMING VCE(SAT) = 0.2 V AND VBE(ON) = 0.7 V,
* THE HAND CALCULATIONS PREDICT A COMMON-MODE RANGE OF
* -12.7 V < VIC < 14.8 V
* IN THE VOLTAGE-FOLLOWER CONFIGURATION, VO = VI = VIC
* AS LONG AS THE AMPLIFIER IS WORKING CORRECTLY.
* THE RESULTS OF THIS SIMULATION SHOW THAT
* VO = VI FOR THE FOLLOWING RANGE:
* -13 V < VI < 14.5 V
* THEREFORE, THIS SIMULATION SHOWS THAT THE
* COMMON MODE INPUT RANGE IS:
* -13 V < (VO = VI = VIC) < 14.5 V
* WHICH IS CLOSE TO THE RESULT
* PREDICTED BY HAND CALCULATIONS.

.PLOT DC V(9)
.END
```

```
****** DC TRANSFER CURVES      TNOM=  27.000 TEMP=  27.000
   VOLT      V(9)
(A       )      -2.000E+01    -1.000E+01         0.       1.000E+01     2.000E+01
                     +             +             +             +             +
-1.500E+01 -1.31E+01-+------+--A---+------+------+------+------+------+------+-
-1.450E+01 -1.31E+01 +      +  A   +      +      +      +      +      +      +
-1.400E+01 -1.31E+01 +      +  A   +      +      +      +      +      +      +
-1.350E+01 -1.31E+01 +      +  A   +      +      +      +      +      +      +
-1.300E+01 -1.30E+01 +      +  A   +      +      +      +      +      +      +
-1.250E+01 -1.25E+01 +      +   A  +      +      +      +      +      +      +
-1.200E+01 -1.20E+01 +      +   A  +      +      +      +      +      +      +
-1.150E+01 -1.15E+01 +      +    A +      +      +      +      +      +      +
-1.100E+01 -1.10E+01 +      +     A+      +      +      +      +      +      +
-1.050E+01 -1.05E+01 +      +     A+      +      +      +      +      +      +
-1.000E+01 -9.99E+00-+------+------A------+------+------+------+------+------+-
-9.500E+00 -9.50E+00 +      +      +A     +      +      +      +      +      +
-9.000E+00 -9.00E+00 +      +      +A     +      +      +      +      +      +
-8.500E+00 -8.50E+00 +      +      + A    +      +      +      +      +      +
-8.000E+00 -8.00E+00 +      +      +  A   +      +      +      +      +      +
-7.500E+00 -7.50E+00 +      +      +   A  +      +      +      +      +      +
-7.000E+00 -7.00E+00 +      +      +   A  +      +      +      +      +      +
-6.500E+00 -6.50E+00 +      +      +    A +      +      +      +      +      +
-6.000E+00 -6.00E+00 +      +      +     A+      +      +      +      +      +
-5.500E+00 -5.50E+00 +      +      +     A+      +      +      +      +      +
-5.000E+00 -5.00E+00-+------+------+------A------+------+------+------+------+-
-4.500E+00 -4.50E+00 +      +      +      +A     +      +      +      +      +
-4.000E+00 -4.00E+00 +      +      +      +A     +      +      +      +      +
-3.500E+00 -3.50E+00 +      +      +      + A    +      +      +      +      +
-3.000E+00 -3.00E+00 +      +      +      +  A   +      +      +      +      +
-2.500E+00 -2.50E+00 +      +      +      +   A  +      +      +      +      +
-2.000E+00 -2.00E+00 +      +      +      +   A  +      +      +      +      +
-1.500E+00 -1.50E+00 +      +      +      +    A +      +      +      +      +
-1.000E+00 -1.00E-00 +      +      +      +     A+      +      +      +      +
-5.000E-01 -5.00E-01 +      +      +      +     A+      +      +      +      +
    0.      2.74E-04-+------+------+------+------A------+------+------+------+-
 5.000E-01  5.00E-01 +      +      +      +      +A     +      +      +      +
 1.000E+00  1.00E+00 +      +      +      +      +A     +      +      +      +
 1.500E+00  1.50E+00 +      +      +      +      + A    +      +      +      +
 2.000E+00  2.00E+00 +      +      +      +      +  A   +      +      +      +
 2.500E+00  2.50E+00 +      +      +      +      +   A  +      +      +      +
 3.000E+00  3.00E+00 +      +      +      +      +   A  +      +      +      +
 3.500E+00  3.50E+00 +      +      +      +      +    A +      +      +      +
 4.000E+00  4.00E+00 +      +      +      +      +     A+      +      +      +
 4.500E+00  4.50E+00 +      +      +      +      +     A+      +      +      +
 5.000E+00  5.00E+00-+------+------+------+------+------A------+------+------+-
 5.500E+00  5.50E+00 +      +      +      +      +      +A     +      +      +
 6.000E+00  6.00E+00 +      +      +      +      +      +A     +      +      +
 6.500E+00  6.50E+00 +      +      +      +      +      + A    +      +      +
 7.000E+00  7.00E+00 +      +      +      +      +      +  A   +      +      +
 7.500E+00  7.50E+00 +      +      +      +      +      +   A  +      +      +
 8.000E+00  8.00E+00 +      +      +      +      +      +   A  +      +      +
 8.500E+00  8.50E+00 +      +      +      +      +      +    A +      +      +
 9.000E+00  9.00E+00 +      +      +      +      +      +     A+      +      +
 9.500E+00  9.50E+00 +      +      +      +      +      +     A+      +      +
 1.000E+01  1.00E+01-+------+------+------+------+------+------A------+------+-
 1.050E+01  1.05E+01 +      +      +      +      +      +      +A     +      +
 1.100E+01  1.10E+01 +      +      +      +      +      +      +A     +      +
 1.150E+01  1.15E+01 +      +      +      +      +      +      + A    +      +
 1.200E+01  1.20E+01 +      +      +      +      +      +      +  A   +      +
 1.250E+01  1.25E+01 +      +      +      +      +      +      +   A  +      +
 1.300E+01  1.30E+01 +      +      +      +      +      +      +   A  +      +
 1.350E+01  1.35E+01 +      +      +      +      +      +      +    A +      +
 1.400E+01  1.40E+01 +      +      +      +      +      +      +     A+      +
 1.450E+01  1.45E+01 +      +      +      +      +      +      +     A+      +
 1.500E+01  1.46E+01-+------+------+------+------+------+------+------A------+-
                     +             +             +             +             +
```

```
**** OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
```

NODE	=VOLTAGE	NODE	=VOLTAGE	NODE	=VOLTAGE
+0:3	= 1.431E+01	0:4	=-1.433E+01	0:5	=-1.490E+01
+0:6	=-1.107E+00	0:7	= 1.441E+01	0:8	= 0.
+0:9	= 2.744E-04	0:10	=-5.439E-01	0:11	=-5.437E-01
+0:12	=-1.389E+01	0:13	=-1.444E+01	0:14	=-1.499E+01
+0:15	=-1.499E+01	0:16	=-1.370E+01	0:17	=-1.426E+01
+0:18	=-1.493E+01	0:19	=-1.260E+00	0:20	= 5.904E-01
+0:21	= 2.345E-02	0:22	=-6.088E-01	0:23	=-2.361E-03
+0:25	= 3.509E-03	0:100	= 1.500E+01	0:200	=-1.500E+01

6.31

First consider the bipolar differential pair with tail current source and resistive loads by itself. Let V_{os_1} represent the offset of that circuit referred to the input of that circuit (the bases of Q_1 and Q_2)

From (6.164),

$$V_{os_1} = V_T\left(-\frac{\Delta I_S}{I_S} - \frac{\Delta R}{R}\right)$$

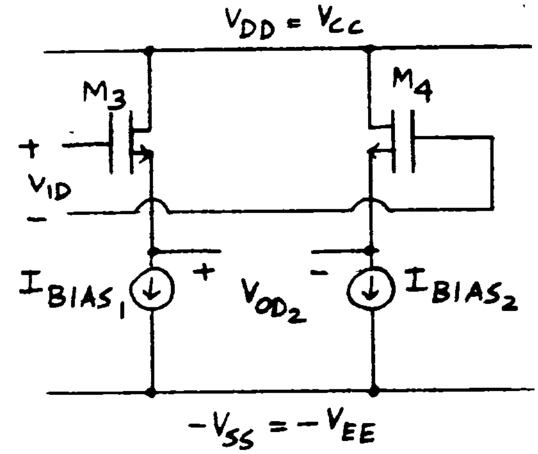
where $$I_S = \frac{I_{S_1} + I_{S_2}}{2}$$

$$\Delta I_S = I_{S_1} - I_{S_2}$$

$$R = \frac{R_1 + R_2}{2}$$

$$\Delta R = R_1 - R_2$$

Second, consider the MOS source followers by themselves. Let V_{os_2} represent the offset of the source followers only referred to the input of the entire circuit (the gates of M_3 and M_4)



$$V_{OD_2} = V_{ID} - (V_{GS_3} - V_{GS_4})$$

$$V_{ID} = V_{OD_2} + V_{GS_3} - V_{GS_4}$$

$V_{os_2} = V_{ID}$ for which $V_{OD_2} = 0$

$$V_{os_2} = V_{GS_3} - V_{GS_4}$$

$$V_{GS_3} = V_{t_3} - V_{ov_3}$$

$$V_{GS_4} = V_{t_4} - V_{ov_4}$$

$$V_{ov_3} = \sqrt{\frac{2 I_{BIAS_1}}{k'\left(\frac{W}{L}\right)_3}}$$

$$V_{ov_4} = \sqrt{\frac{2 I_{BIAS_2}}{k'\left(\frac{W}{L}\right)_4}}$$

$$V_{os_2} = V_{t_3} - V_{t_4} + \sqrt{\frac{2 I_{BIAS_1}}{k'\left(\frac{W}{L}\right)_3}} - \sqrt{\frac{2 I_{BIAS_2}}{k'\left(\frac{W}{L}\right)_4}}$$

Let $$I_{BIAS} = \frac{I_{BIAS_1} + I_{BIAS_2}}{2}$$

$$\Delta I_{BIAS} = I_{BIAS_1} - I_{BIAS_2}$$

$$\therefore\ I_{BIAS_1} = I_{BIAS} + \frac{\Delta I_{BIAS}}{2}$$

$$I_{BIAS_2} = I_{BIAS} - \frac{\Delta I_{BIAS}}{2}$$

Also, $\left(\frac{W}{L}\right)_3 = \left(\frac{W}{L}\right) + \frac{1}{2}\Delta\left(\frac{W}{L}\right)$

$$\left(\frac{W}{L}\right)_4 = \left(\frac{W}{L}\right) - \frac{1}{2}\Delta\left(\frac{W}{L}\right)$$

Where, $\left(\frac{W}{L}\right) = \frac{(W/L)_3 + (W/L)_4}{2}$

$$\Delta\left(\frac{W}{L}\right) = \left(\frac{W}{L}\right)_3 - \left(\frac{W}{L}\right)_4$$

Finally, $\Delta V_t = V_{t_3} - V_{t_4}$

$$V_{OS_2} = \Delta V_t + \sqrt{\frac{2(I_{BIAS})\left(1 + \frac{\Delta I_{BIAS}}{2I_{BIAS}}\right)}{k'\left(\frac{W}{L}\right)\left[1 + \frac{\Delta(W/L)}{2(W/L)}\right]}} - \sqrt{\frac{2(I_{BIAS})\left(1 - \frac{\Delta I_{BIAS}}{2I_{BIAS}}\right)}{k'\left(\frac{W}{L}\right)\left[1 - \frac{\Delta(W/L)}{2(W/L)}\right]}}$$

Let $V_{ov} = \sqrt{\frac{2I_{BIAS}}{k' W/L}}$

$$V_{OS_2} = \Delta V_t + V_{ov}\left[\sqrt{\frac{1 + \frac{\Delta I_{BIAS}}{2I_{BIAS}}}{1 + \frac{\Delta(W/L)}{2(W/L)}}} - \sqrt{\frac{1 - \frac{\Delta I_{BIAS}}{2I_{BIAS}}}{1 - \frac{\Delta(W/L)}{2(W/L)}}}\right]$$

Since $\sqrt{x} \cong 1 + \frac{x}{2}$ for $x \simeq 1$

$$V_{OS_2} \simeq \Delta V_t + \frac{V_{ov}}{2}\left[\frac{1 + \frac{\Delta I_{BIAS}}{2I_{BIAS}}}{1 + \frac{\Delta(W/L)}{2(W/L)}} - \frac{1 - \frac{\Delta I_{BIAS}}{2I_{BIAS}}}{1 - \frac{\Delta(W/L)}{2(W/L)}}\right]$$

since $\frac{1}{1+y} \simeq 1 - y$ for $y << 1$,

$$V_{OS_2} \simeq \Delta V_t + \frac{V_{ov}}{2}\left[1 + \frac{\Delta I_{BIAS}}{2I_{BIAS}} - \frac{\Delta(W/L)}{2(W/L)} - \left(1 - \frac{\Delta I_{BIAS}}{2I_{BIAS}} + \frac{\Delta(W/L)}{2(W/L)}\right)\right]$$

$$V_{OS_2} \approx \Delta V_t + \frac{V_{ov}}{2}\left[\frac{\Delta I_{BIAS}}{I_{BIAS}} - \frac{\Delta(W/L)}{(W/L)}\right]$$

Let V_{OS} represent the total offset including both V_{OS_1} and V_{OS_2}.

$$V_{OS} = \frac{V_{OS_1}}{\text{source-follower gain}} + V_{OS_2}$$

Since the source-follower gain $\simeq 1$,

$$V_{OS} \simeq V_T\left(-\frac{\Delta I_S}{I_S} - \frac{\Delta R}{R}\right) + \Delta V_t + \frac{V_{OV}}{2}\left[\frac{\Delta I_{BIAS}}{I_{BIAS}} - \frac{\Delta(W/L)}{W/L}\right]$$

CHAPTER 7

7.1

(a) Transistor parameters are

$$r_\pi = \frac{\beta_o}{g_m} = 200 \times 52 = 10.4 k\Omega$$

$$\tau_T = \frac{1}{2\pi f_T} = 318 \text{ ps}$$

$$C_\pi + C_\mu = g_m \tau_T = \frac{1}{52} \times 318 = 6.12 \text{ pF}$$

$$\therefore C_\pi = 6.1 - 0.3 = 5.8 \text{ pF}$$

$$C_M = (1 + g_m R_L) C_\mu$$

$$= (1 + \frac{3000}{52}) \times 0.3 = 17.6 \text{ pF}$$

In (7.12) and (7.9)

$$f_{-3dB} = \frac{1}{2\pi} \frac{5000+300+10400}{(5000+300) \times 10400} \frac{10^{12}}{5.8+17.6} \text{ Hz}$$

$$= 1.94 \text{ MHz}$$

(b) From (7.27)

$$P_2 = -\left(\frac{1}{R_L C_\mu} + \frac{1}{R C_\pi} + \frac{1}{R_L C_\pi} + \omega_T\right)$$

$$R = (R_S + r_b) // r_\pi$$

$$= 5300 || 10400 = 3511 \Omega$$

$$\therefore P_2 = -\left(\frac{10^{12}}{3000 \times 0.3} + \frac{10^{12}}{3511 \times 5.8} + \frac{10^{12}}{3000 \times 5.8} + 2\pi \times 500 \times 10^6\right)$$

$$= -(11.1 + 0.49 + 0.57 + 31.4) \times 10^8 \text{ rad/sec}$$

$$= -43.6 \times 10^8 \text{ rad/sec}$$

$$= -693 \text{ MHz}$$

7-2

```
COMMON EMITTER GAIN STAGE
VCC 1 0 5V
RL 1 2 3K
Q1 2 3 0 NPN
RS 4 3 5K
VI 4 0 0.7696 AC
.TF V(2) VI
.PLOT AC VDB(2)
.PLOT AC VP(2)
.AC DEC 10 100K 1GIG
.MODEL NPN NPN IS=1E-16A BF=200
+ RB=300 CJC=0.3PF CJS=0 TF=302PS
* ASSUME CJE SMALL COMPARED TO CB
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END
```

```
******  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000

+0:1       = 5.000E+00 0:2        = 3.497E+00 0:3        = 7.571E-01
+0:4       = 7.696E-01

**** BIPOLAR JUNCTION TRANSISTORS

ELEMENT  0:Q1
MODEL    0:NPN
 IB       2.504E-06
 IC       5.009E-04
 VBE      7.571E-01
 VCE      3.497E+00
 VBC     -2.740E+00
 VS      -3.497E+00
 POWER    1.754E-03
 BETAD    2.000E+02
 GM       1.937E-02
 RPI      1.032E+04
 RX       3.000E+02
 RO       2.741E+16
 CPI      5.849E-12
 CMU      1.806E-13
 CBX      0.
 CCS      0.
 BETAAC   2.000E+02
 FT       5.112E+08

****     SMALL-SIGNAL TRANSFER CHARACTERISTICS

   V(2)/VI                                  = -3.839E+01
   INPUT RESISTANCE AT           VI         =  1.562E+04
   OUTPUT RESISTANCE AT V(2)                =  3.000E+03
```

```
******  AC ANALYSIS                                  TNOM=  27.000 TEMP=  27.000

    FREQ        VDB(2)
(A         )  -4.000E+01    -2.000E+01    0.            2.000E+01     4.000E+01
                       +             +             +             +             +
 1.000E+05  3.16E+01-+------+------+------+------+------+------+------+A-----+-
 1.258E+05  3.16E+01 +      +      +      +      +      +      +      +A     +
 1.584E+05  3.16E+01 +      +      +      +      +      +      +      +A     +
 1.995E+05  3.16E+01 +      +      +      +      +      +      +      +A     +
 2.511E+05  3.16E+01 +      +      +      +      +      +      +      +A     +
 3.162E+05  3.16E+01 +      +      +      +      +      +      +      +A     +
 3.981E+05  3.15E+01 +      +      +      +      +      +      +      +A     +
 5.011E+05  3.15E+01 +      +      +      +      +      +      +      +A     +
 6.309E+05  3.14E+01 +      +      +      +      +      +      +      +A     +
 7.943E+05  3.13E+01 +      +      +      +      +      +      +      +A     +
 1.000E+06  3.11E+01-+------+------+------+------+------+------+------+A-----+-
 1.258E+06  3.08E+01 +      +      +      +      +      +      +      +A     +
 1.584E+06  3.04E+01 +      +      +      +      +      +      +      A      +
 1.995E+06  2.99E+01 +      +      +      +      +      +      +      A      +
 2.511E+06  2.90E+01 +      +      +      +      +      +      +     A+      +
 3.162E+06  2.80E+01 +      +      +      +      +      +      +     A+      +
 3.981E+06  2.67E+01 +      +      +      +      +      +      +    A +      +
 5.011E+06  2.52E+01 +      +      +      +      +      +      +   A  +      +
 6.309E+06  2.36E+01 +      +      +      +      +      +      +  A   +      +
 7.943E+06  2.19E+01 +      +      +      +      +      +      +A     +      +
 1.000E+07  2.01E+01-+------+------+------+------+------+------A------+------+-
 1.258E+07  1.82E+01 +      +      +      +      +      +     A+      +      +
 1.584E+07  1.62E+01 +      +      +      +      +      +   A  +      +      +
 1.995E+07  1.43E+01 +      +      +      +      +      +  A   +      +      +
 2.511E+07  1.23E+01 +      +      +      +      +      + A    +      +      +
 3.162E+07  1.03E+01 +      +      +      +      +      A      +      +      +
 3.981E+07  8.39E+00 +      +      +      +      +     A+      +      +      +
 5.011E+07  6.39E+00 +      +      +      +      +   A  +      +      +      +
 6.309E+07  4.38E+00 +      +      +      +      +  A   +      +      +      +
 7.943E+07  2.37E+00 +      +      +      +      + A    +      +      +      +
 1.000E+08  3.56E-01-+------+------+------+------A------+------+------+------+-
 1.258E+08 -1.67E+00 +      +      +      +     A+      +      +      +      +
 1.584E+08 -3.73E+00 +      +      +      +   A  +      +      +      +      +
 1.995E+08 -5.82E+00 +      +      +      +  A   +      +      +      +      +
 2.511E+08 -7.95E+00 +      +      +      +A     +      +      +      +      +
 3.162E+08 -1.01E+01 +      +      +      A      +      +      +      +      +
 3.981E+08 -1.24E+01 +      +      +    A +      +      +      +      +      +
 5.011E+08 -1.49E+01 +      +      +   A  +      +      +      +      +      +
 6.309E+08 -1.75E+01 +      +      + A    +      +      +      +      +      +
 7.943E+08 -2.03E+01 +      +      A      +      +      +      +      +      +
 1.000E+09 -2.34E+01-+------+----A-+------+------+------+------+------+------+-
                     +             +             +             +             +
```

```
    FREQ        VP(2)
(A         )   0.           5.000E+01     1.000E+02     1.500E+02     2.000E+02
                       +             +             +             +             +
 1.000E+05  1.77E+02-+------+------+------+------+------+------+------+A-----+-
 1.258E+05  1.77E+02 +      +      +      +      +      +      +      +A     +
 1.584E+05  1.76E+02 +      +      +      +      +      +      +      A      +
 1.995E+05  1.75E+02 +      +      +      +      +      +      +      A      +
 2.511E+05  1.74E+02 +      +      +      +      +      +      +      A      +
 3.162E+05  1.73E+02 +      +      +      +      +      +      +      A      +
 3.981E+05  1.71E+02 +      +      +      +      +      +      +     A+      +
 5.011E+05  1.69E+02 +      +      +      +      +      +      +    A +      +
 6.309E+05  1.67E+02 +      +      +      +      +      +      +    A +      +
 7.943E+05  1.63E+02 +      +      +      +      +      +      +   A  +      +
 1.000E+06  1.59E+02-+------+------+------+------+------+------+--A---+------+-
 1.258E+06  1.55E+02 +      +      +      +      +      +      +A     +      +
 1.584E+06  1.49E+02 +      +      +      +      +      +      A      +      +
 1.995E+06  1.43E+02 +      +      +      +      +      +    A +      +      +
 2.511E+06  1.37E+02 +      +      +      +      +      +  A   +      +      +
 3.162E+06  1.30E+02 +      +      +      +      +      + A    +      +      +
 3.981E+06  1.24E+02 +      +      +      +      +      A      +      +      +
 5.011E+06  1.18E+02 +      +      +      +      +    A +      +      +      +
 6.309E+06  1.13E+02 +      +      +      +      +   A  +      +      +      +
 7.943E+06  1.08E+02 +      +      +      +      + A    +      +      +      +
 1.000E+07  1.04E+02-+------+------+------+------+A-----+------+------+------+-
 1.258E+07  1.01E+02 +      +      +      +      A      +      +      +      +
 1.584E+07  9.86E+01 +      +      +      +      A      +      +      +      +
 1.995E+07  9.63E+01 +      +      +      +     A+      +      +      +      +
 2.511E+07  9.44E+01 +      +      +      +    A +      +      +      +      +
 3.162E+07  9.26E+01 +      +      +      +    A +      +      +      +      +
 3.981E+07  9.10E+01 +      +      +      +   A  +      +      +      +      +
 5.011E+07  8.95E+01 +      +      +      +   A  +      +      +      +      +
 6.309E+07  8.79E+01 +      +      +      +   A  +      +      +      +      +
 7.943E+07  8.62E+01 +      +      +      +  A   +      +      +      +      +
 1.000E+08  8.44E+01-+------+------+------+--A---+------+------+------+------+-
 1.258E+08  8.22E+01 +      +      +      + A    +      +      +      +      +
 1.584E+08  7.97E+01 +      +      +      +A     +      +      +      +      +
 1.995E+08  7.66E+01 +      +      +      A      +      +      +      +      +
 2.511E+08  7.30E+01 +      +      +     A+      +      +      +      +      +
 3.162E+08  6.86E+01 +      +      +    A +      +      +      +      +      +
 3.981E+08  6.35E+01 +      +      +   A  +      +      +      +      +      +
 5.011E+08  5.76E+01 +      +      + A    +      +      +      +      +      +
 6.309E+08  5.10E+01 +      +      A      +      +      +      +      +      +
 7.943E+08  4.39E+01 +      +    A +      +      +      +      +      +      +
 1.000E+09  3.66E+01-+------+--A---+------+------+------+------+------+------+-
                     +             +             +             +             +
```

7.2

$$g_m = \sqrt{2k_n' \frac{W}{L} I_D} = \sqrt{2\times 60\times 10^{-6}\times \frac{100}{2-2\times 0.2-0}\times 500\times 10^{-6}}$$

$$= 1.9\times 10^{-3}\ \text{A/V}$$

$$A_v = -g_m R_L = -1.9\times 10^{-3}\times 5\times 10^{3} = -9.5$$

$$C_{gs} = \frac{2}{3} W L_{eff} C_{ox} + W L_d C_{ox}$$

$$= \frac{2}{3}\, 100\times 1.6\times 0.7 + 100\times 0.2\times 0.7$$

$$= 89\ \text{fF}$$

$$C_{gd} = W L_d C_{ox} = 100\times 0.2\times 0.7 = 14\ \text{fF}$$

(a) Use the Miller effect.

$$|P_1| = \frac{1}{R_S[C_{gs} + C_{gd}(1-A_v)]}$$

$$= \frac{1}{10k[89+14(1+9.5)]\times 10^{-15}}$$

$$= \frac{1}{2.4\times 10^{-9}} = 4.2\times 10^{8}\ \text{rad/s}$$

$$f_{-3dB} = \frac{|P_1|}{2\pi} = 67\ \text{MHz}$$

(b) Do not use the Miller effect to calculate the second pole.

From Eq. (7.26),

$$|P_2| = \frac{1}{|P_1|}\frac{1}{R_L R_S C_{gd} C_{gs}}$$

$$= \frac{1}{4.2\times 10^{8}}\frac{1}{5k\times 10k\times 14f\times 89f}$$

$$= 3.8\times 10^{10}\ \text{rad/s}$$

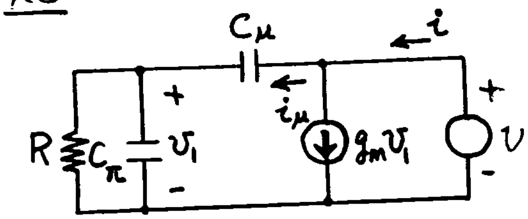
It is equivalent to 6.1 GHz.

```
COMMON SOURCE AMPLIFIER
VDD 1 0 5
VI 2 0 DC 1.216 AC 1
RS 2 3 10K
RL 1 4 5K
M1 4 3 0 0 CMOSN  W=100U  L=2U
* COX'=0.7FF/UM**2=EOX/TOX => TOX=500 ANGSTROMS
.MODEL CMOSN NMOS LEVEL=1 LAMBDA=0 VTO=0.7 KP=60U LD=0.2U TOX=500E-10
.OPTIONS NOMOD
.AC DEC 10 1MEG 10G
.PLOT AC VM(4)
.WIDTH OUT=80
.OPTIONS SPICE
.END
```

```
 ******  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000

+0:1        = 5.000E+00 0:2        = 1.216E+00 0:3        = 1.216E+00
+0:4        = 2.503E+00

**** MOSFETS

SUBCKT
ELEMENT  0:M1
MODEL    0:CMOSN
 ID       4.992E-04
 IBS       0.
 IBD      -2.504E-14
 VGS      1.216E+00
 VDS      2.503E+00
 VBS       0.
 VTH      7.000E-01
 VDSAT    5.160E-01
 BETA     3.750E-03
 GAM EFF   0.
 GM       1.935E-03
 GDS       0.
 GMB       0.
 CDTOT    1.418E-14
 CGTOT    1.050E-13
 CSTOT    8.748E-14
 CBTOT    3.349E-15
 CGS      8.748E-14
 CGD      1.418E-14

 ******  AC ANALYSIS                                 TNOM=  27.000 TEMP=  27.000
```

```
     FREQ       VM(4)
(A        )   1.000E-02     1.000E-01     1.000E+00     9.999E+00     9.999E+01
                  +             +             +             +             +
 1.000E+06  9.67E+00-+------+------+------+------+------+------A------+------+-
 1.258E+06  9.67E+00 +      +      +      +      +      +      A      +      +
 1.584E+06  9.67E+00 +      +      +      +      +      +      A      +      +
 1.995E+06  9.67E+00 +      +      +      +      +      +      A      +      +
 2.511E+06  9.66E+00 +      +      +      +      +      +      A      +      +
 3.162E+06  9.66E+00 +      +      +      +      +      +      A      +      +
 3.981E+06  9.65E+00 +      +      +      +      +      +      A      +      +
 5.011E+06  9.64E+00 +      +      +      +      +      +      A      +      +
 6.309E+06  9.62E+00 +      +      +      +      +      +      A      +      +
 7.943E+06  9.60E+00 +      +      +      +      +      +      A      +      +
 1.000E+07  9.56E+00-+------+------+------+------+------+------A------+------+-
 1.258E+07  9.49E+00 +      +      +      +      +      +      A      +      +
 1.584E+07  9.39E+00 +      +      +      +      +      +      A      +      +
 1.995E+07  9.24E+00 +      +      +      +      +      +      A      +      +
 2.511E+07  9.01E+00 +      +      +      +      +      +     A+      +      +
 3.162E+07  8.68E+00 +      +      +      +      +      +     A+      +      +
 3.981E+07  8.23E+00 +      +      +      +      +      +     A+      +      +
 5.011E+07  7.64E+00 +      +      +      +      +      +    A +      +      +
 6.309E+07  6.91E+00 +      +      +      +      +      +    A +      +      +
 7.943E+07  6.09E+00 +      +      +      +      +      +   A  +      +      +
 1.000E+08  5.24E+00-+------+------+------+------+------+--A---+------+------+-
 1.258E+08  4.41E+00 +      +      +      +      +      + A    +      +      +
 1.584E+08  3.64E+00 +      +      +      +      +      +A     +      +      +
 1.995E+08  2.97E+00 +      +      +      +      +      A      +      +      +
 2.511E+08  2.40E+00 +      +      +      +      +    A +      +      +      +
 3.162E+08  1.93E+00 +      +      +      +      +   A  +      +      +      +
 3.981E+08  1.54E+00 +      +      +      +      + A    +      +      +      +
 5.011E+08  1.23E+00 +      +      +      +      +A     +      +      +      +
 6.309E+08  9.79E-01 +      +      +      +      A      +      +      +      +
 7.943E+08  7.77E-01 +      +      +      +    A +      +      +      +      +
 1.000E+09  6.15E-01-+------+------+------+---A--+------+------+------+------+-
 1.258E+09  4.86E-01 +      +      +      + A    +      +      +      +      +
 1.584E+09  3.82E-01 +      +      +      +A     +      +      +      +      +
 1.995E+09  2.98E-01 +      +      +      A      +      +      +      +      +
 2.511E+09  2.31E-01 +      +      +    A +      +      +      +      +      +
 3.162E+09  1.77E-01 +      +      +  A   +      +      +      +      +      +
 3.981E+09  1.33E-01 +      +      + A    +      +      +      +      +      +
 5.011E+09  9.87E-02 +      +      A      +      +      +      +      +      +
 6.309E+09  7.16E-02 +      +    A +      +      +      +      +      +      +
 7.943E+09  5.09E-02 +      +  A   +      +      +      +      +      +      +
 1.000E+10  3.58E-02-+------+A-----+------+------+------+------+------+------+-
                     +             +             +             +             +
```

7.3



$R = (R_s + r_b) \parallel r_\pi$

$v_1 = \dfrac{Z_\pi}{Z_\pi + \frac{1}{C_\mu S}} v$, where $Z_\pi = \dfrac{R}{1 + RC_\pi S}$

$g_m v_1 = g_m \dfrac{Rv}{R + (1 + RC_\pi S)\frac{1}{C_\mu S}}$

$= \dfrac{g_m R C_\mu S}{1 + RC_\pi S + RC_\mu S} v$

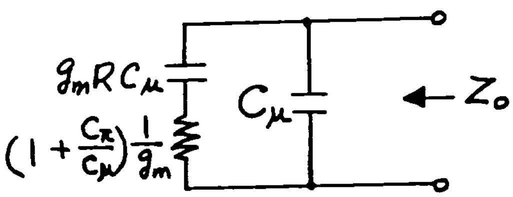
$i = i_\mu + g_m v_1$

$\therefore \dfrac{1}{Z_o} = \dfrac{i}{v} = \dfrac{i_\mu}{v} + \dfrac{g_m v_1}{v}$

$= \dfrac{i_\mu}{v} + \dfrac{g_m R C_\mu S}{1 + RC_\pi S + RC_\mu S}$

But $\dfrac{i_\mu}{v} \simeq C_\mu S$, because $C_\pi >> C_\mu$

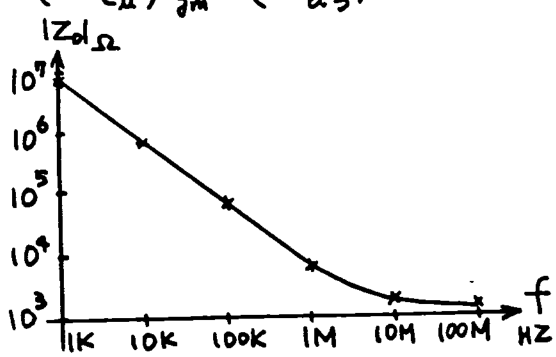
$\therefore Z_o \simeq \dfrac{1}{C_\mu S} \parallel \left(\dfrac{1}{g_m R C_\mu S} + \dfrac{C_\pi}{C_\mu}\dfrac{1}{g_m} + \dfrac{1}{g_m}\right)$



$C_\mu = 0.3 pF$

$g_m R C_\mu = \dfrac{3511}{52} \times 0.3 = 20.3\ PF$

$(1 + \dfrac{C_\pi}{C_\mu})\dfrac{1}{g_m} = (1 + \dfrac{5.8}{0.3}) 52 = 1057 \Omega$



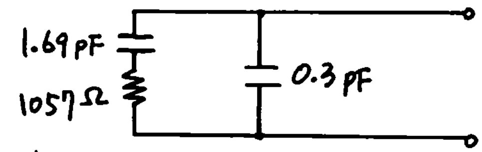
7.4

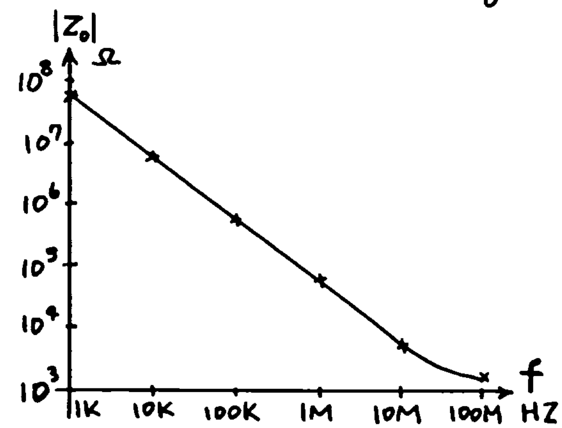
$R_s = 0$, $C_\mu = 0.3$ PF

$R = r_b \parallel r_\pi = 300 \parallel 10400 = 292 \Omega$

$g_m R C_\mu = \dfrac{292}{52} \times 0.3 = 1.69$ PF

$(1 + \dfrac{C_\pi}{C_\mu})\dfrac{1}{g_m} = 1057 \Omega$

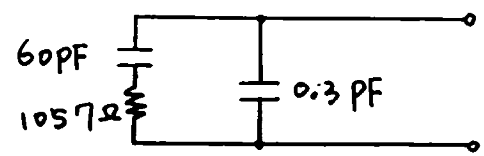


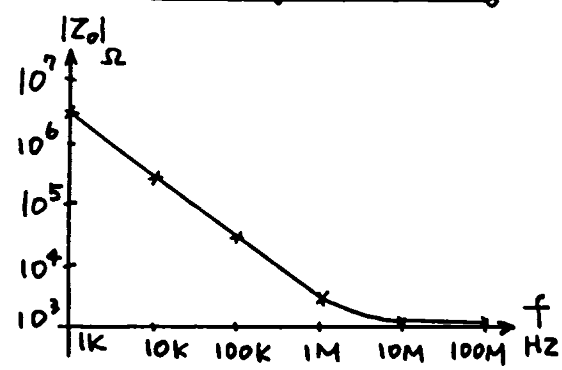


$R_s = \infty$, $C_\mu = 0.3$ PF

$R = r_\pi = 10400 \Omega$

$g_m R C_\mu = \dfrac{10400}{52} \times 0.3 = 60$ PF





7.5

$C_{gs} = \frac{2}{3} W L_{eff} C_{ox} + W L_d C_{ox}$

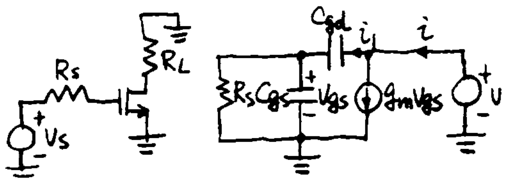
$= \frac{2}{3} 100(2-2\times0.2-0)\times0.7 + 100\times0.2\times0.7$

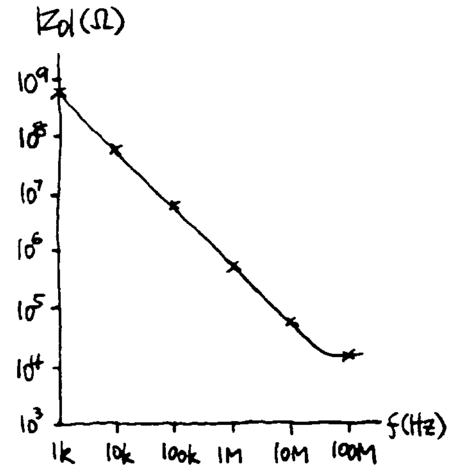
$= 89fF$

$C_{gd} = W L_d C_{ox} = 100\times0.2\times0.7 = 14fF$

$g_m = \sqrt{2k_n' \frac{W}{L_{eff}} I_D} = \sqrt{2\times60\times10^{-6} \frac{100}{2-0.4-0} \times0.5\times10^{-3}}$

$= 1.9\times10^{-3} A/V = 1.9mA/V$





$R_s \| \frac{1}{sC_{gs}} = \frac{R_s}{1+sR_sC_{gs}}$

$V_{gs} = V \dfrac{\frac{R_s}{1+sR_sC_{gs}}}{\frac{1}{sC_{gd}} + \frac{R_s}{1+sR_sC_{gs}}} = V \dfrac{R_s}{R_s + \frac{1+sR_sC_{gs}}{sC_{gd}}}$

$\because C_{gd} \ll C_{gs}$ and $\frac{1}{sC_{gd}} \gg R_s \| \frac{1}{sC_{gs}}$

$\therefore i_1 \approx sC_{gd} V$

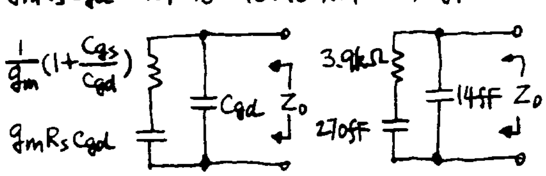
$\frac{1}{Z_0} = \frac{i}{V} = \frac{i_1}{V} + \frac{g_m V_{gs}}{V}$

$= sC_{gd} + \dfrac{g_m R_s}{R_s + \frac{1+sR_sC_{gs}}{sC_{gd}}}$

$Z_0 = \frac{1}{sC_{gd}} \| \left[\frac{1}{g_m}\left(1+\frac{C_{gs}}{C_{gd}}\right) + \frac{1}{s g_m R_s C_{gd}} \right]$

$\frac{1}{g_m}\left(1+\frac{C_{gs}}{C_{gd}}\right) = \frac{1}{1.9\times10^{-3}}\left(1+\frac{89}{14}\right) = 3.9\times10^3 \Omega$

$g_m R_s C_{gd} = 1.9\times10^{-3}\times10\times10^3\times14 = 270fF$



7.6

$$A_{cm} = -\frac{R_L}{2R_T}(1+j\omega C_T R_T)$$

$$= -\frac{3}{600}(1+j\omega\, 300\times10^3 \times 2\times10^{-12})$$

$$= -5\times10^{-3}(1+j\omega \times 600\times10^{-9})$$

Using dominant pole

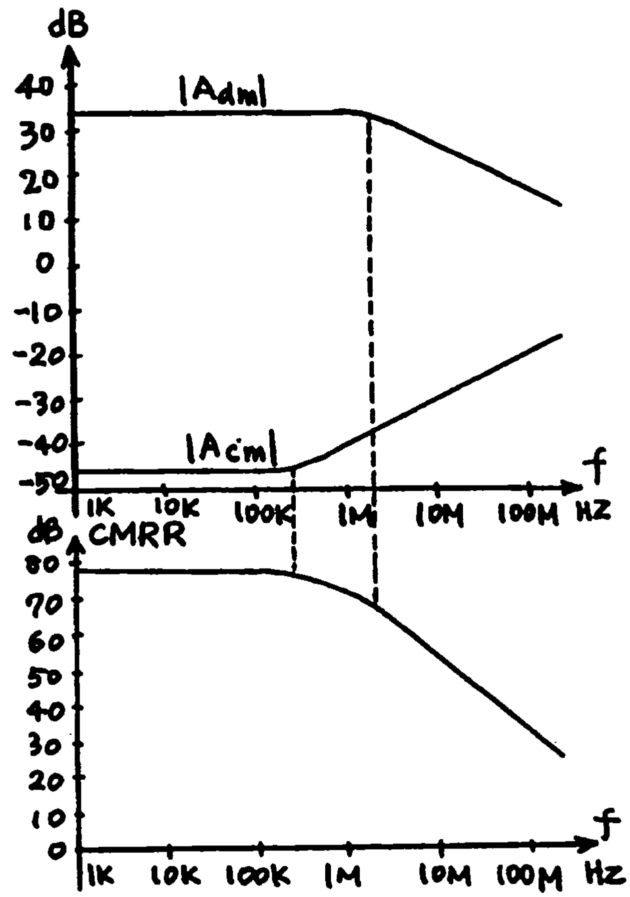
$$A_{dm} = -g_m R_L \frac{r_\pi}{R_s + r_b + r_\pi} \cdot \frac{1}{1+j\frac{\omega}{\omega_1}}$$

$$= -\frac{3000}{52} \frac{10.4k}{10.4k+300+5k} \cdot \frac{1}{1+j\frac{f}{1.94\times10^6}}$$

$$= -\frac{38.2}{1+j\frac{f}{1.94\times10^6}}$$

$$A_{cm} = -0.005\left(1+j\frac{f}{265\times10^3}\right)$$

$$CMRR = \left|\frac{A_{dm}}{A_{cm}}\right|$$



```
DIFFERENTIAL AMP, COMMON MODE
VCC 1 0 5V
VEE 9 0 -5V
IEE 7 9 1MA
REE 7 9 300K
CEE 7 9 2PF
RL1 1 2 3K
RL2 1 8 3K
Q1 2 3 7 NPN
RS1 4 3 5K
Q2 8 6 7 NPN
RS2 5 6 5K
VIC 4 0 0V AC
EVIC 5 0 4 0 1
.TF V(2) VIC
.PLOT AC VDB(2)
.AC DEC 10 10K 20MEG
.MODEL NPN NPN IS=1E-16A BF=200
+ RB=300 CJC=0.3PF CJS=0 TF=302PS
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

******  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
+0:1        = 5.000E+00 0:2        = 3.486E+00 0:3        =-1.261E-02
+0:4        =   0.      0:5        =   0.      0:6        =-1.261E-02
+0:7        =-7.699E-01 0:8        = 3.486E+00 0:9        =-5.000E+00

**** BIPOLAR JUNCTION TRANSISTORS
ELEMENT  0:Q1       0:Q2
MODEL    0:NPN      0:NPN
 IB      2.523E-06  2.523E-06
 IC      5.045E-04  5.045E-04
 VBE     7.573E-01  7.573E-01
 VCE     4.256E+00  4.256E+00
 VBC    -3.499E+00 -3.499E+00
 VS     -3.486E+00 -3.486E+00
 POWER   2.149E-03  2.149E-03
 BETAD   2.000E+02  2.000E+02
 GM      1.951E-02  1.951E-02
 RPI     1.025E+04  1.025E+04
 RX      3.000E+02  3.000E+02
 RO      3.499E+16  3.499E+16
 CPI     5.891E-12  5.891E-12
 CMU     1.693E-13  1.693E-13
 CBX       0.         0.
 CCS       0.         0.
 BETAAC  2.000E+02  2.000E+02
 FT      5.122E+08  5.122E+08

****     SMALL-SIGNAL TRANSFER CHARACTERISTICS
     V(2)/VIC                                   = -4.974E-03
     INPUT RESISTANCE AT        VIC             =  1.206E+08
     OUTPUT RESISTANCE AT V(2)                  =  3.000E+03

******  AC ANALYSIS                         TNOM=  27.000 TEMP=  27.000

   FREQ      VDB(2)
(A       )   -6.000E+01    -4.000E+01    -2.000E+01    0.            2.000E+01
             +             +             +             +             +

9.999E+03 -4.60E+01-+------+--A---+------+------+------+------+------+------+-
1.258E+04 -4.60E+01 +      +  A   +      +      +      +      +      +      +
1.584E+04 -4.60E+01 +      +  A   +      +      +      +      +      +      +
1.995E+04 -4.60E+01 +      +  A   +      +      +      +      +      +      +
2.511E+04 -4.60E+01 +      +  A   +      +      +      +      +      +      +
3.162E+04 -4.60E+01 +      +  A   +      +      +      +      +      +      +
3.981E+04 -4.60E+01 +      +  A   +      +      +      +      +      +      +
5.011E+04 -4.59E+01 +      +  A   +      +      +      +      +      +      +
6.309E+04 -4.59E+01 +      +  A   +      +      +      +      +      +      +
7.943E+04 -4.58E+01 +      +  A   +      +      +      +      +      +      +
1.000E+05 -4.56E+01-+------+--A---+------+------+------+------+------+------+-
1.258E+05 -4.54E+01 +      +  A   +      +      +      +      +      +      +
1.584E+05 -4.51E+01 +      +  A   +      +      +      +      +      +      +
1.995E+05 -4.46E+01 +      +   A  +      +      +      +      +      +      +
2.511E+05 -4.39E+01 +      +   A  +      +      +      +      +      +      +
3.162E+05 -4.31E+01 +      +    A +      +      +      +      +      +      +
3.981E+05 -4.20E+01 +      +     A+      +      +      +      +      +      +
5.011E+05 -4.06E+01 +      +      A      +      +      +      +      +      +
6.309E+05 -3.91E+01 +      +      +A     +      +      +      +      +      +
7.943E+05 -3.75E+01 +      +      + A    +      +      +      +      +      +
1.000E+06 -3.57E+01-+------+------+--A---+------+------+------+------+------+-
1.258E+06 -3.39E+01 +      +      +   A  +      +      +      +      +      +
1.584E+06 -3.19E+01 +      +      +     A+      +      +      +      +      +
1.995E+06 -3.00E+01 +      +      +      A      +      +      +      +      +
2.511E+06 -2.80E+01 +      +      +      +A     +      +      +      +      +
3.162E+06 -2.61E+01 +      +      +      +  A   +      +      +      +      +
3.981E+06 -2.41E+01 +      +      +      +   A  +      +      +      +      +
5.011E+06 -2.21E+01 +      +      +      +     A+      +      +      +      +
6.309E+06 -2.01E+01 +      +      +      +      A      +      +      +      +
7.943E+06 -1.80E+01 +      +      +      +      +A     +      +      +      +
1.000E+07 -1.60E+01-+------+------+------+------+--A---+------+------+------+-
1.258E+07 -1.39E+01 +      +      +      +      +   A  +      +      +      +
1.584E+07 -1.18E+01 +      +      +      +      +     A+      +      +      +
1.995E+07 -9.72E+00 +      +      +      +      +      A      +      +      +
2.511E+07 -7.47E+00 +      +      +      +      +      + A    +      +      +
                    +             +             +             +             +
```

```
*****
DIFFERENTIAL AMP, DIFFERENTIAL MODE
VCC 1 0 5V
VEE 9 0 -5V
IEE 7 9 1MA
REE 7 9 300K
CEE 7 9 2PF
RL1 1 2 3K
RL2 1 8 3K
Q1 2 3 7 NPN
RS1 4 3 5K
Q2 8 6 7 NPN
RS2 5 6 5K
VID 4 0 0V AC
EVID 0 5 4 0 1
.TF V(2) VID
.PLOT AC VDB(2)
.AC DEC 10 10K 20MEG
.MODEL NPN NPN IS=1E-16A BF=200
+ RB=300 CJC=0.3PF CJS=0 TF=302PS
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

****     SMALL-SIGNAL TRANSFER CHARACTERISTICS

     V(2)/VID                                   = -3.857E+01
     INPUT RESISTANCE AT        VID             =  1.555E+04
     OUTPUT RESISTANCE AT V(2)                  =  3.000E+03

******  AC ANALYSIS                         TNOM=  27.000 TEMP=  27.000

   FREQ      VDB(2)
(A       )    1.000E+01     2.000E+01     3.000E+01     4.000E+01     5.000E+01
              +             +             +             +             +

9.999E+03  3.17E+01-+------+------+------+------+-A----+------+------+------+-
1.258E+04  3.17E+01 +      +      +      +      + A    +      +      +      +
1.584E+04  3.17E+01 +      +      +      +      + A    +      +      +      +
1.995E+04  3.17E+01 +      +      +      +      + A    +      +      +      +
2.511E+04  3.17E+01 +      +      +      +      + A    +      +      +      +
3.162E+04  3.17E+01 +      +      +      +      + A    +      +      +      +
3.981E+04  3.17E+01 +      +      +      +      + A    +      +      +      +
5.011E+04  3.17E+01 +      +      +      +      + A    +      +      +      +
6.309E+04  3.17E+01 +      +      +      +      + A    +      +      +      +
7.943E+04  3.17E+01 +      +      +      +      + A    +      +      +      +
1.000E+05  3.17E+01-+------+------+------+------+-A----+------+------+------+-
1.258E+05  3.17E+01 +      +      +      +      + A    +      +      +      +
1.584E+05  3.17E+01 +      +      +      +      + A    +      +      +      +
1.995E+05  3.17E+01 +      +      +      +      + A    +      +      +      +
2.511E+05  3.16E+01 +      +      +      +      + A    +      +      +      +
3.162E+05  3.16E+01 +      +      +      +      + A    +      +      +      +
3.981E+05  3.16E+01 +      +      +      +      + A    +      +      +      +
5.011E+05  3.15E+01 +      +      +      +      + A    +      +      +      +
6.309E+05  3.15E+01 +      +      +      +      + A    +      +      +      +
7.943E+05  3.14E+01 +      +      +      +      + A    +      +      +      +
1.000E+06  3.12E+01-+------+------+------+------+-A----+------+------+------+-
1.258E+06  3.09E+01 +      +      +      +      +A     +      +      +      +
1.584E+06  3.05E+01 +      +      +      +      +A     +      +      +      +
1.995E+06  2.99E+01 +      +      +      +      A      +      +      +      +
2.511E+06  2.92E+01 +      +      +      +     A+      +      +      +      +
3.162E+06  2.82E+01 +      +      +      +   A  +      +      +      +      +
3.981E+06  2.70E+01 +      +      +      +  A   +      +      +      +      +
5.011E+06  2.55E+01 +      +      +      +A     +      +      +      +      +
6.309E+06  2.39E+01 +      +      +     A+      +      +      +      +      +
7.943E+06  2.22E+01 +      +      +  A   +      +      +      +      +      +
1.000E+07  2.04E+01-+------+------+A-----+------+------+------+------+------+-
1.258E+07  1.85E+01 +      +    A +      +      +      +      +      +      +
1.584E+07  1.66E+01 +      + A    +      +      +      +      +      +      +
1.995E+07  1.46E+01 +      A      +      +      +      +      +      +      +
2.511E+07  1.27E+01 +   A  +      +      +      +      +      +      +      +
```

7.7

$$A_{cm} \approx -\frac{R_L}{2R_T}(1+sR_TC_T)$$

$$= -\frac{3}{2\times300}(1+s\times300\times10^3\times2\times10^{-12})$$

$$= -5\times10^{-3}(1+6\times10^{-7}s)$$

To calculate A_{dm}, the dominant pole is

$$|p| = \frac{1}{R_S[C_{gs}+C_{gd}(1+g_mR_L)]}$$

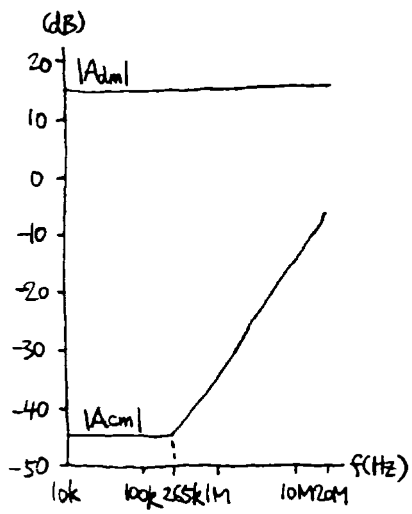
$$= \frac{1}{5\times10^3[98+14(1+1.8\times10^{-3}\times3\times10^3)]\times10^{-15}}$$

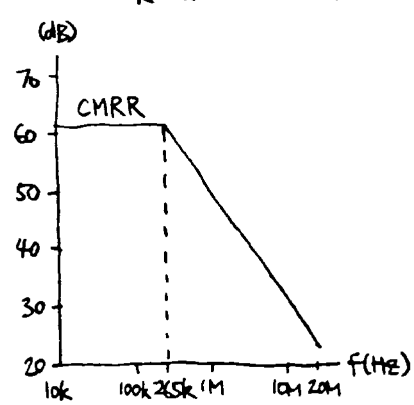
$$= 1.1\times10^9 \text{ rad/s}$$

$$A_{dm} = \frac{-g_mR_L}{1+s/|p|} = \frac{-1.8\times10^{-3}\times3\times10^3}{1+s/(1.1\times10^9)}$$

$$= -\frac{5.4}{1+s/(1.1\times10^9)}$$

$$CMRR = \frac{|A_{dm}|}{|A_{cm}|} = 1.1\times10^3\frac{1+s/(1.7\times10^6)}{1+s/(1.1\times10^9)}$$





```
DIFFERENTIAL AMP, COMMON MODE
VDD 1 0 5V
VSS 9 0 -5V
ISS 7 9 1MA
RSS 7 9 300K
CSS 7 9 2PF
RL1 1 2 3K
RL2 1 8 3K
M1 2 3 7 7 CMOSN W=100U L=2U
RS1 4 3 5K
M2 8 6 7 7 CMOSN  W=100U  L=2U
RS2 5 6 5K
VIC 4 0 -3.514V AC
EVIC 5 0 4 0 1
.TF V(2) VIC
.PLOT AC VDB(2)
.AC DEC 10 10K 20MEG
* COX'=0.7FF/UM**2=EOX/TOX => TOX=500 ANGSTROMS
.MODEL CMOSN NMOS LEVEL=1 LAMBDA=0 VTO=0.7 KP=60U LD=0.2U TOX=500E-10
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

 ******  OPERATING POINT INFORMATION       TNOM=  27.000 TEMP=  27.000
+0:1        = 5.000E+00 0:2        = 3.498E+00 0:3        =-3.514E+00
+0:4        =-3.514E+00 0:5        =-3.514E+00 0:6        =-3.514E+00
+0:7        =-4.730E+00 0:8        = 3.498E+00 0:9        =-5.000E+00

**** MOSFETS
ELEMENT  0:M1       0:M2
MODEL    0:CMOSN    0:CMOSN
 ID       5.004E-04  5.004E-04
 IBS        0.         0.
 IBD     -8.229E-14 -8.229E-14
 VGS      1.216E+00  1.216E+00
 VDS      8.229E+00  8.229E+00
 VBS        0.         0.
 VTH      7.000E-01  7.000E-01
 VDSAT    5.166E-01  5.166E-01
 BETA     3.750E-03  3.750E-03
 GAM EFF    0.         0.
 GM       1.937E-03  1.937E-03
 GDS        0.         0.
 GMB        0.         0.
 CDTOT    1.503E-14  1.503E-14
 CGTOT    1.058E-13  1.058E-13
 CSTOT    8.748E-14  8.748E-14
 CBTOT    3.344E-15  3.344E-15
 CGS      8.748E-14  8.748E-14
 CGD      1.503E-14  1.503E-14

****      SMALL-SIGNAL TRANSFER CHARACTERISTICS

    V(2)/VIC                                      = -4.996E-03

 ******  AC ANALYSIS                            TNOM=  27.000 TEMP=  27.000

      FREQ      VDB(2)
A      )       -6.000E+01          -4.000E+01          -2.000E+01          0.                  2.000E+01
                    +                   +                   +                   +                   +
9.999E+03 -4.60E+01-+---------+---A-----+---------+---------+---------+---------+---------+---------+
1.258E+04 -4.60E+01 +         +   A     +         +         +         +         +         +         +
1.584E+04 -4.60E+01 +         +   A     +         +         +         +         +         +         +
1.995E+04 -4.60E+01 +         +   A     +         +         +         +         +         +         +
2.511E+04 -4.59E+01 +         +   A     +         +         +         +         +         +         +
3.162E+04 -4.59E+01 +         +   A     +         +         +         +         +         +         +
3.981E+04 -4.59E+01 +         +   A     +         +         +         +         +         +         +
5.011E+04 -4.58E+01 +         +   A     +         +         +         +         +         +         +
6.309E+04 -4.58E+01 +         +   A     +         +         +         +         +         +         +
7.943E+04 -4.56E+01 +         +   A     +         +         +         +         +         +         +
1.000E+05 -4.54E+01-+---------+---A-----+---------+---------+---------+---------+---------+---------+
1.258E+05 -4.51E+01 +         +   A     +         +         +         +         +         +         +
1.584E+05 -4.47E+01 +         +     A   +         +         +         +         +         +         +
1.995E+05 -4.41E+01 +         +     A   +         +         +         +         +         +         +
2.511E+05 -4.33E+01 +         +      A  +         +         +         +         +         +         +
3.162E+05 -4.22E+01 +         +      A  +         +         +         +         +         +         +
3.981E+05 -4.10E+01 +         +        A+         +         +         +         +         +         +
5.011E+05 -3.95E+01 +         +         A         +         +         +         +         +         +
6.309E+05 -3.79E+01 +         +         +A        +         +         +         +         +         +
7.943E+05 -3.61E+01 +         +         +   A     +         +         +         +         +         +
1.000E+06 -3.43E+01-+---------+---------+-----A---+---------+---------+---------+---------+---------+
1.258E+06 -3.24E+01 +         +         +       A +         +         +         +         +         +
1.584E+06 -3.05E+01 +         +         +         A         +         +         +         +         +
1.995E+06 -2.85E+01 +         +         +         +A        +         +         +         +         +
2.511E+06 -2.65E+01 +         +         +         +  A      +         +         +         +         +
3.162E+06 -2.46E+01 +         +         +         +    A    +         +         +         +         +
3.981E+06 -2.26E+01 +         +         +         +      A  +         +         +         +         +
5.011E+06 -2.06E+01 +         +         +         +         A         +         +         +         +
6.309E+06 -1.86E+01 +         +         +         +         +A        +         +         +         +
7.943E+06 -1.66E+01 +         +         +         +         +  A      +         +         +         +
1.000E+07 -1.46E+01-+---------+---------+---------+---------+----A----+---------+---------+---------+
1.258E+07 -1.26E+01 +         +         +         +         +      A  +         +         +         +
1.584E+07 -1.06E+01 +         +         +         +         +         A         +         +         +
1.995E+07 -8.59E+00 +         +         +         +         +         +A        +         +         +
2.511E+07 -6.56E+00 +         +         +         +         +         +  A      +         +         +
                    +                   +                   +                   +                   +
```

```
*****
DIFFERENTIAL AMP, DIFFERENTIAL MODE
VDD 1 0 5V
VSS 9 0 -5V
ISS 7 9 1MA
RSS 7 9 300K
CSS 7 9 2PF
RL1 1 2 3K
RL2 1 8 3K
M1 2 3 7 7 CMOSN  W=100U  L=2U
RS1 4 3 5K
M2 8 6 7 7 CMOSN  W=100U  L=2U
RS2 5 6 5K
VID 4 10 0 AC
EVID 10 5 4 10 1
VBIAS 10 0 -3.514V
.TF V(2) VID
.PLOT AC VDB(2)
.AC DEC 10 10K 20MEG
* COX'=0.7FF/UM**2=EOX/TOX => TOX=500 ANGSTROMS
.MODEL CMOSN NMOS LEVEL=1 LAMBDA=0 VTO=0.7 KP=60U LD=0.2U TOX=500E-10
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

****      SMALL-SIGNAL TRANSFER CHARACTERISTICS

    V(2)/VID                                      = -5.812E+00

 ******  AC ANALYSIS                            TNOM=  27.000 TEMP=  27.000

      FREQ      VDB(2)
(A     )        1.515E+01           1.520E+01           1.525E+01           1.530E+01           1.535E+01
                    +                   +                   +                   +                   +
9.999E+03  1.52E+01-+---------+---------+---------+---------+---------+---A-----+---------+---------+
1.258E+04  1.52E+01 +         +         +         +         +         +   A     +         +         +
1.584E+04  1.52E+01 +         +         +         +         +         +   A     +         +         +
1.995E+04  1.52E+01 +         +         +         +         +         +   A     +         +         +
2.511E+04  1.52E+01 +         +         +         +         +         +   A     +         +         +
3.162E+04  1.52E+01 +         +         +         +         +         +   A     +         +         +
3.981E+04  1.52E+01 +         +         +         +         +         +   A     +         +         +
5.011E+04  1.52E+01 +         +         +         +         +         +   A     +         +         +
6.309E+04  1.52E+01 +         +         +         +         +         +   A     +         +         +
7.943E+04  1.52E+01 +         +         +         +         +         +   A     +         +         +
1.000E+05  1.52E+01-+---------+---------+---------+---------+---------+---A-----+---------+---------+
1.258E+05  1.52E+01 +         +         +         +         +         +   A     +         +         +
1.584E+05  1.52E+01 +         +         +         +         +         +   A     +         +         +
1.995E+05  1.52E+01 +         +         +         +         +         +   A     +         +         +
2.511E+05  1.52E+01 +         +         +         +         +         +   A     +         +         +
3.162E+05  1.52E+01 +         +         +         +         +         +   A     +         +         +
3.981E+05  1.52E+01 +         +         +         +         +         +   A     +         +         +
5.011E+05  1.52E+01 +         +         +         +         +         +   A     +         +         +
6.309E+05  1.52E+01 +         +         +         +         +         +   A     +         +         +
7.943E+05  1.52E+01 +         +         +         +         +         +   A     +         +         +
1.000E+06  1.52E+01-+---------+---------+---------+---------+---------+---A-----+---------+---------+
1.258E+06  1.52E+01 +         +         +         +         +         +   A     +         +         +
1.584E+06  1.52E+01 +         +         +         +         +         +   A     +         +         +
1.995E+06  1.52E+01 +         +         +         +         +         +   A     +         +         +
2.511E+06  1.52E+01 +         +         +         +         +         +   A     +         +         +
3.162E+06  1.52E+01 +         +         +         +         +         +   A     +         +         +
3.981E+06  1.52E+01 +         +         +         +         +         +   A     +         +         +
5.011E+06  1.52E+01 +         +         +         +         +         +  A      +         +         +
6.309E+06  1.52E+01 +         +         +         +         +         +A        +         +         +
7.943E+06  1.52E+01 +         +         +         +         +         A         +         +         +
1.000E+07  1.52E+01-+---------+---------+---------+---------+--------A+---------+---------+---------+
1.258E+07  1.52E+01 +         +         +         +         +   A     +         +         +         +
1.584E+07  1.52E+01 +         +         +         +       A +         +         +         +         +
1.995E+07  1.52E+01 +         +         +        A+         +         +         +         +         +
2.511E+07  1.51E+01 +         +  A      +         +         +         +         +         +         +
                    +                   +                   +                   +                   +
```

7.8

$$\frac{v_o}{v_i}=\frac{g_mR_E+\frac{R_E}{r_\pi}}{1+g_mR_E+\frac{R_b+R_E}{r_\pi}}\;\frac{1-\frac{s}{z_1}}{1-\frac{s}{P_1}}$$

$$=\frac{\frac{0.3}{26}\times 4000+\frac{4000}{50}\;\frac{0.3}{26}}{1+\frac{0.3}{26}\times 4000+\frac{4450}{50}\;\frac{0.3}{26}}\;\frac{1-\frac{j\omega}{z_1}}{1-\frac{j\omega}{P_1}}$$

$$=0.977\;\frac{1-j\frac{\omega}{z_1}}{1-j\frac{\omega}{P_1}}$$

$$z_1=-\frac{g_m}{C_\pi}=-\omega_T=-2\pi\times 4\times 10^6$$

$$=-25.1\times 10^6\ \text{rad/sec}$$

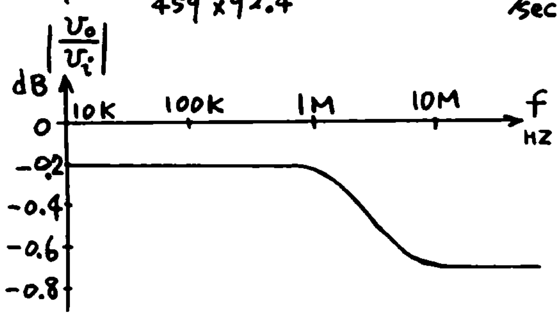
$$P_1=-\frac{1}{C_\pi R_1}$$

$$R_1=r_\pi\,\|\,\frac{R_b+R_E}{1+g_mR_E}=\frac{50\times 26}{0.3}\,\|\,\frac{450+4000}{1+\frac{0.3\times 4000}{26}}$$

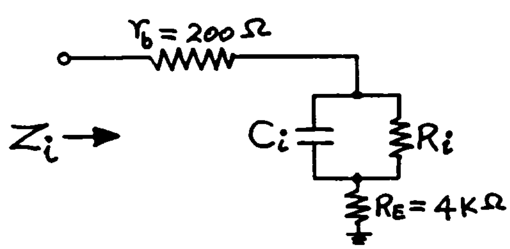
$$=4333\,\|\,94.4=92.4\ \Omega$$

$$C_\pi=\frac{g_m}{\omega_T}=\frac{0.3}{26}\;\frac{1}{2\pi\times 4\times 10^6}=459\ \text{pF}$$

$$\therefore P_1=-\frac{10^{12}}{459\times 92.4}=-23.6\times 10^6\ \text{rad/sec}$$



7.9

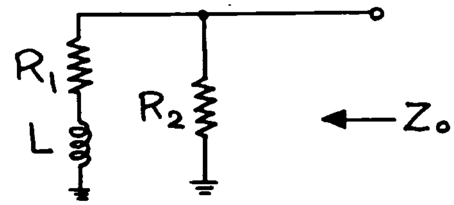


$$C_i=\frac{C_\pi}{1+g_mR_E}=\frac{459}{1+\frac{0.3\times 4000}{26}}=9.73\ \text{pF}$$

$$R_i=(1+g_mR_E)r_\pi=\left(1+\frac{0.3\times 4000}{26}\right)\times\frac{50\times 26}{0.3}$$

$$=204\ \text{K}\Omega$$

$$Z_i=4.2\text{k}\Omega+204\text{K}\Omega\,\|\,\frac{1}{j\omega C_i}$$

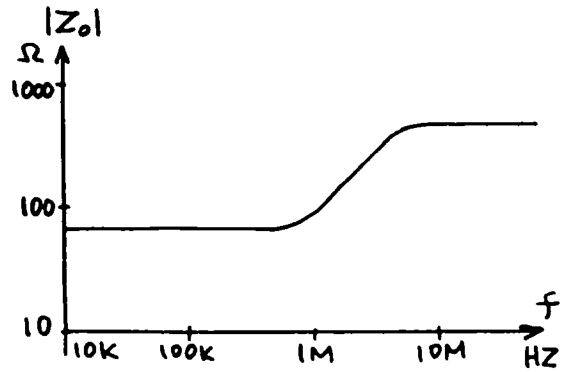


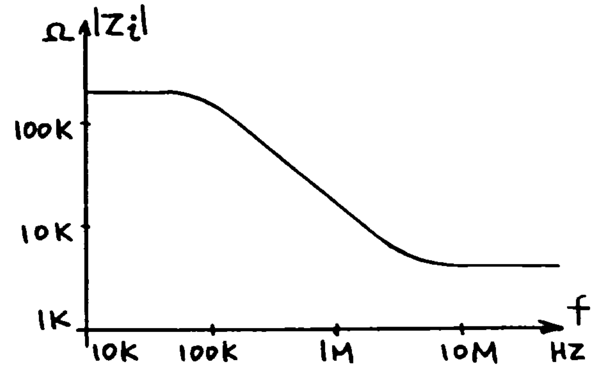
$$R_1=\frac{1}{g_m}+\frac{R_b}{\beta_o}=\frac{26}{0.3}+\frac{450}{50}=95.7\ \Omega$$

$$R_2=R_b=450\ \Omega$$

$$L=C_\pi r_\pi\frac{R_b}{\beta_o}=459\times\frac{50\times 26}{0.3}\times\frac{450}{50}\times 10^{-12}$$

$$=17.9\ \mu\text{H}$$





```
PNP EMITTER FOLLOWER, REISTIVE LOAD
* DC VO=0V, 300UA*4K=1.2V=VCC
VCC 1 0 1.2V
VEE 2 0 -1.2V
RE 1 5 4K
Q1 2 4 5 PNP
RS 3 4 250
RLOAD 5 0 1K
VBIAS 3 6 -0.745V AC
VPULSE 6 0 PULSE 0V 1MV 1NS 0NS 0NS 100NS
.TRAN 0.25NS 10NS
.PLOT TRAN V(5)
.MODEL PNP PNP IS=1E-16A BF=50
+ RB=200 CJE=0 CJC=0 CJS=0 TF=39.8NS
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END
```

```
 ******  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000

+0:1        = 1.200E+00 0:2        =-1.200E+00 0:3        =-7.450E-01
+0:4        =-7.435E-01 0:5        = 1.819E-04 0:6        =    0.

**** BIPOLAR JUNCTION TRANSISTORS

ELEMENT  0:Q1
MODEL    0:PNP
 IB      -5.878E-06
 IC      -2.939E-04
 VBE     -7.437E-01
 VCE     -1.200E+00
 VBC      4.565E-01
 VS       7.424E-01
 POWER    3.571E-04
 BETAD    5.000E+01
 GM       1.136E-02
 RPI      4.400E+03
 RX       2.000E+02
 RO       4.576E+15
 CPI      4.522E-10
 CMU        0.
 CBX        0.
 CCS        0.
 BETAAC   5.000E+01
 FT       3.998E+06
```

```
 ******  TRANSIENT ANALYSIS                    TNOM=  27.000 TEMP=  27.000

   TIME       V(5)
(A       )  -5.000E-04     0.         5.000E-04     1.000E-03     1.500E-03
                     +             +             +             +             +

     0.     1.82E-04-+------+------+----A-+------+------+------+------+------+-
 2.500E-10  1.82E-04 +      +      +    A +      +      +      +      +      +
 5.000E-10  1.82E-04 +      +      +    A +      +      +      +      +      +
 7.500E-10  1.82E-04 +      +      +    A +      +      +      +      +      +
 1.000E-09  1.82E-04 +      +      +    A +      +      +      +      +      +
 1.250E-09  8.23E-04 +      +      +      +      +      + A    +      +      +
 1.500E-09  8.24E-04 +      +      +      +      +      + A    +      +      +
 1.750E-09  8.25E-04 +      +      +      +      +      + A    +      +      +
 2 000E-09  9.26E-04 +      +      +      +      +      + A    +      +      +
 2.250E-09  8.27E-04 +      +      +      +      +      + A    +      +      +
 2.500E-09  8.28E-04-+------+------+------+------+------+-A----+------+------+-
 2.750E-09  8.29E-04 +      +      +      +      +      + A    +      +      +
 3.000E-09  8.31E-04 +      +      +      +      +      + A    +      +      +
 3.250E-09  8.32E-04 +      +      +      +      +      + A    +      +      +
 3.500E-09  8.33E-04 +      +      +      +      +      + A    +      +      +
 3.750E-09  8.34E-04 +      +      +      +      +      + A    +      +      +
 4.000E-09  8.35E-04 +      +      +      +      +      + A    +      +      +
 4.250E-09  8.36E-04 +      +      +      +      +      + A    +      +      +
 4.500E-09  8.37E-04 +      +      +      +      +      + A    +      +      +
 4.750E-09  8.38E-04 +      +      +      +      +      + A    +      +      +
 5.000E-09  8.39E-04-+------+------+------+------+------+--A---+------+------+-
 5.250E-09  8.40E-04 +      +      +      +      +      +  A   +      +      +
 5.500E-09  8.42E-04 +      +      +      +      +      +  A   +      +      +
 5.750E-09  8.43E-04 +      +      +      +      +      +  A   +      +      +
 6 000E-09  8.44E-04 +      +      +      +      +      +  A   +      +      +
 6.250E-09  8.45E-04 +      +      +      +      +      +  A   +      +      +
 6.500E-09  8.46E-04 +      +      +      +      +      +  A   +      +      +
 6.750E-09  8.47E-04 +      +      +      +      +      +  A   +      +      +
 7.000E-09  8 49E-04 +      +      +      +      +      +  A   +      +      +
 7.250E-09  8.49E-04 +      +      +      +      +      +  A   +      +      +
 7 500E-09  8.50E-04-+------+------+------+------+------+--A---+------+------+-
 7.750E-09  8.51E-04 +      +      +      +      +      +  A   +      +      +
                     +             +             +             +             +

*****
```

```
PNP EMITTER FOLLOWER, CAPACITIVE LOAD
VCC 1 0 1.2V
VEE 2 0 -1.2V
IEE 1 5 300UA
Q1 2 4 5 PNP
RS 3 4 250
CLOAD 5 0 400PF
VBIAS 3 6 -0.745V AC
VPULSE 6 0 PULSE 0V 1MV 1NS 0NS 0NS 1300NS
.TRAN 20NS 800NS
.PLOT TRAN V(5)
.MODEL PNP PNP IS=1E-16A BF=50
+ RB=200 CJE=0 CJC=0 CJS=0 TF=39.8NS
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END
```

```
**** BIPOLAR JUNCTION TRANSISTORS

ELEMENT  0:Q1
MODEL    0:PNP
 IB      -5.882E-06
 IC      -2.941E-04
 VBE     -7.437E-01
 VCE     -1.200E+00
 VBC      4.565E-01
 VS       7.424E-01
 POWER    3.574E-04
 BETAD    5.000E+01
 GM       1.137E-02
 RPI      4.396E+03
 RX       2.000E+02
 RO       4.576E+15
 CPI      4.526E-10
 CMU        0.
 CBX        0.
 CCS        0.
 BETAAC   5.000E+01
 FT       3.998E+06
```

```
 ******  TRANSIENT ANALYSIS                    TNOM=  27.000 TEMP=  27.000

   TIME       V(5)
(A       )      0.         5.000E-04     1.000E-03     1.500E-03     2.000E-03
                     +             +             +             +             +

     0.     2.03E-04-+-----A+------+------+------+------+------+------+------+-
 2.000E-08  2.59E-04 +      A      +      +      +      +      +      +      +
 4.000E-08  3.94E-04 +      +   A  +      +      +      +      +      +      +
 6.000E-08  5.42E-04 +      +      +A     +      +      +      +      +      +
 8.000E-08  6.95E-04 +      +      +    A +      +      +      +      +      +
 1.000E-07  8.44E-04 +      +      +      +  A   +      +      +      +      +
 1.200E-07  9.81E-04 +      +      +      +     A+      +      +      +      +
 1.400E-07  1.10E-03 +      +      +      +      +  A   +      +      +      +
 1.600E-07  1.21E-03 +      +      +      +      +     A+      +      +      +
 1.800E-07  1.29E-03 +      +      +      +      +      +A     +      +      +
 2.000E-07  1.35E-03-+------+------+------+------+------+--A---+------+------+-
 2.200E-07  1.39E-03 +      +      +      +      +      +   A  +      +      +
 2.400E-07  1.42E-03 +      +      +      +      +      +    A +      +      +
 2.600E-07  1.43E-03 +      +      +      +      +      +    A +      +      +
 2.800E-07  1.42E-03 +      +      +      +      +      +    A +      +      +
 3.000E-07  1.41E-03 +      +      +      +      +      +   A  +      +      +
 3.200E-07  1.39E-03 +      +      +      +      +      +   A  +      +      +
 3.400E-07  1.36E-03 +      +      +      +      +      +  A   +      +      +
 3.600E-07  1.33E-03 +      +      +      +      +      + A    +      +      +
 3.300E-07  1.30E-03 +      +      +      +      +      +A     +      +      +
 4.000E-07  1.27E-03-+------+------+------+------+------+A-----+------+------+-
 4.200E-07  1.24E-03 +      +      +      +      +      A      +      +      +
 4.400E-07  1.22E-03 +      +      +      +      +     A+      +      +      +
 4.600E-07  1.20E-03 +      +      +      +      +     A+      +      +      +
 4.800E-07  1.18E-03 +      +      +      +      +    A +      +      +      +
 5.000E-07  1.17E-03 +      +      +      +      +    A +      +      +      +
 5.200E-07  1.16E-03 +      +      +      +      +    A +      +      +      +
 5.400E-07  1.16E-03 +      +      +      +      +   A  +      +      +      +
 5.600E-07  1.16E-03 +      +      +      +      +   A  +      +      +      +
 5.800E-07  1.16E-03 +      +      +      +      +   A  +      +      +      +
 6.000E-07  1.16E-03-+------+------+------+------+----A-+------+------+------+-
 6.200E-07  1.17E-03 +      +      +      +      +    A +      +      +      +
 6.400E-07  1.17E-03 +      +      +      +      +    A +      +      +      +
 6.600E-07  1.18E-03 +      +      +      +      +    A +      +      +      +
 6.800E-07  1.19E-03 +      +      +      +      +    A +      +      +      +
 7.000E-07  1.19E-03 +      +      +      +      +    A +      +      +      +
 7.200E-07  1 20E-03 +      +      +      +      +     A+      +      +      +
 7.400E-07  1.20E-03 +      +      +      +      +     A+      +      +      +
 7.600E-07  1.20E-03 +      +      +      +      +     A+      +      +      +
 7.800E-07  1.21E-03 +      +      +      +      +     A+      +      +      +
 8.000E-07  1.21E-03-+------+------+------+------+-----A+------+------+------+-
                     +             +             +             +             +

*****
CAPACITIVE LOAD RESULTS IN SOME PEAKING [V(5) JUMPS BY > 1MV]
```

7.10

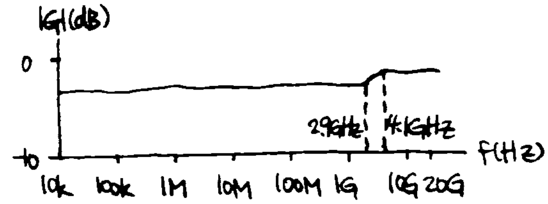
$$\frac{v_o}{v_i} = \frac{g_m R_L}{1+g_m R_L} \frac{1+S/|Z|}{1+S/|P|} = G(S)$$

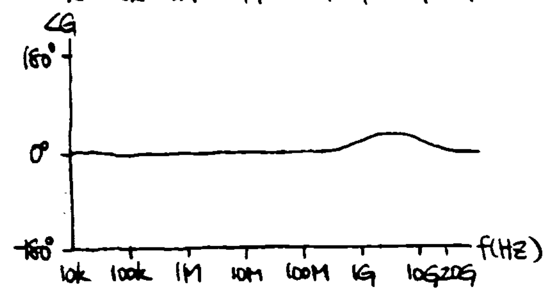
$$\frac{g_m R_L}{1+g_m R_L} = \frac{1.8\times10^{-3}\times10^{3}}{1+1.8\times10^{-3}\times10^{3}} = 0.64$$

$$|Z| = \frac{g_m}{C_s} = \frac{1.8\times10^{-3}}{98\times10^{-15}} = 1.8\times10^{10} \text{ rad/s}$$

$$|P| = \frac{1}{C_{gs}\frac{R_s+R_L}{1+g_m R_L}} = \frac{1}{98\times10^{-15}\frac{100+10^3}{1+1.8\times10^{-3}\times10^3}}$$

$$= 2.6\times10^{10} \text{ rad/s}$$





```
SOURCE FOLLOWER, REISTIVE LOAD
VDD 1 0 5V
RL 4 0 1K
M1 1 2 4 4 CMOSN W=100U L=2U
RS 3 2 250
VBIAS 3 6 1.716V AC
VPULSE 6 0 PULSE 0V 1MV 1NS 0NS 0NS 100NS
.AC DEC 10 10K 20GIG
.PLOT AC VDB(4)
.PLOT AC VP(4)
.TRAN 0.25NS 10NS
.PLOT TRAN V(4)
* COX'=0.7FF/UM**2=EOX/TOX => TOX=500 ANGSTROMS
.MODEL CMOSN NMOS LEVEL=1 LAMBDA=0 VTO=0.7 KP=60U LD=0.2U TOX=500E-10
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END
```

```
****** OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000

+0:1      = 5.000E+00 0:2      = 1.716E+00 0:3      = 1.716E+00
+0:4      = 4.997E-01 0:6      =   0.

**** MOSFETS

ELEMENT  0:M1
MODEL    0:CMOSN
 ID        4.997E-04
 IBS          0.
 IBD      -4.500E-14
 VGS       1.216E+00
 VDS       4.500E+00
 VBS          0.
 VTH       7.000E-01
 VDSAT     5.163E-01
 BETA      3.750E-03
 GAM EFF      0.
 GM        1.936E-03
 GDS          0.
 GMB          0.
 CDTOT     1.448E-14
 CGTOT     1.053E-13
 CSTOT     8.748E-14
 CBTOT     3.347E-15
 CGS       8.748E-14
 CGD       1.448E-14
```

```
****** AC ANALYSIS                                       TNOM=  27.000 TEMP=  27.000

    FREQ      VDB(4)
(A        )    -4.000E+00      -3.500E+00      -3.000E+00      -2.500E+00      -2.000E+00
                    +               +               +               +               +
9.999E+03 -3.61E+00-+-------+---A---+-------+-------+-------+-------+-------+-------+-
1.258E+04 -3.61E+00 +       +   A   +       +       +       +       +       +       +
1.584E+04 -3.61E+00 +       +   A   +       +       +       +       +       +       +
1.995E+04 -3.61E+00 +       +   A   +       +       +       +       +       +       +
2.511E+04 -3.61E+00 +       +   A   +       +       +       +       +       +       +
3.162E+04 -3.61E+00 +       +   A   +       +       +       +       +       +       +
3.981E+04 -3.61E+00 +       +   A   +       +       +       +       +       +       +
5.011E+04 -3.61E+00 +       +   A   +       +       +       +       +       +       +
6.309E+04 -3.61E+00 +       +   A   +       +       +       +       +       +       +
7.943E+04 -3.61E+00 +       +   A   +       +       +       +       +       +       +
1.000E+05 -3.61E+00-+-------+---A---+-------+-------+-------+-------+-------+-------+-
1.258E+05 -3.61E+00 +       +   A   +       +       +       +       +       +       +
1.584E+05 -3.61E+00 +       +   A   +       +       +       +       +       +       +
1.995E+05 -3.61E+00 +       +   A   +       +       +       +       +       +       +
2.511E+05 -3.61E+00 +       +   A   +       +       +       +       +       +       +
3.162E+05 -3.61E+00 +       +   A   +       +       +       +       +       +       +
3.981E+05 -3.61E+00 +       +   A   +       +       +       +       +       +       +
5.011E+05 -3.61E+00 +       +   A   +       +       +       +       +       +       +
6.309E+05 -3.61E+00 +       +   A   +       +       +       +       +       +       +
7.943E+05 -3.61E+00 +       +   A   +       +       +       +       +       +       +
1.000E+06 -3.61E+00-+-------+---A---+-------+-------+-------+-------+-------+-------+-
1.258E+06 -3.61E+00 +       +   A   +       +       +       +       +       +       +
1.584E+06 -3.61E+00 +       +   A   +       +       +       +       +       +       +
1.995E+06 -3.61E+00 +       +   A   +       +       +       +       +       +       +
2.511E+06 -3.61E+00 +       +   A   +       +       +       +       +       +       +
3.162E+06 -3.61E+00 +       +   A   +       +       +       +       +       +       +
3.981E+06 -3.61E+00 +       +   A   +       +       +       +       +       +       +
5.011E+06 -3.61E+00 +       +   A   +       +       +       +       +       +       +
6.309E+06 -3.61E+00 +       +   A   +       +       +       +       +       +       +
7.943E+06 -3.61E+00 +       +   A   +       +       +       +       +       +       +
1.000E+07 -3.61E+00-+-------+---A---+-------+-------+-------+-------+-------+-------+-
1.258E+07 -3.61E+00 +       +   A   +       +       +       +       +       +       +
1.584E+07 -3.61E+00 +       +   A   +       +       +       +       +       +       +
1.995E+07 -3.61E+00 +       +   A   +       +       +       +       +       +       +
2.511E+07 -3.61E+00 +       +   A   +       +       +       +       +       +       +
3.162E+07 -3.61E+00 +       +   A   +       +       +       +       +       +       +
3.981E+07 -3.61E+00 +       +   A   +       +       +       +       +       +       +
5.011E+07 -3.61E+00 +       +   A   +       +       +       +       +       +       +
6.309E+07 -3.61E+00 +       +   A   +       +       +       +       +       +       +
7.943E+07 -3.61E+00 +       +   A   +       +       +       +       +       +       +
1.000E+08 -3.61E+00-+-------+---A---+-------+-------+-------+-------+-------+-------+-
1.258E+08 -3.61E+00 +       +   A   +       +       +       +       +       +       +
1.584E+08 -3.61E+00 +       +   A   +       +       +       +       +       +       +
1.995E+08 -3.61E+00 +       +   A   +       +       +       +       +       +       +
2.511E+08 -3.61E+00 +       +   A   +       +       +       +       +       +       +
3.162E+08 -3.60E+00 +       +    A  +       +       +       +       +       +       +
3.981E+08 -3.60E+00 +       +    A  +       +       +       +       +       +       +
5.011E+08 -3.59E+00 +       +    A  +       +       +       +       +       +       +
6.309E+08 -3.57E+00 +       +     A +       +       +       +       +       +       +
7.943E+08 -3.55E+00 +       +      A+       +       +       +       +       +       +
1.000E+09 -3.51E+00-+-------+-------A-------+-------+-------+-------+-------+-------+-
1.258E+09 -3.46E+00 +       +       +A      +       +       +       +       +       +
1.584E+09 -3.38E+00 +       +       +   A   +       +       +       +       +       +
1.995E+09 -3.28E+00 +       +       +      A+       +       +       +       +       +
2.511E+09 -3.15E+00 +       +       +       +  A    +       +       +       +       +
3.162E+09 -2.99E+00 +       +       +       +       A       +       +       +       +
3.981E+09 -2.83E+00 +       +       +       +       +     A +       +       +       +
5.011E+09 -2.67E+00 +       +       +       +       +       +  A    +       +       +
6.309E+09 -2.55E+00 +       +       +       +       +       +      A+       +       +
7.943E+09 -2.46E+00 +       +       +       +       +       +       +A      +       +
1.000E+10 -2.43E+00-+-------+-------+-------+-------+-------+-------+--A----+-------+-
1.258E+10 -2.44E+00 +       +       +       +       +       +       + A     +       +
1.584E+10 -2.52E+00 +       +       +       +       +       +      A+       +       +
1.995E+10 -2.68E+00 +       +       +       +       +       +  A    +       +       +
2.511E+10 -2.93E+00 +       +       +       +       + A     +       +       +       +
                    +               +               +               +               +
```

7-14

```
     FREQ        VP(4)
(A          )   -3.000E+01    -2.000E+01    -1.000E+01     0.           1.000E+01
                    +             +             +             +             +

9.999E+03  1.67E-05-+------+------+------+------+------+------A------+------+-
1.258E+04  2.10E-05 +      +      +      +      +      +      A      +      +
1.584E+04  2.64E-05 +      +      +      +      +      +      A      +      +
1.995E+04  3.32E-05 +      +      +      +      +      +      A      +      +
2.511E+04  4.18E-05 +      +      +      +      +      +      A      +      +
3.162E+04  5.27E-05 +      +      +      +      +      +      A      +      +
3.981E+04  6.63E-05 +      +      +      +      +      +      A      +      +
5.011E+04  8.35E-05 +      +      +      +      +      +      A      +      +
6.309E+04  1.05E-04 +      +      +      +      +      +      A      +      +
7.943E+04  1.32E-04 +      +      +      +      +      +      A      +      +
1.000E+05  1.67E-04-+------+------+------+------+------+------A------+------+-
1.258E+05  2.10E-04 +      +      +      +      +      +      A      +      +
1.584E+05  2.64E-04 +      +      +      +      +      +      A      +      +
1.995E+05  3.32E-04 +      +      +      +      +      +      A      +      +
2.512E+05  4.18E-04 +      +      +      +      +      +      A      +      +
3.162E+05  5.27E-04 +      +      +      +      +      +      A      +      +
3.981E+05  6.63E-04 +      +      +      +      +      +      A      +      +
5.011E+05  8.35E-04 +      +      +      +      +      +      A      +      +
6.309E+05  1.05E-03 +      +      +      +      +      +      A      +      +
7.943E+05  1.32E-03 +      +      +      +      +      +      A      +      +
1.000E+06  1.67E-03-+------+------+------+------+------+------A------+------+-
1.258E+06  2.10E-03 +      +      +      +      +      +      A      +      +
1.584E+06  2.64E-03 +      +      +      +      +      +      A      +      +
1.995E+06  3.32E-03 +      +      +      +      +      +      A      +      +
2.511E+06  4.18E-03 +      +      +      +      +      +      A      +      +
3.162E+06  5.27E-03 +      +      +      +      +      +      A      +      +
3.981E+06  6.63E-03 +      +      +      +      +      +      A      +      +
5.011E+06  8.35E-03 +      +      +      +      +      +      A      +      +
6.309E+06  1.05E-02 +      +      +      +      +      +      A      +      +
7.943E+06  1.32E-02 +      +      +      +      +      +      A      +      +
1.000E+07  1.67E-02-+------+------+------+------+------+------A------+------+-
1.258E+07  2.10E-02 +      +      +      +      +      +      A      +      +
1.584E+07  2.64E-02 +      +      +      +      +      +      A      +      +
1.995E+07  3.32E-02 +      +      +      +      +      +      A      +      +
2.511E+07  4.18E-02 +      +      +      +      +      +      A      +      +
3.162E+07  5.27E-02 +      +      +      +      +      +      A      +      +
3.981E+07  6.63E-02 +      +      +      +      +      +      A      +      +
5.011E+07  8.34E-02 +      +      +      +      +      +      A      +      +
6.309E+07  1.05E-01 +      +      +      +      +      +      A      +      +
7.943E+07  1.32E-01 +      +      +      +      +      +      A      +      +
1.000E+08  1.66E-01-+------+------+------+------+------+------A------+------+-
1.258E+08  2.09E-01 +      +      +      +      +      +      A      +      +
1.584E+08  2.63E-01 +      +      +      +      +      +      A      +      +
1.995E+08  3.31E-01 +      +      +      +      +      +      A      +      +
2.511E+08  4.15E-01 +      +      +      +      +      +      +A     +      +
3.162E+08  5.20E-01 +      +      +      +      +      +      +A     +      +
3.981E+08  6.51E-01 +      +      +      +      +      +      +A     +      +
5.011E+08  8.10E-01 +      +      +      +      +      +      +A     +      +
6.309E+08  1.00E+00 +      +      +      +      +      +      +A     +      +
7.943E+08  1.22E+00 +      +      +      +      +      +      + A    +      +
1.000E+09  1.48E+00-+------+------+------+------+------+------+-A----+------+-
1.258E+09  1.74E+00 +      +      +      +      +      +      + A    +      +
1.584E+09  1.97E+00 +      +      +      +      +      +      +  A   +      +
1.995E+09  2.10E+00 +      +      +      +      +      +      +  A   +      +
2.511E+09  2.04E+00 +      +      +      +      +      +      +  A   +      +
3.162E+09  1.67E+00 +      +      +      +      +      +      + A    +      +
3.981E+09  8.85E-01 +      +      +      +      +      +      +A     +      +
5.011E+09 -3.68E-01 +      +      +      +      +      +     A+      +      +
6.309E+09 -2.09E+00 +      +      +      +      +      +  A   +      +      +
7.943E+09 -4.26E+00 +      +      +      +      +      +A     +      +      +
1.000E+10 -6.87E+00-+------+------+------+------+---A--+------+------+------+-
1.258E+10 -9.96E+00 +      +      +      +      A      +      +      +      +
1.584E+10 -1.35E+01 +      +      +      + A    +      +      +      +      +
1.995E+10 -1.78E+01 +      +      +   A  +      +      +      +      +      +
2.512E+10 -2.26E+01 +      +   A  +      +      +      +      +      +      +
                    +             +             +             +             +
```

```
****** TRANSIENT ANALYSIS                    TNOM=  27.000 TEMP=  27.000

     TIME        V(4)
(A          )    4.990E-01     4.995E-01     5.000E-01     5.005E-01     5.010E-01
                    +             +             +             +             +

0.         5.00E-01-+------+------+------A------+------+------+------+------+-
2.500E-10  5.00E-01 +      +      +      A      +      +      +      +      +
5.000E-10  5.00E-01 +      +      +      A      +      +      +      +      +
7.500E-10  5.00E-01 +      +      +      A      +      +      +      +      +
1.000E-09  5.00E-01 +      +      +      A      +      +      +      +      +
1.250E-09  5.00E-01 +      +      +      +      +      +    A +      +      +
1.500E-09  5.00E-01 +      +      +      +      +      +   A  +      +      +
1.750E-09  5.00E-01 +      +      +      +      +      +   A  +      +      +
2.000E-09  5.00E-01 +      +      +      +      +      +   A  +      +      +
2.250E-09  5.00E-01 +      +      +      +      +      +   A  +      +      +
2.500E-09  5.00E-01-+------+------+------+------+------+---A--+------+------+-
2.750E-09  5.00E-01 +      +      +      +      +      +   A  +      +      +
3.000E-09  5.00E-01 +      +      +      +      +      +   A  +      +      +
3.250E-09  5.00E-01 +      +      +      +      +      +   A  +      +      +
3.500E-09  5.00E-01 +      +      +      +      +      +   A  +      +      +
3.750E-09  5.00E-01 +      +      +      +      +      +   A  +      +      +
4.000E-09  5.00E-01 +      +      +      +      +      +   A  +      +      +
4.250E-09  5.00E-01 +      +      +      +      +      +   A  +      +      +
4.500E-09  5.00E-01 +      +      +      +      +      +   A  +      +      +
4.750E-09  5.00E-01 +      +      +      +      +      +   A  +      +      +
5.000E-09  5.00E-01-+------+------+------+------+------+---A--+------+------+-
5.250E-09  5.00E-01 +      +      +      +      +      +   A  +      +      +
5.500E-09  5.00E-01 +      +      +      +      +      +   A  +      +      +
5.750E-09  5.00E-01 +      +      +      +      +      +   A  +      +      +
6.000E-09  5.00E-01 +      +      +      +      +      +   A  +      +      +
6.250E-09  5.00E-01 +      +      +      +      +      +   A  +      +      +
6.500E-09  5.00E-01 +      +      +      +      +      +   A  +      +      +
6.750E-09  5.00E-01 +      +      +      +      +      +   A  +      +      +
7.000E-09  5.00E-01 +      +      +      +      +      +   A  +      +      +
7.250E-09  5.00E-01 +      +      +      +      +      +   A  +      +      +
7.500E-09  5.00E-01-+------+------+------+------+------+---A--+------+------+-
7.750E-09  5.00E-01 +      +      +      +      +      +   A  +      +      +
8.000E-09  5.00E-01 +      +      +      +      +      +   A  +      +      +
8.250E-09  5.00E-01 +      +      +      +      +      +   A  +      +      +
8.500E-09  5.00E-01 +      +      +      +      +      +   A  +      +      +
8.750E-09  5.00E-01 +      +      +      +      +      +   A  +      +      +
9.000E-09  5.00E-01 +      +      +      +      +      +   A  +      +      +
9.250E-09  5.00E-01 +      +      +      +      +      +   A  +      +      +
9.500E-09  5.00E-01 +      +      +      +      +      +   A  +      +      +
9.750E-09  5.00E-01 +      +      +      +      +      +   A  +      +      +
1.000E-08  5.00E-01-+------+------+------+------+------+---A--+------+------+-
                    +             +             +             +             +
```

```
*****
SOURCE FOLLOWER, CAPACITIVE LOAD
VDD 1 0 5V
IL 4 0 0.5MA
CL 4 0 400PF
M1 1 2 4 4 CMOSN W=100U L=2U
RS 3 2 250
VBIAS 3 6 1.716V AC
VPULSE 6 0 PULSE 0V 1MV 1NS 0NS 0NS 100NS
.AC DEC 10 10K 20GIG
.PLOT AC VDB(4)
.PLOT AC VP(4)
.TRAN 20NS 800NS
.PLOT TRAN V(4)
* COX'=0.7FF/UM**2=EOX/TOX => TOX=500 ANGSTROMS
.MODEL CMOSN NMOS LEVEL=1 LAMBDA=0 VTO=0.7 KP=60U LD=0.2U TOX=500E-10
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

 ****** OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000

+0:1       = 5.000E+00 0:2       = 1.716E+00 0:3       = 1.716E+00
+0:4       = 4.996E-01 0:6       =    0.
```

```
****** AC ANALYSIS                    TNOM=  27.000 TEMP=  27.000

 FREQ        VDB(4)
(A     )    -1.500E+02  -1.000E+02  -5.000E+01   0.    5.000E+01

9.999E+03 -7.32E-04
1.258E+04 -1.16E-03
1.584E+04 -1.84E-03
1.995E+04 -2.91E-03
2.511E+04 -4.61E-03
3.162E+04 -7.31E-03
3.981E+04 -1.16E-02
5.011E+04 -1.83E-02
6.309E+04 -2.90E-02
7.943E+04 -4.59E-02
1.000E+05 -7.26E-02
1.258E+05 -1.14E-01
1.584E+05 -1.80E-01
1.995E+05 -2.82E-01
2.511E+05 -4.39E-01
3.162E+05 -6.76E-01
3.981E+05 -1.02E+00
5.011E+05 -1.53E+00
6.309E+05 -2.22E+00
7.943E+05 -3.14E+00
1.000E+06 -4.28E+00
1.258E+06 -5.64E+00
1.584E+06 -7.18E+00
1.995E+06 -8.86E+00
2.511E+06 -1.06E+01
3.162E+06 -1.25E+01
3.981E+06 -1.44E+01
5.011E+06 -1.63E+01
6.309E+06 -1.83E+01
7.943E+06 -2.03E+01
1.000E+07 -2.22E+01
1.258E+07 -2.42E+01
1.584E+07 -2.62E+01
1.995E+07 -2.82E+01
2.511E+07 -3.02E+01
3.162E+07 -3.22E+01
3.981E+07 -3.42E+01
5.011E+07 -3.62E+01
6.309E+07 -3.82E+01
7.943E+07 -4.02E+01
1.000E+08 -4.22E+01
1.258E+08 -4.42E+01
1.584E+08 -4.62E+01
1.995E+08 -4.82E+01
2.511E+08 -5.02E+01
3.162E+08 -5.22E+01
3.981E+08 -5.42E+01
5.011E+08 -5.62E+01
6.309E+08 -5.81E+01
7.943E+08 -6.01E+01
1.000E+09 -6.20E+01
1.258E+09 -6.38E+01
1.584E+09 -6.57E+01
1.995E+09 -6.74E+01
2.511E+09 -6.90E+01
3.162E+09 -7.06E+01
3.981E+09 -7.20E+01
5.011E+09 -7.35E+01
6.309E+09 -7.49E+01
7.943E+09 -7.65E+01
1.000E+10 -7.81E+01
1.258E+10 -7.98E+01
1.584E+10 -8.16E+01
1.995E+10 -8.35E+01
2.511E+10 -8.54E+01
```

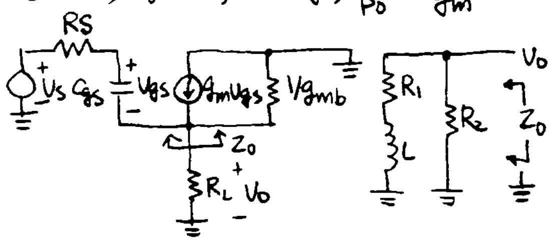
```
 FREQ        VP(4)
(A     )    -1.500E+02  -1.000E+02  -5.000E+01   0.    5.000E+01

9.999E+03 -7.44E-01
1.258E+04 -9.36E-01
1.584E+04 -1.17E+00
1.995E+04 -1.48E+00
2.511E+04 -1.86E+00
3.162E+04 -2.35E+00
3.981E+04 -2.95E+00
5.011E+04 -3.72E+00
6.309E+04 -4.68E+00
7.943E+04 -5.88E+00
1.000E+05 -7.39E+00
1.258E+05 -9.28E+00
1.584E+05 -1.16E+01
1.995E+05 -1.45E+01
2.511E+05 -1.80E+01
3.162E+05 -2.23E+01
3.981E+05 -2.73E+01
5.011E+05 -3.30E+01
6.309E+05 -3.93E+01
7.943E+05 -4.58E+01
1.000E+06 -5.23E+01
1.258E+06 -5.85E+01
1.584E+06 -6.40E+01
1.995E+06 -6.88E+01
2.511E+06 -7.29E+01
3.162E+06 -7.62E+01
3.981E+06 -7.90E+01
5.011E+06 -8.12E+01
6.309E+06 -8.29E+01
7.943E+06 -8.44E+01
1.000E+07 -8.55E+01
1.258E+07 -8.64E+01
1.584E+07 -8.71E+01
1.995E+07 -8.76E+01
2.511E+07 -8.80E+01
3.162E+07 -8.83E+01
3.981E+07 -8.86E+01
5.011E+07 -8.87E+01
6.309E+07 -8.88E+01
7.943E+07 -8.88E+01
1.000E+08 -8.88E+01
1.258E+08 -8.87E+01
1.584E+08 -8.85E+01
1.995E+08 -8.83E+01
2.511E+08 -8.79E+01
3.162E+08 -8.75E+01
3.981E+08 -8.69E+01
5.011E+08 -8.62E+01
6.309E+08 -8.53E+01
7.943E+08 -8.42E+01
1.000E+09 -8.29E+01
1.258E+09 -8.13E+01
1.584E+09 -7.96E+01
1.995E+09 -7.77E+01
2.511E+09 -7.60E+01
3.162E+09 -7.46E+01
3.981E+09 -7.37E+01
5.011E+09 -7.37E+01
6.309E+09 -7.44E+01
7.943E+09 -7.58E+01
1.000E+10 -7.75E+01
1.258E+10 -7.94E+01
1.584E+10 -8.12E+01
1.995E+10 -8.27E+01
2.511E+10 -8.41E+01
```

```
******  TRANSIENT ANALYSIS                TNOM=  27.000 TEMP=  27.000

   TIME      V(4)
(A       )     4.996E-01     4.998E-01     5.000E-01     5.002E-01     5.004E-01
                    +             +             +             +             +

0.         5.00E-01-A------+------+------+------+------+------+------+------+-
2.000E-08  5.00E-01 +  A   +      +      +      +      +      +      +      +
4.000E-08  5.00E-01 +      + A    +      +      +      +      +      +      +
6.000E-08  5.00E-01 +      +      +A     +      +      +      +      +      +
8.000E-08  5.00E-01 +      +      +     A+      +      +      +      +      +
1.000E-07  5.00E-01 +      +      +      +   A  +      +      +      +      +
1.200E-07  5.00E-01 +      +      +      +      +A     +      +      +      +
1.400E-07  5.00E-01 +      +      +      +      + A    +      +      +      +
1.600E-07  5.00E-01 +      +      +      +     A+      +      +      +      +
1.800E-07  5.00E-01 +      +      +      +  A   +      +      +      +      +
2.000E-07  5.00E-01-+------+------+------+A-----+------+------+------+------+-
2.200E-07  5.00E-01 +      +      +     A+      +      +      +      +      +
2.400E-07  5.00E-01 +      +      +   A  +      +      +      +      +      +
2.600E-07  5.00E-01 +      +      +  A   +      +      +      +      +      +
2.800E-07  5.00E-01 +      +      +A     +      +      +      +      +      +
3.000E-07  5.00E-01 +      +      A      +      +      +      +      +      +
3.200E-07  5.00E-01 +      +    A +      +      +      +      +      +      +
3.400E-07  5.00E-01 +      +   A  +      +      +      +      +      +      +
3.600E-07  5.00E-01 +      +  A   +      +      +      +      +      +      +
3.800E-07  5.00E-01 +      + A    +      +      +      +      +      +      +
4.000E-07  5.00E-01-+------+-A----+------+------+------+------+------+------+-
4.200E-07  5.00E-01 +      +A     +      +      +      +      +      +      +
4.400E-07  5.00E-01 +      A      +      +      +      +      +      +      +
4.600E-07  5.00E-01 +     A+      +      +      +      +      +      +      +
4.800E-07  5.00E-01 +     A+      +      +      +      +      +      +      +
5.000E-07  5.00E-01 +    A +      +      +      +      +      +      +      +
5.200E-07  5.00E-01 +    A +      +      +      +      +      +      +      +
5.400E-07  5.00E-01 +   A  +      +      +      +      +      +      +      +
5.600E-07  5.00E-01 +   A  +      +      +      +      +      +      +      +
5.800E-07  5.00E-01 +   A  +      +      +      +      +      +      +      +
6.000E-07  5.00E-01-+--A---+------+------+------+------+------+------+------+-
6.200E-07  5.00E-01 +  A   +      +      +      +      +      +      +      +
6.400E-07  5.00E-01 +  A   +      +      +      +      +      +      +      +
6.600E-07  5.00E-01 +  A   +      +      +      +      +      +      +      +
6.800E-07  5.00E-01 + A    +      +      +      +      +      +      +      +
7.000E-07  5.00E-01 + A    +      +      +      +      +      +      +      +
7.200E-07  5.00E-01 + A    +      +      +      +      +      +      +      +
7.400E-07  5.00E-01 + A    +      +      +      +      +      +      +      +
7.600E-07  5.00E-01 + A    +      +      +      +      +      +      +      +
7.800E-07  5.00E-01 +A     +      +      +      +      +      +      +      +
8.000E-07  5.00E-01-+A-----+------+------+------+------+------+------+------+-
                    +             +             +             +             +

*****
CAPACITIVE LOAD INTRODUCES PEAKING.
```

7.11

(a) Use (7.67)–(7.69), and make the replacements:

$R_S' \to R_S$, $\beta_0 \to \infty$, $C_\pi \to C_{gs}$, $\frac{r_\pi}{\beta_0} \to \frac{1}{g_m}$



$R_1 = \frac{1}{g_m}$

$R_2 = R_S // \frac{1}{g_{mb}}$

$1/g_{mb}$ can be added in parallel to the R_2 for the bipolar case. Or it can be shown that $R_2 = Z_0(\omega \to \infty)$ and equals $R_S // \frac{1}{g_{mb}}$ here.

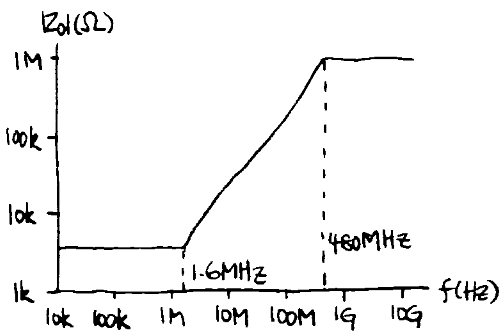
$L = \frac{R_S C_{gs}}{g_m}$

(b) $R_1 = \frac{1}{g_m} = \frac{1}{0.3\times10^{-3}} = 3.3\times10^{3}\Omega = 3.3\,k\Omega$

$R_2 = R_S = 1M\Omega$ ($\gamma = 0$ and no g_{mb})

$L = \frac{R_S C_{gs}}{g_m} = \frac{10^6 \times 100\times10^{-15}}{0.3\times10^{-3}} = 3.3\times10^{-4}H$

$= 0.33mH$



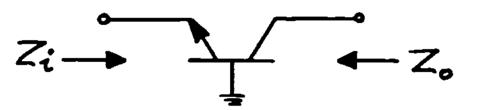
7.12

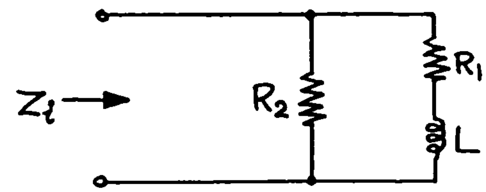
(a) $\frac{i_o}{i_i} = \frac{\alpha_0}{1 + j\omega \frac{C_\pi}{g_m}}$ $\qquad \alpha_0 = \frac{\beta_0}{1+\beta_0} = 0.99$

$= \frac{0.99}{1 + j\omega\times10^{-11}\times52} = \frac{0.99}{1 + j\frac{\omega}{1.92\times10^{9}}}$

$\left|\frac{i_o}{i_i}\right| = 0.7$ at $\frac{1}{2\pi}\times1.92\times10^{9} = 306MHz$

(b)



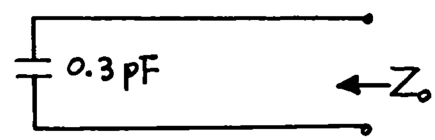


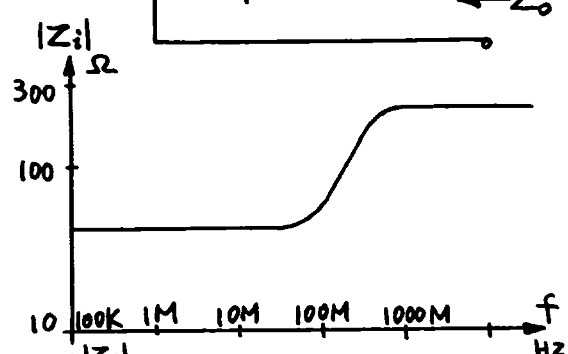
$R_2 = R_b = r_b = 200\Omega$

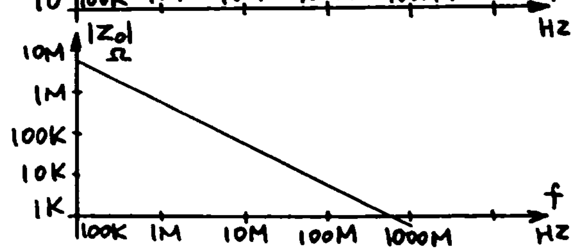
$R_1 = \frac{1}{g_m} + \frac{R_b}{\beta_0} = 52 + \frac{200}{100} = 54\Omega$

$L = C_\pi r_\pi \frac{R_b}{\beta_0} = 10^{-11}\times5200\times\frac{200}{100}$

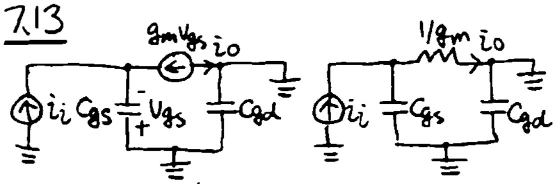
$= 0.104\,\mu H$







7.13

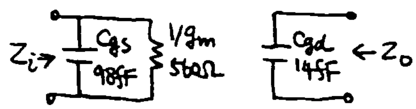


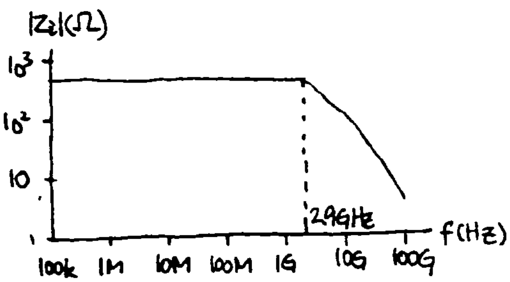
(a) $$\frac{i_o}{i_i} = \frac{\frac{1}{sC_{gs}}}{\frac{1}{sC_{gs}} + \frac{1}{g_m}} = \frac{1}{1 + s\frac{C_{gs}}{g_m}} = \frac{1}{1 + s\frac{98\times10^{-15}}{1.8\times10^{-3}}} = \frac{1}{1 + s/(1.8\times10^{10})}$$

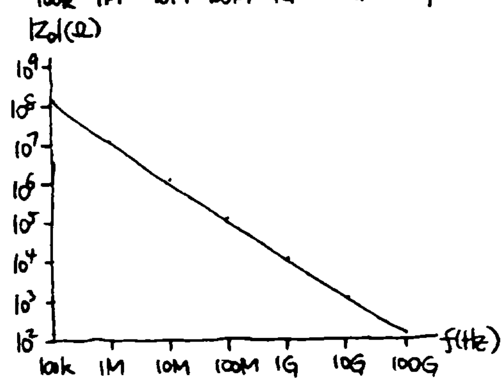
$f_{3dB} = 2.9\,GHz$

(b) $Z_i = \frac{1}{g_m} \| \frac{1}{sC_{gs}}$

$Z_o = \frac{1}{sC_{gd}}$







7.14

At low freq.

$$\frac{v_o}{v_i} = -\frac{r_\pi}{r_\pi + R_s} g_m R_L = -\frac{5.2K}{5.2K + 10K}\,\frac{5000}{26} = -65.8$$

Zero value time constant

$R_{\pi o} = r_\pi \| (R_s + r_b)$

$= 5.2K \| 10K = 3.42\,K\Omega$

$R_{\mu o} = R_{\pi o} + R_L + g_m R_L R_{\pi o}$

$= 3.42 + 5 + \frac{5000}{26} \times 3.42$

$= 666\,K\Omega$

$R_{cso} = R_L = 5K\Omega$

$C_\pi + C_\mu = \frac{g_m}{2\pi f_T}$

$= \frac{1}{2\pi \times 26 \times 600\times10^6} = 10.2\,pF$

$\therefore C_\pi = 10\,pF$

$\therefore C_\pi R_{\pi o} = 10 \times 3.42 = 34.2\,ns$

$C_\mu R_{\mu o} = 0.2 \times 666 = 133.2\,ns$

$C_{cs} R_{cso} = 1 \times 5 = 5\,ns$

$\therefore \Sigma T_o = 34.2 + 133.2 + 5 = 172.4\,ns$

$\therefore f_{-3dB} = \frac{1}{2\pi \Sigma T_o} = 0.923\,MHz$

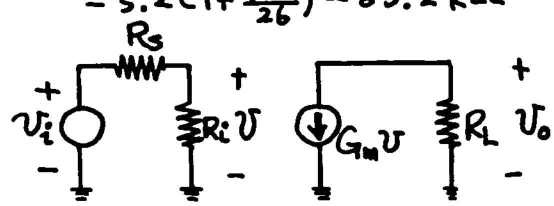
7.15

$G_m = \frac{g_m}{1 + g_m R_E}$

$= \frac{1}{26}\,\frac{1}{1 + \frac{300}{26}} = 3.07\times10^{-3}\,A/V$

$R_i = r_\pi (1 + g_m R_E)$

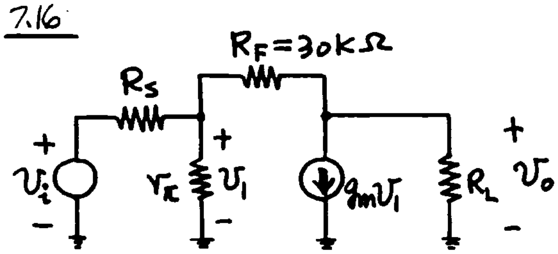
$= 5.2(1 + \frac{300}{26}) = 65.2\,K\Omega$

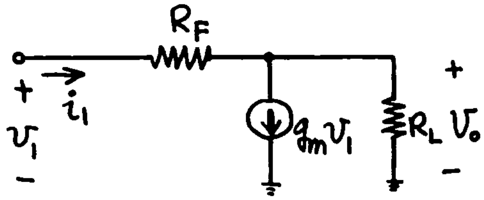


$$\frac{v_o}{v_i} = -\frac{R_i}{R_s+R_i} G_m R_L$$
$$= -\frac{65.2}{10+65.2} \times 3.07\times10^{-3} \times 5000$$
$$= -13.31$$

$$R_{\mu o} = R_x + R_L + G_m R_x R_L$$
$$R_x = R_i \| R_s = 10 \| 65.2 = 8.67\,K\Omega$$
$$\therefore R_{\mu o} = 8.67 + 5 + 3.07\times5\times8.67$$
$$= 147\,K\Omega$$
$$\therefore C_\mu R_{\mu o} = 0.2\times147 = 29.4\,ns$$
$$C_{cs}R_{cso} = 1\times5 = 5\,ns$$
$$R_{\pi o} = r_\pi \| \frac{R_s + r_b + R_E}{1 + g_m R_E}$$
$$= 5.2k \| \frac{10+0.3}{1+\frac{300}{26}} k = 709\,\Omega$$
$$C_\pi R_{\pi o} = 10\times0.709 = 7.09\,ns$$
$$\therefore \Sigma T_o = 29.4 + 5 + 7.09 = 41.49\,ns$$
$$\therefore f_{-3dB} = \frac{1}{2\pi\Sigma T_o} = 3.84\,MHz$$

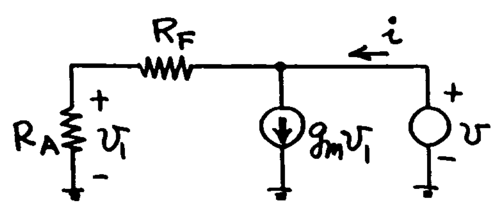
7.16





$$\frac{v_1 - v_o}{R_F} = g_m v_1 + \frac{v_o}{R_L}$$
$$\therefore v_1\left(\frac{1}{R_F} - g_m\right) = v_o\left(\frac{1}{R_F} + \frac{1}{R_L}\right)$$

$$\therefore \frac{v_o}{v_1} = \frac{\frac{1}{R_F} - g_m}{\frac{1}{R_F} + \frac{1}{R_L}}$$
$$= -\frac{1}{26}\,\frac{1}{\frac{1}{30}+\frac{1}{5}} \times 1000$$
$$= -\frac{1000}{26}\times\frac{30}{7} = -165$$
$$\therefore i_1 = \frac{v_1 - v_o}{R_F} = \frac{166\,v_1}{R_F}$$
$$\therefore \frac{v_1}{i_1} = \frac{R_F}{166} = 181\,\Omega = R_1$$
$$R_1 \| r_\pi = 181 \| 5.2k = 175\,\Omega$$
$$\therefore \frac{v_o}{v_i} = \frac{175}{175+R_s}\times\frac{v_o}{v_1}$$
$$= -\frac{175}{175+10000}\times165 = -2.84$$
$$R_{\pi o} = R_s \| r_\pi \| R_1$$
$$= 10k \| 5.2k \| 181 = 172\,\Omega$$
$$\therefore C_\pi R_{\pi o} = 10\times0.172 = 1.72\,ns$$
$$R_{\mu o} = 30k \| 666k = 28.7\,K\Omega$$
$$\therefore C_\mu R_{\mu o} = 0.2\times28.7 = 5.74\,ns$$



$$R_A = R_s \| r_\pi = 10k \| 5.2k = 3.42\,K\Omega$$
$$i \simeq g_m v_1 = g_m \frac{R_A}{R_A + R_F} v$$
$$\therefore \frac{v}{i} = \frac{1}{g_m}\times\frac{R_A + R_F}{R_A}$$
$$= 26\times\frac{3.42+30}{3.42} = 254\,\Omega = R_{cso}$$
$$\therefore C_{cs}R_{cso} = 1\times0.254 = 0.25\,ns$$
$$\therefore \Sigma T_o = (1.72 + 5.74 + 0.25) = 7.71\,ns$$
$$\therefore f_{-3dB} = \frac{1}{2\pi\,\Sigma T_o} = 20.6\,MHz$$

7.17

$g_m = \sqrt{2k_n' \frac{W}{L} I_D} = \sqrt{2\times60\times10^{-6}\times\frac{100}{2-2\times0.2-0}\times500\times10^{-6}}$

$= 1.9\times10^{-3}\ A/V$

$A_V = -g_m R_L = -1.9\times10^{-3}\times5\times10^{3} = -9.5$

$V_o = 10 - 0.5\times5 = 7.5V$

$C_{db0} = A_D C_{j0} + P_D C_{jsw0}$

$= 5\times100\times0.4 + 100\times0.4$

$= 240fF$

$C_{db} = \frac{C_{db0}}{\sqrt{1+\frac{V_{DB}}{\psi_0}}} = \frac{240}{\sqrt{1+\frac{7.5}{0.6}}} = 65fF$

$R_L C_{db} = 5\times10^{3}\times65\times10^{-15} = 0.3ns$

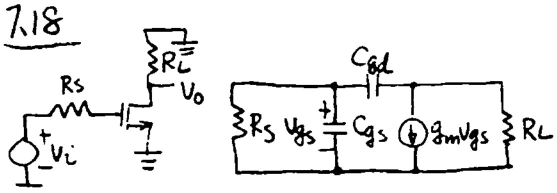
$R_S[C_{gs} + C_{gd}(1-A_v)]$

$= 10\times10^{3}[89+14(1+9.5)]\times10^{-15}$

$= 2.4ns$

$f_{-3dB} = \frac{1}{2\pi}\frac{1}{0.3ns+2.4ns} = 59MHz$

7.18



$\frac{V_o}{V_i} = -g_m R_L = -1.8\times10^{-3}\times5\times10^{3} = -9$

$R_{gs0} = R_S = 10\times10^{3}\Omega$

$C_{gs}R_{gs0} = 98\times10^{-15}\times10\times10^{3} = 9.8\times10^{-10}s$

$R_{gd0} = R_S + R_L + g_m R_S R_L$

$= 10\times10^{3} + 5\times10^{3} + 1.8\times10^{-3}\times10\times10^{3}\times5\times10^{3}$

$= 105\times10^{3}\Omega = 105k\Omega$

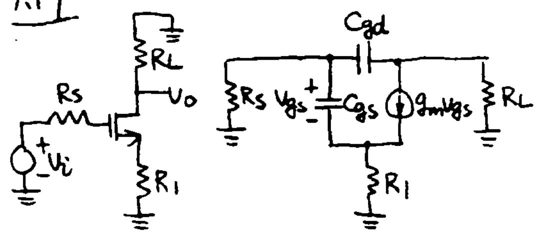
$C_{gd}R_{gd0} = 14\times10^{-15}\times105\times10^{3} = 1.5\times10^{-9}s$

$\Sigma T_0 = 9.8\times10^{-10} + 1.5\times10^{-9} = 2.5\times10^{-9}s$

$f_{-3dB} = \frac{1}{2\pi\Sigma T_0} = \frac{1}{6.28\times2.5\times10^{-9}} = 6.4\times10^{7}Hz$

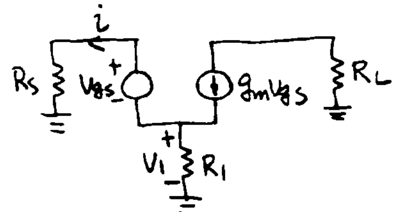
$= 64MHz$

7.19



$\frac{V_o}{V_i} = -\frac{g_m}{1+g_m R_1}R_L = -\frac{1.8\times10^{-3}}{1+1.8\times10^{-3}\times900}\times5\times10^{3}$

$= -3.4$



$i = \frac{V_{gs}+V_1}{R_S} = g_m V_{gs} - \frac{V_1}{R_1}$

$V_1 = (R_S\|R_1)(g_m - \frac{1}{R_S})V_{gs}$

$i = \frac{1}{R_S}[(R_S\|R_1)(g_m - \frac{1}{R_S})+1]V_{gs} = \frac{1+g_m R_1}{R_S+R_1}V_{gs}$

$R_{gs0} = \frac{R_S+R_1}{1+g_m R_1} = \frac{10\times10^{3}+900}{1+1.8\times10^{-3}\times900} = 4.2\times10^{3}\Omega$

$C_{gs}R_{gs0} = 98\times10^{-15}\times4.2\times10^{3} = 4.1\times10^{-10}s$

$R_{gd0} = R_S + R_L + \frac{g_m}{1+g_m R_1}R_S R_L$

$= 10\times10^{3} + 5\times10^{3} + \frac{1.8\times10^{-3}}{1+1.8\times10^{-3}\times900}\times$

$10\times10^{3}\times5\times10^{3}$

$= 49\times10^{3}\Omega$

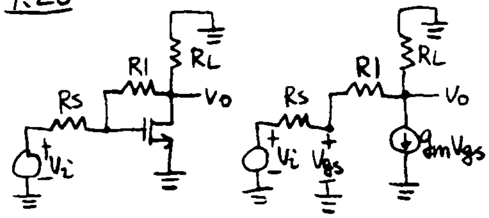
$C_{gd}R_{gd0} = 14\times10^{-15}\times49\times10^{3} = 6.9\times10^{-10}s$

$\Sigma T_0 = 4.1\times10^{-10} + 6.9\times10^{-10} = 1.1\times10^{-9}s$

$f_{-3dB} = \frac{1}{2\pi\Sigma T_0} = \frac{1}{6.28\times1.1\times10^{-9}} = 1.4\times10^{8}Hz$

$= 140MHz$

7.20



$$\frac{V_o}{R_L} + g_m V_{gs} + \frac{V_o - V_{gs}}{R_1} = 0$$

$$V_{gs} = \frac{V_o}{(R_L \| R_1)(\frac{1}{R_1} - g_m)} = V_o \frac{R_L + R_1}{R_L(1 - g_m R_1)}$$

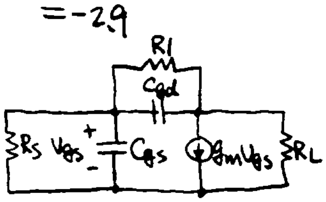
$$V_{gs} = \frac{R_S}{R_S + R_1} V_o + \frac{R_1}{R_S + R_1} V_i$$

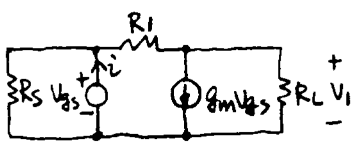
$$\frac{R_L + R_1}{R_L(1 - g_m R_1)} V_o = \frac{R_S}{R_S + R_1} V_o + \frac{R_1}{R_S + R_1} V_i$$

$$\frac{V_o}{V_i} = \frac{\frac{R_1}{R_1 + R_S}}{\frac{R_L + R_1}{R_L(1 - g_m R_L)} - \frac{R_S}{R_1 + R_S}}$$

$$= \frac{\frac{50\times10^3}{50\times10^3 + 10\times10^3}}{\frac{5\times10^3 + 50\times10^3}{5\times10^3(1 - 1.8\times10^{-3}\times5\times10^3)} - \frac{10\times10^3}{50\times10^3 + 10\times10^3}}$$

$$= -2.9$$





$$\frac{V_1}{R_L} + g_m V_{gs} = \frac{V_{gs} - V_1}{R_1}$$

$$V_1 = (R_L \| R_1)(\frac{1}{R_1} - g_m) V_{gs}$$

$$i = \frac{V_{gs}}{R_S} + \frac{V_{gs} - V_1}{R_1} = V_{gs}\left[\frac{1}{R_S} + \frac{1 - (R_L \| R_1)(\frac{1}{R_1} - g_m)}{R_1}\right]$$

$$= V_{gs}\left[\frac{1}{R_S} + \frac{1 + g_m R_L}{R_L + R_1}\right]$$

$$R_{gso} = \left[\frac{1}{R_S} + \frac{1 + g_m R_L}{R_L + R_1}\right]^{-1} = R_S \| \frac{R_L + R_1}{1 + g_m R_L}$$

$$= 10k \| \frac{5\times10^3 + 50\times10^3}{1 + 1.8\times10^{-3}\times5\times10^3} = 3.5\times10^3\,\Omega$$

$$C_{gs} R_{gso} = 98\times10^{-15}\times3.5\times10^3 = 3.4\times10^{-10}\,s$$

$$R_{gdo} = R_1 \| (R_S + R_L + g_m R_S R_L) = 50\times10^3 \| 105\times10^3$$

$$= 34\times10^3\,\Omega$$

$$C_{gd} R_{gdo} = 14\times10^{-15}\times34\times10^3 = 4.8\times10^{-10}\,s$$

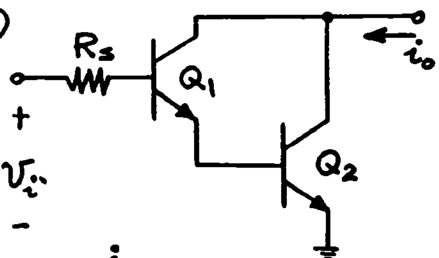
$$\sum T_0 = 3.4\times10^{-10} + 4.8\times10^{-10} = 8.2\times10^{-10}\,s$$

$$f_{-3dB} = \frac{1}{2\pi \sum T_0} = \frac{1}{6.28\times8.2\times10^{-10}} = 1.9\times10^8\,Hz$$

$$= 190\,MHz$$

7.21

(a)



$G_m = \frac{i_o}{v_i} \simeq \frac{1}{2} g_{m2} = \frac{1}{2}\,\frac{1}{26}$

$= \frac{1}{52}$ A/V — both circuits

$R_i \simeq r_{\pi 1}(1+g_{m1}r_{\pi 2}) = 2r_{\pi 1} = 2\frac{\beta}{g_{m1}}$

$= 2\times 100\times 2.6k = 520 k\Omega$

— both Circuits

$\therefore \frac{v_o}{v_i} = -\frac{R_i}{R_i+R_s}G_m R_L$

$= -\frac{520}{620}\times\frac{1}{52}\times 3000$

$= -48.4$ — both circuits

(b) Darlington

$R_{cso} = R_L = 3k\Omega$ for Q_1 and Q_2

$\therefore R_{cso}(C_{cs1}+C_{cs2}) = 3\times 2 = 6$ ns

$R_{\pi o1} = r_{\pi 1}\|\frac{R_s+R_E}{1+g_{m1}R_E} = r_{\pi 1}\|\frac{R_s+r_{\pi 2}}{1+g_{m1}r_{\pi 2}}$

$= 260k\|\frac{102.6K}{2} = 42.9 k\Omega$

$C_\pi + C_\mu = \frac{g_m}{2\pi f_T} = \frac{1}{26}\,\frac{1}{2\pi\times 500\times 10^6}$

$= 12.2$ pF at $I_c = 1$mA

$\therefore C_\pi = 11.8$ pF at $I_c = 1$mA

$C_b = 9.8$ pF

$\therefore C_{b1} = 0.1$pF, $\therefore C_{\pi 1} = 2.1$pF

$\therefore C_{\pi 1}R_{\pi o1} = 2.1\times 42.9 = 90.1$ ns

$R_{\mu o1} = R_x + R_L + G_m R_x R_L$

$R_x = R_i\|R_s = 520k\|100k = 83.9 k\Omega$

$\therefore R_{\mu o1} = 83.9 + 3 + \frac{1}{52}\times 3000\times 83.9$

$= 4.93$ MΩ

$\therefore C_{\mu 1}R_{\mu o1} = 0.4\times 4.93\times 10^3 = 1972$ ns

$C_{\pi 2} = 11.8$ pF

$R_{\pi o2} = r_{\pi 2}\|(\frac{1}{g_{m1}} + \frac{R_s}{\beta_1})$

$= 2.6k\|(2.6k + \frac{100k}{100})$

$= 2.6k\| 3.6k = 1.51 k\Omega$

$\therefore C_{\pi 2}R_{\pi o2} = 17.8$ ns

$R_{\mu o} = R_{\pi o2} + R_L + g_{m2}R_L R_{\pi o2}$

$= 1.51 + 3 + \frac{3000}{26}\times 1.51$

$= 179 k\Omega$

$\therefore C_{\mu 2}R_{\mu o2} = 0.4\times 179 = 71$ ns

$\therefore \Sigma T_o = 6+90+1972+18+71$

$= 2157$ ns

$\therefore f_{-3dB} = \frac{1}{2\pi\Sigma T_o} = 73.8$ kHz

Common-collector-Common emitter

$R_{cso}C_{cs2} = 3$ ns

$R_{cso}C_{cs1} = 0$

$C_{\pi 1}R_{\pi o1} = 90.1$ ns

$C_{\pi 2}R_{\pi o2} = 17.8$ns

$C_{\mu 2}R_{\mu o2} = 71$ ns

$R_{\mu o1} = R_i\|R_s = 83.9 k\Omega$

$\therefore C_{\mu 1}R_{\mu o1} = 0.4\times 83.9 = 33.6$ ns

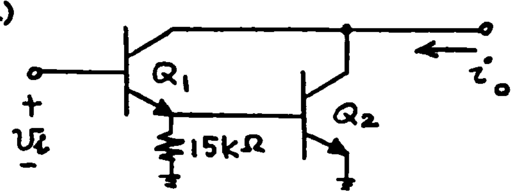
$\therefore \Sigma T_o = 3 + 90.1 + 17.8 + 71 + 33.6$

$= 215.5$ns

$\therefore f_{-3dB} = \frac{1}{2\pi\Sigma T_o} = 738$ kHz

7.22

(a)



Effective value of $r_{\pi 2} = 15k \| 2.6k = 2.2\,k\Omega$

$$G_m = \frac{i_o}{v_i} \simeq \frac{g_{m1} R_E}{g_{m1} R_E + 1} \times g_{m2}$$

$R_E = 2.2\,k\Omega$

$$\therefore G_m = \frac{\frac{0.05}{26} \times 2200}{1 + \frac{0.05}{26} \times 2200} \times \frac{1}{26}$$

$= 31.2\ mA/V$ — for both circuits

$$R_i = r_{\pi 1}(1 + g_{m1} R_E) = \frac{100 \times 26}{0.05}\left(1 + \frac{0.05}{26} \times 2200\right) = 274\,K\Omega$$

$$\therefore \frac{v_o}{v_i} = -\frac{R_i}{R_i + R_s} G_m R_L = -\frac{274}{274+100} \times 31.2 \times 10^{-3} \times 3000$$

$= -68.6$ — for both circuits

(b) $I_{C1} = 50\,\mu A \quad \therefore C_{\mu 1} = 0.5\,pF$

$C_{\pi 1} = 2.5\,pF$

<u>Darlington</u>

$R_{cso} = R_L = 3\,K\Omega$

$\therefore R_{cso}(C_{cs1} + C_{cs2}) = 3 \times 2 = 6\,ns$

$$R_{\pi o1} = r_{\pi 1} \Big\| \frac{R_s + R_E}{1 + g_{m1} R_E} = 52k \Big\| \frac{102.2K}{1 + 4.27} = 14.1\,K\Omega$$

$\therefore C_{\pi 1} R_{\pi o1} = 2.5 \times 14.1 = 35.3\,ns$

$R_{\mu o1} = R_x + R_L + G_m R_x R_L$

$R_x = R_i \| R_s = 274 \| 100 = 73.3\,K\Omega$

$\therefore R_{\mu o1} = 73.3 + 3 + 31.2 \times 73.3 \times 3 = 6.94\,M\Omega$

$\therefore C_{\mu 1} R_{\mu o1} = 0.4 \times 6940 = 2776\,ns$

$$R_{\pi o2} = r_{\pi 2} \Big\| \left(\frac{1}{g_{m1}} + \frac{R_s}{\beta_1}\right) = 2.6K \Big\| \left(520 + \frac{100k}{100}\right) = 2.6k \| 1.52k = 959\,\Omega$$

$\therefore C_{\pi 2} R_{\pi o2} = 11.8 \times 0.959 = 11.3\,ns$

$$R_{\mu o2} = R_{\pi o2} + R_L + g_{m2} R_L R_{\pi o2} = 0.959 + 3 + \frac{3000}{26} \times 0.959 = 114.6\,K\Omega$$

$\therefore C_{\mu 2} R_{\mu o2} = 0.4 \times 114.6 = 45.8\,ns$

$\therefore \Sigma T_o = 6 + 35.3 + 2776 + 11.3 + 45.8 = 2874\,ns$

$$\therefore f_{-3dB} = \frac{1}{2\pi \Sigma T_o} = 55.4\,KHz$$

<u>Common-collector - common emitter</u>

$R_{cso} C_{cs2} = 3\,ns$

$R_{cso} C_{cs1} = 0$

$C_{\pi 1} R_{\pi o1} = 35.3\,ns$

$C_{\pi 2} R_{\pi o2} = 11.3\,ns$

$C_{\mu 2} R_{\mu o2} = 45.8\,ns$

$R_{\mu o1} = R_i \| R_s = 274 \| 100 = 73.3\,k\Omega$

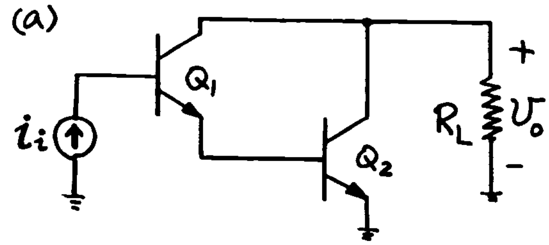
$\therefore C_{\mu 1} R_{\mu o1} = 0.4 \times 73.3 = 29.3\,ns$

$\therefore \Sigma T_o = 3 + 35.3 + 11.3 + 45.8 + 29.3 = 124.7\,ns$

$$\therefore f_{-3dB} = \frac{1}{2\pi \Sigma T_o} = 1.28\,MHz$$

<u>7.23</u>

(a)



In both cases

$$\frac{v_o}{i_i} \simeq -\beta_1 \beta_2 R_L = -100 \times 100 \times 3K = -30\,M\Omega$$

$R_i = r_{\pi 1}(1 + g_{m1} r_{\pi 2}) = 520\,K\Omega$

(b) <u>Darlington</u>

$R_{cso}(C_{cs1} + C_{cs2}) = 6\,ns$

$$R_{\pi o1} = r_{\pi 1} \| \frac{R_s + R_E}{1 + g_{m1} R_E} \qquad R_s = \infty$$

$$= r_{\pi 1} = 260\,k\Omega$$

$$\therefore C_{\pi 1} R_{\pi o1} = 2.1 \times 260 = 546\,ns$$

$$R_{\mu o1} = R_x + R_L + G_m R_x R_L$$

$$R_x = R_i \| R_s = R_i = 520\,k\Omega$$

$$\therefore R_{\mu o1} = 520 + 3 + \frac{3000}{52} \times 520$$

$$= 30.52\,M\Omega$$

$$\therefore C_{\mu 1} R_{\mu o1} = 0.4 \times 30520 = 12{,}208\,ns$$

$$R_{\pi o2} = r_{\pi 2} \| \left(\frac{1}{g_{m1}} + \frac{R_s}{\beta_1}\right) \quad R_s = \infty$$

$$= r_{\pi 2} = 2.6\,k\Omega$$

$$\therefore C_{\pi 2} R_{\pi o2} = 11.8 \times 2.6 = 30.7\,ns$$

$$R_{\mu o2} = R_{\pi o2} + R_L + g_{m2} R_L R_{\pi o2}$$

$$= 2.6 + 3 + \frac{3000}{26} \times 2.6$$

$$= 305.6\,k\Omega$$

$$\therefore C_{\mu 2} R_{\mu o2} = 0.4 \times 305.6 = 122\,ns$$

$$\therefore \sum T_o = (6 + 546 + 12{,}208 + 30.7 + 122)\,ns$$

$$= 12.9\,\mu s$$

$$\therefore f_{-3dB} = \frac{1}{2\pi \sum T_o} = 12.3\,KHz$$

<u>Common-Collector-common emitter</u>

$$R_{cso} C_{cs2} = 3\,ns$$

$$R_{cso} C_{cs1} = 0$$

$$C_{\pi 1} R_{\pi o1} = 546\,ns$$

$$C_{\pi 2} R_{\pi o2} = 30.7\,ns$$

$$C_{\mu 2} R_{\mu o2} = 122\,ns$$

$$R_{\mu o1} = R_i \| R_s = R_i = 520\,k\Omega$$

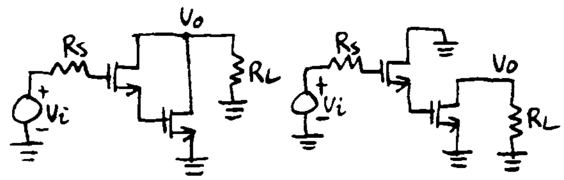
$$\therefore C_{\mu 1} R_{\mu o1} = 0.4 \times 520 = 208\,ns$$

$$\therefore \sum T_o = 3 + 546 + 30.7 + 122 + 208$$

$$= 910\,ns$$

$$\therefore f_{-3dB} = \frac{1}{2\pi \sum T_o} = 175\,KHz$$

7.24

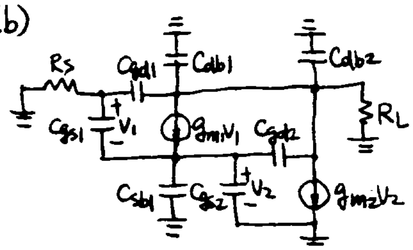


(a) In both cases,

$$G_m = g_{m2} = \sqrt{2k_n'\left(\frac{W}{L}\right)_2 I_{D2}}$$
$$= \sqrt{2\times 60\times 10^{-6}\times \frac{100}{1.6}\times 10^{-3}}$$
$$= 2.7\times 10^{-3}\,A/V$$

$$\frac{V_o}{V_i} = -G_m R_L = -2.7\times 10^{-3}\times 3\times 10^{3} = -8.1$$

(b)



For the "Darlington" stage,

$C_{gs} = 89\,fF$, $C_{gd} = 14\,fF$.

$$g_{m1} = \sqrt{2\times 60\times 10^{-6}\times \frac{100}{1.6}\times 50\times 10^{-6}} = 6.1\times 10^{-4}\,A/V$$

$$(C_{db1}+C_{db2})R_L = (200+200)\times 10^{-15}\times 3\times 10^{3}$$
$$= 1.2\times 10^{-9}\,s$$

$$C_{gs1}\frac{1}{g_{m1}} = 89\times 10^{-15}\frac{1}{6.1\times 10^{-4}} = 1.4\times 10^{-10}\,s$$

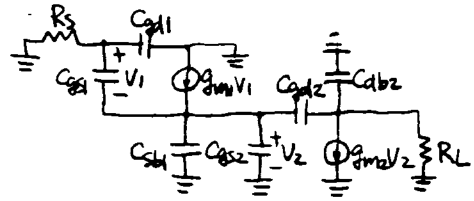
$$(C_{gs2}+C_{sb1})\frac{1}{g_{m1}} = (89+180)\times 10^{-15}\frac{1}{6.1\times 10^{-4}}$$
$$= 4.4\times 10^{-10}\,s$$

$$C_{gd1}(R_S + R_L + g_{m2}R_S R_L)$$
$$= 14\times 10^{-15}(100\times 10^{3} + 3\times 10^{3} + 2.7\times 10^{-3}\times 100\times 10^{3}\times 3\times 10^{3})$$
$$= 1.3\times 10^{-8}\,s$$

$$C_{gd2}\left(\frac{1}{g_{m1}} + R_L + g_{m2}\frac{1}{g_{m1}}R_L\right)$$
$$= 14\times 10^{-15}\left(\frac{1}{6.1\times 10^{-4}} + 3\times 10^{3} + \frac{2.7\times 10^{-3}}{6.1\times 10^{-4}}\times 3\times 10^{3}\right)$$
$$= 2.5\times 10^{-10}\,s$$

$$\Sigma T_0 = 1.5\times 10^{-8}\,s$$

$$f_{-3dB} = \frac{1}{2\pi \Sigma T_0} = \frac{1}{6.28\times 1.5\times 10^{-8}} = 1.0\times 10^{7}\,Hz$$
$$= 10\,MHz$$



For the CD-CS stage,

$$C_{db2}R_L = 200\times 10^{-15}\times 3\times 10^{3} = 6\times 10^{-10}\,s$$

$$C_{gs1}\frac{1}{g_{m1}} = 89\times 10^{-15}\frac{1}{6.1\times 10^{-4}} = 1.4\times 10^{-10}\,s$$

$$(C_{gs2}+C_{sb1})\frac{1}{g_{m1}} = (89+180)\times 10^{-15}\frac{1}{6.1\times 10^{-4}}$$
$$= 4.4\times 10^{-10}\,s$$

$$C_{gd1}R_S = 14\times 10^{-15}\times 100\times 10^{3} = 1.4\times 10^{-9}\,s$$

$$C_{gd2}\left(\frac{1}{g_{m1}} + R_L + g_{m2}\frac{1}{g_{m1}}R_L\right)$$
$$= 14\times 10^{-15}\left(\frac{1}{6.1\times 10^{-4}} + 3\times 10^{3} + \frac{2.7\times 10^{-3}}{6.1\times 10^{-4}}\times 3\times 10^{3}\right)$$
$$= 2.5\times 10^{-10}\,s$$

$$\Sigma T_0 = 2.8\times 10^{-9}\,s$$

$$f_{-3dB} = 5.6\times 10^{7}\,Hz = 56\,MHz$$

While the CD-CS stage has the same DC gain as the "Darlington" stage, the CD-CS stage has better frequency response.

7.25

(a) $I_{C3} \simeq \frac{10-0.6}{30} = 313\,\mu A = I_{C2} = I_{C1}$

Q1 $V_{CB} = -10+0.6 = -9.4V$

$$\therefore C_{\mu 1} = \frac{C_{\mu o}}{\sqrt{1+\frac{|V_{CB}|}{\psi_o}}} = \frac{1}{\sqrt{1+\frac{9.4}{0.55}}} = 0.24\ pF$$

$V_{BS} = 20-0.6 = 19.4V$

$$\therefore C_{bs1} = \frac{2}{\sqrt{1+\frac{19.4}{0.55}}} = 0.33\ pF$$

$$C_{bs1} + C_{\pi 1} + C_{\mu 1} = \frac{g_m}{2\pi f_T} = \frac{1}{2\pi \times 52 \times 4\times 10^6} = 765\ pF \text{ at } I_c = a5mA$$

$\therefore C_{\pi 1} = 764\ pF$ at $I_c = 0.5mA$

$C_{b1} = 761\ pF$ at $I_c = 0.5mA$

$\therefore$ at $I_{C1} = 0.313\ mA$

$C_{b1} = 477\ pF$

$C_{\pi 1} = 480\ pF$

$$r_{o1} = \frac{V_{A1}}{I_{C1}} = \frac{50}{0.313} = 160k\Omega$$

$$r_{\pi 1} = \frac{\beta_1}{g_{m1}} = \frac{26\times 50}{0.313} = 4.15k\Omega$$

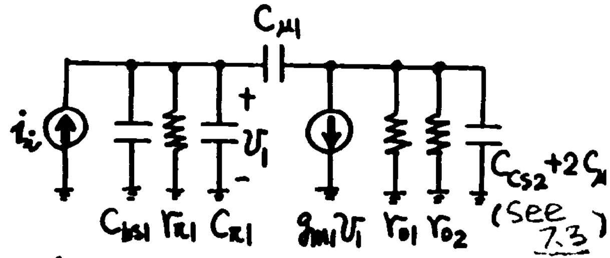
Q2 $V_{CB} = 9.4V$

$$\therefore C_{\mu 2} = \frac{0.7}{\sqrt{1+\frac{9.4}{0.55}}} = 0.16\ pF$$

$V_{CS} = 10V$

$$\therefore C_{cs2} = \frac{2}{\sqrt{1+\frac{10}{0.55}}} = 0.46\ pF$$

$$r_{o2} = \frac{V_{A2}}{I_{C2}} = \frac{120}{0.313} = 383k\Omega$$



$(C_{\pi 1}+C_{bs1})r_{\pi 1} = 480\times 4.15 = 1.99\,\mu s$

$R_{\mu o1} = r_{\pi 1} + r_o + g_{m1} r_{\pi 1} r_o$

$r_o = r_{o1} \| r_{o2} = 160 \| 383 = 113k\Omega$

$$\therefore R_{\mu o1} = 4.15 + 113 + \frac{0.313}{26}\times 4150 \times 113 = 5.76\ M\Omega$$

$\therefore C_{\mu 1}R_{\mu o1} = 0.24\times 5.76 = 1.38\,\mu s$

$r_o(C_{cs2}+2C_{\mu 2}) = 113\times 0.78 = 88ns$

$\therefore \Sigma T_o = 1.99 + 1.38 + 0.09 = 3.46\,\mu s$

$$\therefore f_{-3dB} = \frac{1}{2\pi \Sigma T_o} = 46\ KHz$$

(b) $\frac{v_o}{i_i} = \beta_1 r_o = 50\times 113 = 5.65M\Omega$

$C_{\mu 1}R_{\mu o1} = 20.24\times 5.76 = 116.6\,\mu s$

$\therefore \Sigma T_o = 1.99 + 116.6 + 0.09 = 118.7\,\mu s$

$$\therefore f_{-3dB} = \frac{1}{2\pi \Sigma T_o} = 1.34\ KHz$$

7.26

Iterate to find the bias current

Start with $V_{ov3}=0$

$I_3=\frac{10-V_t}{30k}=\frac{9}{30k}=300\mu A$

$V_{ov3}=\sqrt{\frac{2\times300}{60\times100/(2-0.4-1)}}=0.24V$

$I_3=\frac{10-1-0.24}{30k}=290\mu A$

Still $V_{ov3}=0.24V$, so this is close enough.

Now $V_{DS2}=10V$, $V_{DS3}=1.24V$

$\Delta V_{DS}=8.8V$,

$I_1=I_2=290(1+\frac{8.8}{100})=315\mu A$

$g_{m1}=\sqrt{2\times20\times(200/0.6)\times315}=2mA/V$

$r_{o1}=50/315=160k\Omega$

$g_{m2}=\sqrt{2\times60\times(100/0.6)\times315}=2.5mA/V$

$r_{o2}=100/315=320k\Omega$

$g_{m3}=\sqrt{2\times60\times(100/0.6)\times290}=2.4mA/V$

$r_{o3}=100/290=340k\Omega$

(a) $A=-\frac{1}{g_{m1}}g_{m1}(r_{o1}||r_{o2})=-160k||320k$

$=-110k\Omega$

$C_{gs1}=\frac{2}{3}WLC_{ox}+WL_dC_{ox}$

$=\frac{2}{3}\times200\times(2-0.2\times2-1)\times0.7+200\times0.2\times0.7$

$=84fF$

$R(C_{gs1})=\frac{1}{g_{m1}}=500\Omega$

$T_{gs1}=0.084\times0.5=0.04ns$

$C_{db01}=A_DC_{j0}+P_DC_{jsw0}=5\times200\times0.2+200\times0.2$

$=240fF$

$C_{db02}=5\times100\times0.4+100\times0.4=240fF$

$C_{db1}=C_{db2}=\frac{240}{\sqrt{1+10/0.6}}=57fF$

$R(C_{db1})=R(C_{db2})=r_{o1}||r_{o2}=110k\Omega$

$T_{db1-2}=2\times0.057\times110=12.5ns$

$C_{gd2}=WL_dC_{ox}=100\times0.2\times0.7=14fF$

$R(C_{gd2})=\frac{1}{g_{m3}}||r_{o3}||30k+r_{o1}||r_{o2}$

$+g_{m2}[\frac{1}{g_{m3}}||r_{o3}||30k][r_{o1}||r_{o2}]$

$\approx2(r_{o1}||r_{o2})=220k\Omega$

$T_{gd2}=0.014\times220=3ns$

$C_{gd1}=WL_dC_{ox}=200\times0.2\times0.7=28fF$

$R(C_{gd1})=\frac{1}{g_{m1}}+r_{o1}||r_{o2}+g_{m1}\frac{1}{g_{m1}}(r_{o1}||r_{o2})$

$\approx2(r_{o1}||r_{o2})=220k\Omega$

$T_{gd1}=0.028\times220=6.2ns$

$f_{-3dB}=\frac{1}{2\pi\Sigma T_0}=\frac{1}{2\pi(0.04+12.5+3+6.2)}$

$=7.3MHz$

(b) $C_{gd1}=20pF+28fF\approx20pF$

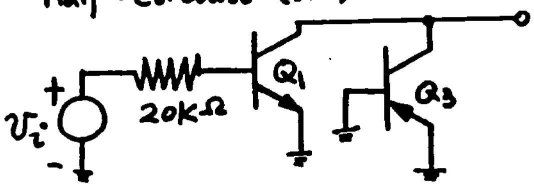
Still $R(C_{gd1})=220k$

$T=20\times220=4400ns$ (dominant!)

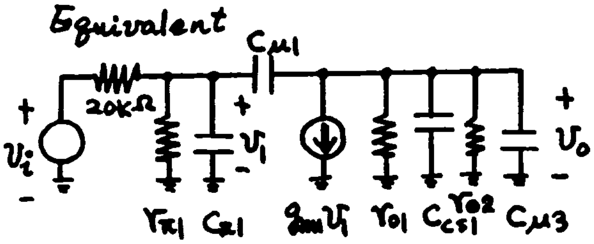
$f_{-3dB}\approx\frac{1}{2\pi\times4400ns}=36kHz$

7.27

Half-circuits (ac)



Equivalent



$$I_{C6} = \frac{9.4}{20} = 470\ \mu A$$

$$I_{C5} = \frac{V_T}{R_E} \ln \frac{I_{C6}}{I_{C5}} = 2.6 \ln \frac{470}{I_{C5}}\ \mu A$$

$$= 10\ \mu A$$

$$\therefore I_{C1} = I_{C3} = I_{C5}/2 = 5\ \mu A$$

Q1

$$r_{o1} = \frac{V_A}{I_{C1}} = \frac{120}{5} = 24\ M\Omega$$

$$r_{\pi 1} = \frac{\beta}{g_{m1}} = 200 \times \frac{26}{0.005} = 1.04\ M\Omega$$

$$C_{\mu 1} = \frac{0.7}{\sqrt{1 + \frac{5}{0.55}}} = 0.22\ pF$$

$$C_{cs1} = \frac{2}{\sqrt{1 + \frac{15}{0.55}}} = 0.38\ pF$$

$$C_{\pi 1} + C_{\mu 1} = \frac{g_m}{2\pi f_T} = \frac{1}{2\pi \times 26 \times 500 \times 10^6}$$

$$= 12.2\ pF \quad \text{at } 1mA$$

$$\therefore C_{\pi 1} = 12\ pF \quad \text{at } 1mA$$

$$C_{b1} = 9\ pF \quad \text{at } 1mA$$

$$\simeq 0 \quad \text{at } 5\mu A$$

$$\therefore C_{\pi 1} = 3\ pF \text{ at } 5\mu A$$

Q3

$$r_{o3} = \frac{50}{5} = 10\ M\Omega$$

$$C_{\mu 3} = \frac{1}{\sqrt{1 + \frac{4.4}{0.55}}} = 0.33\ pF$$

$$\frac{v_o}{v_i} = -\frac{r_{\pi 1}}{r_{\pi 1} + R_S} g_{m1} r_o$$

$$r_o = r_{o1} \| r_{o3} = 24 \| 10 = 7.06\ M\Omega$$

$$\frac{v_o}{v_i} = -\frac{1.04}{1.06} \times \frac{0.005}{26} \times 7.06 \times 10^6$$

$$= -1332$$

$$R_{\pi o1} = r_{\pi 1} \| R_S = 1M \| 20k = 19.6 k\Omega$$

$$\therefore C_{\pi 1} R_{\pi o1} = 3 \times 19.6 = 59\ ns$$

$$R_{\mu o1} = R_{\pi o1} + r_o + g_{m1} R_{\pi o1} r_o$$

$$R_{\mu o1} = 19.6K + 7.06M + \frac{0.005}{26} \times 19600 \times 7.06M$$

$$= 33.7\ M\Omega$$

$$\therefore C_{\mu 1} R_{\mu o1} = 0.22 \times 33.7 = 7.41\ \mu s$$

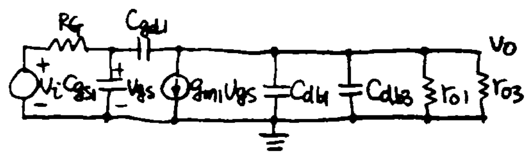
$$(C_{cs1} + C_{\mu 3}) r_o = 0.71 \times 7.06 = 5.0\ \mu s$$

$$\therefore \Sigma T_o = 0.06 + 7.41 + 5 = 12.47\ \mu s$$

$$\therefore f_{-3dB} = \frac{1}{2\pi \Sigma T_o} = 12.8\ KHz$$

<u>7.28</u>

Half circuit



$g_{m1} = \sqrt{2k_n'\left(\frac{W}{L}\right)_1 I_{D1}}$

$= \sqrt{2 \times 60 \times 10^{-6} \frac{100}{2-0.2\times2-1} \times 0.5 \times 10^{-3}}$

$= 3.2 \times 10^{-3}$ A/V

$r_{o1} = \frac{1}{\lambda_n I_{D1}} = \frac{100}{0.5\times10^{-3}} = 2\times10^5 \Omega$

$r_{o3} = \frac{1}{|\lambda_p||I_{D3}|} = \frac{50}{0.5\times10^{-3}} = 1\times10^5 \Omega$

$r_{o1} || r_{o3} = 2\times10^5 || 1\times10^5 = 6.7\times10^4$

$A = -g_{m1}(r_{o1}||r_{o3}) = -3.2\times10^{-3} \times 6.7\times10^4$

$= -210$

$C_{gs1} = \frac{2}{3} W L_{eff} C_{ox} + W L_d C_{ox}$

$= \frac{2}{3} 100 \times (2-0.2\times2-1) \times 0.7 + 100 \times 0.2 \times 0.7$

$= 42$ fF

$C_{gd1} = W L_d C_{ox} = 100 \times 0.2 \times 0.7 = 14$ fF

$C_{dbo1} = A_D C_{j0} + P_D C_{jsw0} = 5 \times 100 \times 0.4 + 100 \times 0.4$

$= 240$ fF

$C_{dbo3} = 5 \times 50 \times 0.2 + 50 \times 0.2 = 60$ fF

$C_{db1} = \frac{C_{dbo1}}{\sqrt{1+\frac{V_{DB}}{\phi_0}}} = \frac{240}{\sqrt{1+\frac{5}{0.6}}} = 78$ fF

$C_{db3} = \frac{60}{\sqrt{1+\frac{5}{0.6}}} = 20$ fF

$C_{gs1} R_G = 42\times10^{-15} \times 20\times10^3 = 8.2\times10^{-10}$ s

$C_{gd1}[R_G + (r_{o1}||r_{o3}) + g_{m1} R_G (r_{o1}||r_{o3})]$

$= 14\times10^{-15}[20\times10^3 + 6.7\times10^4 + 3.2\times10^{-3} \times 20\times10^3 \times 6.7\times10^4]$

$= 6.1\times10^{-8}$ s

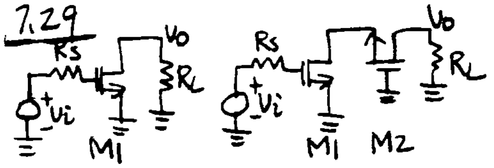
$(C_{db1} + C_{db2})(r_{o1}||r_{o3}) = (78+20)\times10^{-15} \times 6.7\times10^4$

$= 6.6\times10^{-9}$ s

$\Sigma T_o = 6.8\times10^{-8}$ s

$f_{-3dB} = \frac{1}{2\pi \Sigma T_o} = 2.3\times10^6$ Hz $= 2.3$ MHz

7.29



$g_{m1} = \sqrt{2k_n' \frac{W}{L} I_D} = \sqrt{2 \times 60 \times 10^{-6} \times \frac{100}{2-0.2\times2-0} \times 500 \times 10^{-6}}$

$= 1.9 \times 10^{-3}$ A/V

$C_{gs} = \frac{2}{3} W L_{eff} C_{ox} + W L_d C_{ox}$

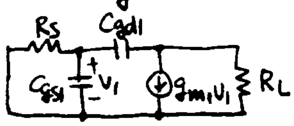
$= \frac{2}{3} 100 \times 1.6 \times 0.7 + 100 \times 0.2 \times 0.7$

$= 89$ fF

$C_{gd} = W L_d C_{ox} = 100 \times 0.2 \times 0.7 = 14$ fF

(a) $\frac{v_o}{v_i} = -g_{m1} R_L = -1.9 \times 10^{-3} \times 20 \times 10^3 = -38$

(b) The CS stage



$C_{gs1} R_S = 89 \times 10^{-15} \times 10 \times 10^3 = 8.9 \times 10^{-10}$ s

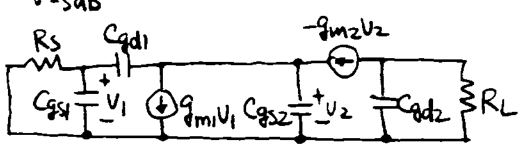
$C_{gd1}(R_S + R_L + g_{m1} R_S R_L)$

$= 14 \times 10^{-15} (10k + 20k + 1.9m \times 10k \times 20k)$

$= 5.7 \times 10^{-9}$ s

$f_{-3dB} = \frac{1}{2\pi} \frac{1}{8.9 \times 10^{-10} + 5.7 \times 10^{-9}} = 2.4 \times 10^7$ Hz

$t_r = \frac{0.35}{f_{-3dB}} = \frac{0.35}{2.4 \times 10^7} = 1.4 \times 10^{-8}$ s



The cascode

$C_{gs1} R_S = 89 \times 10^{-15} \times 10 \times 10^3 = 8.9 \times 10^{-10}$ s

For M1, the load resistance is $\frac{1}{g_{m2}}$

$C_{gd1}(R_S + \frac{1}{g_{m2}} + g_{m1} R_S \frac{1}{g_{m2}})$

$= C_{gd1}(2R_S + \frac{1}{g_{m2}})$

$= 14 \times 10^{-15} (2 \times 10 \times 10^3 + \frac{1}{1.9 \times 10^{-3}}) = 2.9 \times 10^{-10}$ s

$C_{gs2} \frac{1}{g_{m2}} = 89 \times 10^{-15} \frac{1}{1.9 \times 10^{-3}} = 4.7 \times 10^{-11}$ s

$C_{gd2} R_L = 14 \times 10^{-15} \times 20 \times 10^3 = 2.8 \times 10^{-10}$ s

$\Sigma T_0 = 1.5 \times 10^{-9}$ s

$f_{-3dB} = \frac{1}{2\pi} \frac{1}{1.5 \times 10^{-9}} = 1 \times 10^8$ Hz

$t_r = \frac{0.35}{1 \times 10^8} = 3.5 \times 10^{-9}$ s

The cascode has a wider bandwidth.

7.30

$$C_\pi + C_\mu = \frac{g_m}{2\pi f_T} = \frac{1}{2\pi \times 26 \times 500 \times 10^6}$$

$$= 12.2\ \text{pF} \quad \text{at } I_C = 1\text{mA}$$

$$\therefore C_\pi = 11.8\ \text{pF}$$

$$r_\pi = \frac{\beta}{g_m} = 2.6\ \text{K}\Omega,\ r_o = \infty$$

(a) For each circuit

$$\frac{v_o}{v_i} = -\frac{r_\pi}{r_\pi + R_S} g_m R_L$$

$$= -\frac{2.6}{2.6+5}\,\frac{3000}{26} = -39.5$$

(b) Common emitter

$$R_{\pi o} = r_\pi \| R_S = 2.6 \| 5 = 1.71\ \text{K}\Omega$$

$$R_{\mu o} = R_{\pi o} + R_L + g_m R_L R_{\pi o}$$

$$= 1.71 + 3 + \frac{3000}{26} \times 1.71$$

$$= 202\ \text{K}\Omega$$

$$C_\pi R_{\pi o} = 11.8 \times 1.71 = 20.2\ \text{ns}$$

$$C_\mu R_{\mu o} = 0.4 \times 202 = 80.8\ \text{ns}$$

$$C_{cs} R_L = 1 \times 3 = 3\ \text{ns}$$

$$\therefore \Sigma T_o = 20.2 + 80.8 + 3 = 104\ \text{ns}$$

$$\therefore f_{-3dB} = \frac{1}{2\pi \Sigma T_o} = 1.53\,\text{MHz}$$

Cascode

$$C_{\pi 1} R_{\pi o1} = 20.2\ \text{ns}$$

$$R_{\mu o1} = R_{\pi o1} + R_{L1} + g_{m1} R_{L1} R_{\pi o1}$$

$$R_{L1} = \frac{1}{g_{m2}} = 26\ \Omega$$

$$\therefore R_{\mu o1} = 1.71 + 0.026 + \frac{1}{26} \times 26 \times 1.71$$

$$= 3.45\ \text{k}\Omega$$

$$\therefore C_{\mu 1} R_{\mu o1} = 0.4 \times 3.45 = 1.38\ \text{ns}$$

$$C_{cs1} R_{L1} = 1 \times 0.026 = 0.026\ \text{ns}$$

$$R_{\pi o2} = \frac{1}{g_{m2}} = 26\ \Omega$$

$$\therefore C_{\pi 2} R_{\pi o2} = 11.8 \times 0.026 = 0.31\ \text{ns}$$

$$(C_{\mu 2} + C_{cs2}) R_{L2} = 1.4 \times 3 = 4.2\ \text{ns}$$

$$\therefore \Sigma T_o = 20.2 + 1.38 + 0.03 + 0.31 + 4.2$$

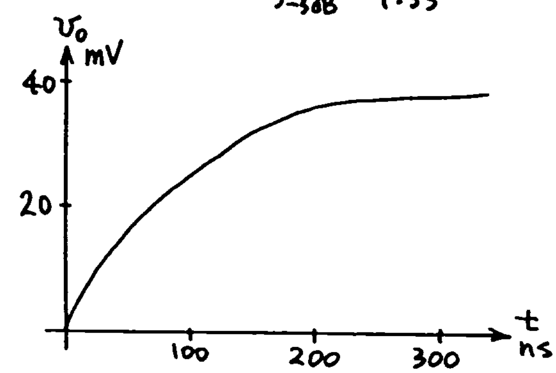
$$= 26.1\ \text{ns}$$

$$\therefore f_{-3dB} = 6.1\ \text{MHz}$$

This is 4 times higher than the Common-emitter stage, because Miller effect in Q_1 is eliminated.

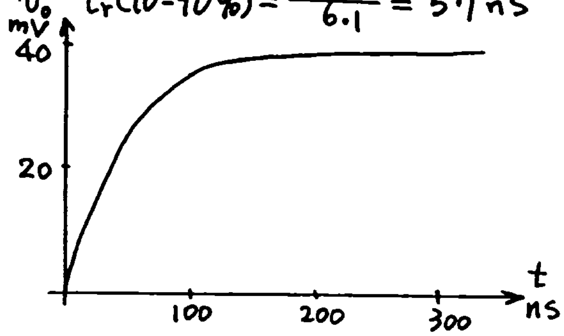
(c) Common-emitter

$$t_r(10\text{-}90\%) = \frac{0.35}{f_{-3dB}} = \frac{0.35}{1.53} = 229\ \text{ns}$$



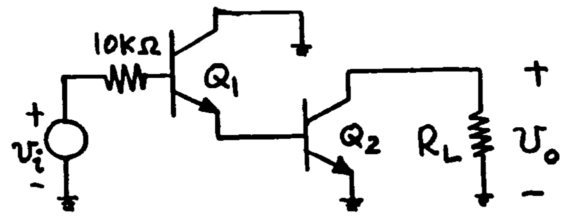
Cascode

$$t_r(10\text{-}90\%) = \frac{0.35}{6.1} = 57\ \text{ns}$$



7.31

(a) Half-circuit



Q1 $I_{C1} = 10 + I_{b2} = 12.5\ \mu A$

$r_{\pi1} = 200 \times \frac{26}{0.013} = 416\ k\Omega$

$C_{\mu1} = \frac{0.5}{\sqrt{1+\frac{6}{0.55}}} = 0.14\ pF$

$C_{\pi1} + C_{\mu1} = \frac{g_{m1}}{2\pi f_T} = \frac{1}{2\pi \times 13 \times 500 \times 10^6}$

$= 24.5\ pF$ at $2mA$

$\therefore C_{b1} = 20.4\ pF$ at $2mA$

$= 0.1\ pF$ at $12.5\ \mu A$

$\therefore C_{\pi1} = 4.1\ pF$

Q2 $I_{C2} = 0.5\ mA$

$r_{\pi2} = 200 \times \frac{26}{0.5} = 10.4\ k\Omega$

$V_{C2} = 6 - 5 \times \frac{1}{2} = 3.5\ V$

$\therefore C_{\mu2} = \frac{0.5}{\sqrt{1+\frac{4.1}{0.55}}} = 0.17\ pF$

$C_{cs2} = \frac{1}{\sqrt{1+\frac{9.5}{0.55}}} = 0.23\ pF$

$C_{b2} = 5.1\ pF$ at $0.5\ mA$

$\therefore C_{\pi2} = 9.1\ pF$

$R_i = r_{\pi1}(1 + g_{m1} r_{\pi2})$

$= 416\left(1 + \frac{0.0125}{26} \times 10400\right) k\Omega$

$= 2.5\ M\Omega$

$\frac{v_o}{v_i} = -\frac{R_i}{R_i + R_s}\frac{g_{m1} r_{\pi2}}{1 + g_{m1} r_{\pi2}} g_{m2} R_L$

$\frac{v_o}{v_i} = -\frac{2.5}{2.51}\,\frac{5}{6}\,\frac{0.5}{26} \times 5000$

$= -79.8$

(b) $R_{\mu o1} = R_s \| R_i \simeq 10\ k\Omega$

$\therefore C_{\mu1} R_{\mu o1} = 0.14 \times 10 = 1.4\ ns$

$R_{\pi o1} = r_{\pi1} \left\| \frac{R_s + R_E}{1 + g_{m1} R_E} \right. = r_{\pi1} \left\| \frac{R_s + r_{\pi2}}{1 + g_{m1} r_{\pi2}} \right.$

$= 416k \left\| \frac{20.4k}{1 + \frac{0.0125}{26} \times 10400} \right.$

$= 416K \| 3.4K = 3.37\ K\Omega$

$\therefore C_{\pi1} R_{\pi o1} = 4.1 \times 3.37 = 13.8\ ns$

$R_{\pi o2} = r_{\pi2} \left\| \left(\frac{1}{g_{m1}} + \frac{R_s}{\beta_1}\right) \right.$

$= 10.4k \left\| \left(\frac{26}{0.0125} + \frac{10000}{200}\right) \right.$

$= 10.4k \| 2.13K = 1.77\ K\Omega$

$\therefore C_{\pi2} R_{\pi o2} = 9.1 \times 1.77 = 16.1\ ns$

$R_{\mu o2} = R_{\pi o2} + R_L + g_{m2} R_{\pi o2} R_L$

$= 1.77K + 5K + \frac{0.5}{26} \times 1770 \times 5K$

$= 177\ K\Omega$

$\therefore C_{\mu2} R_{\mu o2} = 0.17 \times 177 = 30.1\ ns$

$C_{cs2} R_L = 0.23 \times 5 = 1.15\ ns$

$\therefore \Sigma T_o = 1.4 + 13.8 + 16.1 + 30.1 + 1.2$

$= 62.6\ ns$

$\therefore f_{-3dB} = \frac{1}{2\pi \Sigma T_o} = 2.54\ MHZ$

```
AMPLIFIER, RB=0
VCC 1 0 6V
VEE 2 0 -6V
RL1 1 3 5K
RL2 1 4 5K
Q1 1 9 5 NPN
Q2 3 5 7 NPN
Q3 4 6 7 NPN
Q4 1 10 6 NPN
IBIAS1 5 2 10UA
IBIAS4 6 2 10UA
IBIAS23 7 2 1MA
RS1 8 9 10K
RS4 10 0 10K
VI 8 0 0V AC
.PLOT AC VDB(3,4)
.PLOT AC VP(3,4)
.AC DEC 10 10K 100MEG
.MODEL NPN NPN IS=1E-16A BF=200 RB=0
+ CJE=4PF CJC=0.5PF CJS=2PF TF=208PS
+ MJE=0.5 MJC=0.5 MJS=0.5 VJE=0.55 VJC=0.55 VJS=0.55
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END
******  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
+0:1        = 6.000E+00 0:2        =-6.000E+00 0:3        = 3.512E+00
+0:4        = 3.512E+00 0:5        =-6.613E-01 0:6        =-6.613E-01
+0:7        =-1.417E+00 0:8        =   0.      0:9        =-6.212E-04
+0:10       =-6.212E-04
**** BIPOLAR JUNCTION TRANSISTORS
ELEMENT  0:Q1        0:Q2        0:Q3        0:Q4
MODEL    0:NPN       0:NPN       0:NPN       0:NPN
 IB       6.213E-08   2.488E-06   2.488E-06   6.213E-08
 IC       1.243E-05   4.975E-04   4.975E-04   1.243E-05
 VBE      6.607E-01   7.562E-01   7.562E-01   6.607E-01
 VCE      6.661E+00   4.929E+00   4.929E+00   6.661E+00
 VBC     -6.000E+00  -4.173E+00  -4.173E+00  -6.000E+00
 VS      -6.000E+00  -3.512E+00  -3.512E+00  -6.000E+00
 POWER    8.281E-05   2.455E-03   2.455E-03   8.281E-05
 BETAD    2.000E+02   2.000E+02   2.000E+02   2.000E+02
 GM       4.804E-04   1.924E-02   1.924E-02   4.804E-04
 RPI      4.163E+05   1.039E+04   1.039E+04   4.163E+05
 RX        0.          0.          0.          0.
 RO       6.000E+16   4.173E+16   4.173E+16   6.000E+16
 CPI      9.724E-12   1.461E-11   1.461E-11   9.724E-12
 CMU      1.449E-13   1.706E-13   1.706E-13   1.449E-13
 CBX       0.          0.          0.          0.
 CCS      5.795E-13   7.359E-13   7.359E-13   5.795E-13
 BETAAC   2.000E+02   2.000E+02   2.000E+02   2.000E+02
 FT       7.747E+06   2.071E+08   2.071E+08   7.747E+06
******  AC ANALYSIS                              TNOM=  27.000 TEMP=  27.000
   FREQ        VDB(3,4)
(A        )   -2.000E+01     0.          2.000E+01     4.000E+01     6.000E+01
                    +             +             +             +             +
9.999E+03  3.80E+01-+------+------+------+------+------+-----A+------+------+-
1.258E+04  3.80E+01 +      +      +      +      +      +     A+      +      +
1.584E+04  3.80E+01 +      +      +      +      +      +     A+      +      +
1.995E+04  3.80E+01 +      +      +      +      +      +     A+      +      +
2.511E+04  3.80E+01 +      +      +      +      +      +     A+      +      +
3.162E+04  3.80E+01 +      +      +      +      +      +     A+      +      +
3.981E+04  3.80E+01 +      +      +      +      +      +     A+      +      +
5.011E+04  3.80E+01 +      +      +      +      +      +     A+      +      +
6.309E+04  3.80E+01 +      +      +      +      +      +     A+      +      +
7.943E+04  3.80E+01 +      +      +      +      +      +     A+      +      +
1.000E+05  3.80E+01-+------+------+------+------+------+-----A+------+------+-
1.258E+05  3.80E+01 +      +      +      +      +      +     A+      +      +
1.584E+05  3.80E+01 +      +      +      +      +      +     A+      +      +
1.995E+05  3.80E+01 +      +      +      +      +      +     A+      +      +
2.511E+05  3.80E+01 +      +      +      +      +      +     A+      +      +
3.162E+05  3.81E+01 +      +      +      +      +      +     A+      +      +
3.981E+05  3.81E+01 +      +      +      +      +      +     A+      +      +
5.011E+05  3.81E+01 +      +      +      +      +      +     A+      +      +
6.309E+05  3.82E+01 +      +      +      +      +      +     A+      +      +
7.943E+05  3.82E+01 +      +      +      +      +      +     A+      +      +
1.000E+06  3.83E+01-+------+------+------+------+------+-----A+------+------+-
1.258E+06  3.83E+01 +      +      +      +      +      +     A+      +      +
1.584E+06  3.90E+01 +      +      +      +      +      +     A+      +      +
1.995E+06  3.70E+01 +      +      +      +      +      +    A +      +      +
2.511E+06  3.50E+01 +      +      +      +      +      +  A   +      +      +
3.162E+06  3.20E+01 +      +      +      +      +      +A     +      +      +
3.981E+06  2.86E+01 +      +      +      +      +     A+      +      +      +
5.011E+06  2.51E+01 +      +      +      +      +   A  +      +      +      +
6.309E+06  2.17E+01 +      +      +      +      +A     +      +      +      +
7.943E+06  1.85E+01 +      +      +      +     A+      +      +      +      +
1.000E+07  1.56E+01-+------+------+------+---A--+------+------+------+------+-
1.258E+07  1.29E+01 +      +      +      + A    +      +      +      +      +
1.584E+07  1.03E+01 +      +      +      A      +      +      +      +      +
1.995E+07  7.88E+00 +      +      +     A+      +      +      +      +      +
2.511E+07  5.48E+00 +      +      +   A  +      +      +      +      +      +
3.162E+07  3.08E+00 +      +      + A    +      +      +      +      +      +
3.981E+07  6.18E-01 +      +      A      +      +      +      +      +      +
5.011E+07 -1.97E+00 +      +     A+      +      +      +      +      +      +
6.309E+07 -4.73E+00 +      +   A  +      +      +      +      +      +      +
7.943E+07 -7.70E+00 +      + A    +      +      +      +      +      +      +
1.000E+08 -1.09E+01-+-----A+------+------+------+------+------+------+------+-
                    +             +             +             +             +
```

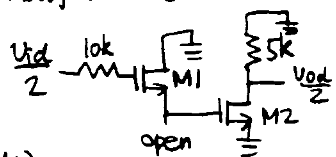
```
   FREQ        VP(3,4)
(A        )      0.          5.000E+01     1.000E+02     1.500E+02     2.000E+02
                    +             +             +             +             +
9.999E+03  1.79E+02-+------+------+------+------+------+------+------+A-----+-
1.258E+04  1.79E+02 +      +      +      +      +      +      +      +A     +
1.584E+04  1.79E+02 +      +      +      +      +      +      +      +A     +
1.995E+04  1.79E+02 +      +      +      +      +      +      +      +A     +
2.511E+04  1.79E+02 +      +      +      +      +      +      +      +A     +
3.162E+04  1.79E+02 +      +      +      +      +      +      +      +A     +
3.981E+04  1.78E+02 +      +      +      +      +      +      +      +A     +
5.011E+04  1.78E+02 +      +      +      +      +      +      +      +A     +
6.309E+04  1.78E+02 +      +      +      +      +      +      +      +A     +
7.943E+04  1.77E+02 +      +      +      +      +      +      +      +A     +
1.000E+05  1.77E+02-+------+------+------+------+------+------+------+A-----+-
1.258E+05  1.76E+02 +      +      +      +      +      +      +      A      +
1.584E+05  1.75E+02 +      +      +      +      +      +      +      A      +
1.995E+05  1.74E+02 +      +      +      +      +      +      +      A      +
2.511E+05  1.73E+02 +      +      +      +      +      +      +      A      +
3.162E+05  1.71E+02 +      +      +      +      +      +      +     A+      +
3.981E+05  1.69E+02 +      +      +      +      +      +      +    A +      +
5.011E+05  1.66E+02 +      +      +      +      +      +      +    A +      +
6.309E+05  1.62E+02 +      +      +      +      +      +      +  A   +      +
7.943E+05  1.57E+02 +      +      +      +      +      +      + A    +      +
1.000E+06  1.50E+02-+------+------+------+------+------+------A------+------+-
1.258E+06  1.40E+02 +      +      +      +      +      +   A  +      +      +
1.584E+06  1.27E+02 +      +      +      +      +      +A     +      +      +
1.995E+06  1.10E+02 +      +      +      +      +  A   +      +      +      +
2.511E+06  9.23E+01 +      +      +      +    A +      +      +      +      +
3.162E+06  7.75E+01 +      +      +      +A     +      +      +      +      +
3.981E+06  6.76E+01 +      +      +    A +      +      +      +      +      +
5.011E+06  6.20E+01 +      +      +  A   +      +      +      +      +      +
6.309E+06  5.96E+01 +      +      +  A   +      +      +      +      +      +
7.943E+06  5.92E+01 +      +      +  A   +      +      +      +      +      +
1.000E+07  5.98E+01-+------+------+--A---+------+------+------+------+------+-
1.258E+07  6.07E+01 +      +      +  A   +      +      +      +      +      +
1.584E+07  6.13E+01 +      +      +  A   +      +      +      +      +      +
1.995E+07  6.12E+01 +      +      +  A   +      +      +      +      +      +
2.511E+07  6.01E+01 +      +      +  A   +      +      +      +      +      +
3.162E+07  5.79E+01 +      +      + A    +      +      +      +      +      +
3.981E+07  5.45E+01 +      +      +A     +      +      +      +      +      +
5.011E+07  5.02E+01 +      +      A      +      +      +      +      +      +
6.309E+07  4.50E+01 +      +     A+      +      +      +      +      +      +
7.943E+07  3.93E+01 +      +   A  +      +      +      +      +      +      +
1.000E+08  3.35E+01-+------+-A----+------+------+------+------+------+------+-
                    +             +             +             +             +
```

```
*****
AMPLIFIER, RB=200
VCC 1 0 6V
VEE 2 0 -6V
RL1 1 3 5K
RL2 1 4 5K
Q1 1 9 5 NPN
Q2 3 5 7 NPN
Q3 4 6 7 NPN
Q4 1 10 6 NPN
IBIAS1 5 2 10UA
IBIAS4 6 2 10UA
IBIAS23 7 2 1MA
RS1 8 9 10K
RS4 10 0 10K
VI 8 0 0V AC
.PLOT AC VDB(3,4)
.PLOT AC VP(3,4)
.AC DEC 10 10K 100MEG
.MODEL NPN NPN IS=1E-16A BF=200 RB=200
+ CJE=4PF CJC=0.5PF CJS=2PF TF=208PS
+ MJE=0.5 MJC=0.5 MJS=0.5 VJE=0.55 VJC=0.55 VJS=0.55
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

******  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000

+0:1        = 6.000E+00 0:2        =-6.000E+00 0:3        = 3.512E+00
+0:4        = 3.512E+00 0:5        =-6.613E-01 0:6        =-6.613E-01
+0:7        =-1.418E+00 0:8        =   0.      0:9        =-6.212E-04
+0:10       =-6.212E-04

**** BIPOLAR JUNCTION TRANSISTORS

ELEMENT  0:Q1        0:Q2        0:Q3        0:Q4
MODEL    0:NPN       0:NPN       0:NPN       0:NPN
 IB       6.213E-08   2.488E-06   2.488E-06   6.213E-08
 IC       1.243E-05   4.975E-04   4.975E-04   1.243E-05
 VBE      6.607E-01   7.566E-01   7.566E-01   6.607E-01
 VCE      6.661E+00   4.930E+00   4.930E+00   6.661E+00
 VBC     -6.000E+00  -4.173E+00  -4.173E+00  -6.000E+00
 VS      -6.000E+00  -3.512E+00  -3.512E+00  -6.000E+00
 POWER    8.281E-05   2.455E-03   2.455E-03   8.281E-05
 BETAD    2.000E+02   2.000E+02   2.000E+02   2.000E+02
 GM       4.804E-04   1.924E-02   1.924E-02   4.804E-04
 RPI      4.163E+05   1.039E+04   1.039E+04   4.163E+05
 RX       2.000E+02   2.000E+02   2.000E+02   2.000E+02
 RO       6.000E+16   4.174E+16   4.174E+16   6.000E+16
 CPI      9.724E-12   1.461E-11   1.461E-11   9.724E-12
```

```
CMU      1.449E-13  1.706E-13  1.706E-13  1.449E-13
CBX        0.         0.         0.         0.
CCS      5.795E-13  7.359E-13  7.359E-13  5.795E-13
BETAAC   2.000E+02  2.000E+02  2.000E+02  2.000E+02
FT       7.747E+06  2.071E+08  2.071E+08  7.747E+06

******  AC ANALYSIS                         TNOM=  27.000 TEMP=  27.000

   FREQ       VDB(3,4)
(A        )   -2.000E+01    0.          2.000E+01     4.000E+01     6.000E+01
                    +             +             +             +             +
9.999E+03  3.79E+01-+------+------+------+------+------+-----A+------+------+-
1.258E+04  3.79E+01 +      +      +      +      +      +     A+      +      +
1.584E+04  3.79E+01 +      +      +      +      +      +     A+      +      +
1.995E+04  3.79E+01 +      +      +      +      +      +     A+      +      +
2.511E+04  3.79E+01 +      +      +      +      +      +     A+      +      +
3.162E+04  3.79E+01 +      +      +      +      +      +     A+      +      +
3.981E+04  3.79E+01 +      +      +      +      +      +     A+      +      +
5.011E+04  3.79E+01 +      +      +      +      +      +     A+      +      +
6.309E+04  3.79E+01 +      +      +      +      +      +     A+      +      +
7.943E+04  3.79E+01 +      +      +      +      +      +     A+      +      +
1.000E+05  3.79E+01-+------+------+------+------+------+-----A+------+------+-
1.258E+05  3.79E+01 +      +      +      +      +      +     A+      +      +
1.584E+05  3.79E+01 +      +      +      +      +      +     A+      +      +
1.995E+05  3.79E+01 +      +      +      +      +      +     A+      +      +
2.511E+05  3.79E+01 +      +      +      +      +      +     A+      +      +
3.162E+05  3.79E+01 +      +      +      +      +      +     A+      +      +
3.981E+05  3.79E+01 +      +      +      +      +      +     A+      +      +
5.011E+05  3.79E+01 +      +      +      +      +      +     A+      +      +
6.309E+05  3.80E+01 +      +      +      +      +      +     A+      +      +
7.943E+05  3.80E+01 +      +      +      +      +      +     A+      +      +
1.000E+06  3.80E+01-+------+------+------+------+------+-----A+------+------+-
1.258E+06  3.80E+01 +      +      +      +      +      +     A+      +      +
1.584E+06  3.76E+01 +      +      +      +      +      +    A +      +      +
1.995E+06  3.65E+01 +      +      +      +      +      +    A +      +      +
2.511E+06  3.44E+01 +      +      +      +      +      +  A   +      +      +
3.162E+06  3.15E+01 +      +      +      +      +      +A     +      +      +
3.981E+06  2.81E+01 +      +      +      +      +     A+      +      +      +
5.011E+06  2.47E+01 +      +      +      +      +  A   +      +      +      +
6.309E+06  2.13E+01 +      +      +      +      +A     +      +      +      +
7.943E+06  1.82E+01 +      +      +      +     A+      +      +      +      +
1.000E+07  1.52E+01-+------+------+------+---A--+------+------+------+------+-
1.258E+07  1.25E+01 +      +      +      + A    +      +      +      +      +
1.584E+07  9.97E+00 +      +      +      A      +      +      +      +      +
1.995E+07  7.53E+00 +      +      +    A +      +      +      +      +      +
2.511E+07  5.13E+00 +      +      +   A  +      +      +      +      +      +
3.162E+07  2.73E+00 +      +      + A    +      +      +      +      +      +
3.981E+07  2.73E-01 +      +      A      +      +      +      +      +      +
5.011E+07 -2.31E+00 +      +    A +      +      +      +      +      +      +
6.309E+07 -5.07E+00 +      +  A   +      +      +      +      +      +      +
7.943E+07 -8.04E+00 +      +A     +      +      +      +      +      +      +
1.000E+08 -1.12E+01-+-----A+------+------+------+------+------+------+------+-
                    +             +             +             +             +

   FREQ       VP(3,4)
(A        )      0.        5.000E+01     1.000E+02     1.500E+02     2.000E+02
                    +             +             +             +             +
9.999E+03  1.79E+02-+------+------+------+------+------+------+------+A-----+-
1.258E+04  1.79E+02 +      +      +      +      +      +      +      +A     +
1.584E+04  1.79E+02 +      +      +      +      +      +      +      +A     +
1.995E+04  1.79E+02 +      +      +      +      +      +      +      +A     +
2.511E+04  1.79E+02 +      +      +      +      +      +      +      +A     +
3.162E+04  1.79E+02 +      +      +      +      +      +      +      +A     +
3.981E+04  1.78E+02 +      +      +      +      +      +      +      +A     +
5.011E+04  1.78E+02 +      +      +      +      +      +      +      +A     +
6.309E+04  1.78E+02 +      +      +      +      +      +      +      +A     +
7.943E+04  1.77E+02 +      +      +      +      +      +      +      +A     +
1.000E+05  1.77E+02-+------+------+------+------+------+------+------+A-----+-
1.258E+05  1.76E+02 +      +      +      +      +      +      +      A      +
1.584E+05  1.75E+02 +      +      +      +      +      +      +      A      +
1.995E+05  1.74E+02 +      +      +      +      +      +      +      A      +
2.511E+05  1.72E+02 +      +      +      +      +      +      +     A+      +
3.162E+05  1.71E+02 +      +      +      +      +      +      +     A+      +
3.981E+05  1.68E+02 +      +      +      +      +      +      +    A +      +
5.011E+05  1.65E+02 +      +      +      +      +      +      +   A  +      +
6.309E+05  1.61E+02 +      +      +      +      +      +      +  A   +      +
7.943E+05  1.56E+02 +      +      +      +      +      +      + A    +      +
1.000E+06  1.48E+02-+------+------+------+------+------+------A------+------+-
1.258E+06  1.38E+02 +      +      +      +      +      +   A  +      +      +
1.584E+06  1.25E+02 +      +      +      +      +      A      +      +      +
1.995E+06  1.08E+02 +      +      +      +      + A    +      +      +      +
2.511E+06  9.17E+01 +      +      +      +    A +      +      +      +      +
3.162E+06  7.75E+01 +      +      +      +A     +      +      +      +      +
3.981E+06  6.79E+01 +      +      +    A +      +      +      +      +      +
5.011E+06  6.25E+01 +      +      +  A   +      +      +      +      +      +
6.309E+06  6.00E+01 +      +      +  A   +      +      +      +      +      +
7.943E+06  5.95E+01 +      +      +  A   +      +      +      +      +      +
1.000E+07  6.01E+01-+------+------+--A---+------+------+------+------+------+-
1.258E+07  6.09E+01 +      +      +  A   +      +      +      +      +      +
1.584E+07  6.14E+01 +      +      +  A   +      +      +      +      +      +
1.995E+07  6.12E+01 +      +      +  A   +      +      +      +      +      +
2.511E+07  6.06E+01 +      +      +  A   +      +      +      +      +      +
3.162E+07  5.77E+01 +      +      + A    +      +      +      +      +      +
3.981E+07  5.42E+01 +      +      +A     +      +      +      +      +      +
5.011E+07  4.97E+01 +      +      A      +      +      +      +      +      +
6.309E+07  4.44E+01 +      +    A +      +      +      +      +      +      +
7.943E+07  3.96E+01 +      +   A  +      +      +      +      +      +      +
1.000E+08  3.26E+01-+------+-A----+------+------+------+------+------+------+-
```

7.32

Half circuit



(a)

$g_{m1} = \sqrt{2 \times 60 \times \frac{100}{1.6} \times 10} = 270 \mu A/V$

$g_{m2} = \sqrt{2 \times 60 \times \frac{100}{1.6} \times 500} = 1.9 mA/V$

M1 is a source follower with a perfect current source, $\lambda = 0$ and no body effect. Its gain is 1.

$\frac{V_{od}}{V_{id}} = -g_{m2} \times 5k = -9.6$

(b) Since M1 is an ideal source follower, its gain is 1. Therefore, the voltage across C_{gs1} does not change. So ignore C_{gs1}.

$C_{gd1} = WL_d C_{ox} = 100 \times 0.2 \times 0.7 = 14 fF$

$R(C_{gd1}) = 10k\Omega$

$T_{gd1} = 0.014 \times 10 = 0.14 ns$

$C_{sb01} = A_D C_{j0} + P_D C_{jsw0}$
$= 5 \times 100 \times 0.4 + 100 \times 0.4 = 240 fF$

$V_{S1} = 0 - V_t - V_{ov1}$

$V_{ov1} = \sqrt{\frac{2 \times 10}{60 \times (100/1.6)}} = 0.07V$

$V_{S1} = -1.07V$

$C_{sb1} = \frac{C_{sb01}}{\sqrt{1 + \frac{V_{DB}}{\Psi_0}}} = \frac{240}{\sqrt{1 + \frac{-1.07 - (-6)}{0.6}}} = 80 fF$

$R(C_{sb1}) = \frac{1}{g_{m1}} = 3.7 k\Omega$

$T_{sb1} = 0.08 \times 3.7 = 0.3 ns$

$C_{gs2} = \frac{2}{3} W L_{eff} C_{ox} + WL_d C_{ox}$
$= \frac{2}{3} \times 100 \times 1.6 \times 0.7 + 100 \times 0.2 \times 0.7$
$= 90 fF$

$R(C_{gs2}) = \frac{1}{g_{m1}} = 3.7k\Omega$

$T_{gs2} = 0.09 \times 3.7 = 0.33 ns$

$C_{db02} = A_D C_{j0} + P_D C_{jsw0}$
$= 5 \times 100 \times 0.4 + 100 \times 0.4 = 240 fF$

$V_{D2} = 6 - 5k \times 0.5mA = 3.5V$

$C_{db2} = \frac{C_{db02}}{\sqrt{1 + \frac{V_{DB}}{\Psi_0}}} = \frac{240}{\sqrt{1 + \frac{3.5 - (-6)}{0.6}}} = 60 fF$

$R(C_{db2}) = 5k\Omega$

$T_{db2} = 0.06 \times 5 = 0.3 ns$

$C_{gd2} = WL_d C_{ox} = 100 \times 0.2 \times 0.7 = 14 fF$

$R(C_{gd2}) = \frac{1}{g_{m1}} + 5k + g_{m2} \frac{1}{g_{m1}} 5k$
$= \frac{1}{270 \times 10^{-6}} + 5 \times 10^3 + \frac{1.9 \times 10^{-3}}{270 \times 10^{-6}} \times 5 \times 10^3$
$= 44 \times 10^3 \Omega$

$T_{gd2} = 0.014 \times 44 = 0.62 ns$

$f_{-3dB} = \frac{1}{2\pi} \frac{1}{0.14 + 0.3 + 0.33 + 0.3 + 0.62} = 94 MHz$

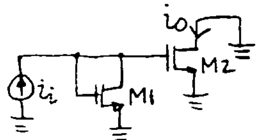
7-36

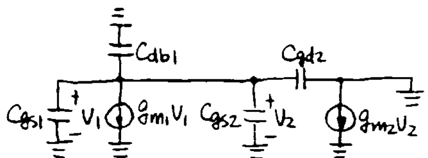
```
AMPLIFIER
VDD 1 0 6V
VSS 2 0 -6V
RL1 1 3 5K
RL2 1 4 5K
M1 1 9 5 5 CMOSN W=100U L=2U AD=500E-12 PD=100U
M2 3 5 7 7 CMOSN W=100U L=2U AD=500E-12 PD=100U
M3 4 6 7 7 CMOSN W=100U L=2U AD=500E-12 PD=100U
M4 1 10 6 6 CMOSN W=100U L=2U AD=500E-12 PD=100U
IBIAS1 5 2 10UA
IBIAS4 6 2 10UA
IBIAS23 7 2 1MA
RS1 8 9 10K
RS4 10 0 10K
VI 8 0 0V AC
.TF V(3,4) VI
.PLOT AC VDB(3,4)
.PLOT AC VP(3,4)
.AC DEC 10 10K 100MEG
* COX'=0.7FF/UM**2=EOX/TOX => TOX=500 ANGSTROMS
.MODEL CMOSN NMOS LEVEL=1 LAMBDA=0 GAMMA=0 VTO=1 KP=60U LD=0.2U
+ CJ=0.4E-15 CJSW=0.4E-15 TOX=500E-10 PB=0.6
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END
```

```
 ******  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000

+0:1      = 6.000E+00 0:2      =-6.000E+00 0:3      = 3.500E+00
+0:4      = 3.500E+00 0:5      =-1.073E+00 0:6      =-1.073E+00
+0:7      =-2.589E+00 0:8      =  0.       0:9      =  0.
+0:10     =  0.

**** MOSFETS

ELEMENT  0:M1       0:M2       0:M3       0:M4
MODEL    0:CMOSN    0:CMOSN    0:CMOSN    0:CMOSN
 ID       1.000E-05  5.000E-04  5.000E-04  1.000E-05
 IBS      0.         0.         0.         0.
 IBD     -7.073E-14 -6.089E-14 -6.089E-14 -7.073E-14
 VGS      1.073E+00  1.516E+00  1.516E+00  1.073E+00
 VDS      7.073E+00  6.089E+00  6.089E+00  7.073E+00
 VBS      0.         0.         0.         0.
 VTH      1.000E+00  1.000E+00  1.000E+00  1.000E+00
 VDSAT    7.303E-02  5.164E-01  5.164E-01  7.303E-02
 BETA     3.750E-03  3.750E-03  3.750E-03  3.750E-03
 GAM EFF  0.         0.         0.         0.
 GM       2.739E-04  1.936E-03  1.936E-03  2.739E-04
 GDS      0.         0.         0.         0.
 GMB      0.         0.         0.         0.
 CDTOT    1.485E-14  1.471E-14  1.471E-14  1.485E-14
 CGTOT    1.253E-13  1.055E-13  1.055E-13  1.253E-13
 CSTOT    8.748E-14  8.748E-14  8.748E-14  8.748E-14
 CBTOT    2.293E-14  3.346E-15  3.346E-15  2.293E-14
 CGS      8.748E-14  8.748E-14  8.748E-14  8.748E-14
 CGD      1.485E-14  1.471E-14  1.471E-14  1.485E-14

****     SMALL-SIGNAL TRANSFER CHARACTERISTICS

      V(3,4)/VI                              = -9.682E+00
      INPUT RESISTANCE AT          VI        =  9.999E+19
      OUTPUT RESISTANCE AT V(3,4)            =  9.999E+03
```

```
 ******  AC ANALYSIS                      TNOM=  27.000 TEMP=  27.000

     FREQ       VDB(3,4)
 (A        )    1.920E+01     1.940E+01     1.960E+01     1.980E+01     2.000E+01
                   +             +             +             +             +
 9.999E+03 1.97E+01-+------+------+------+------+------+A-----+------+------+-
 1.258E+04 1.97E+01 +      +      +      +      +      +A     +      +      +
 1.584E+04 1.97E+01 +      +      +      +      +      +A     +      +      +
 1.995E+04 1.97E+01 +      +      +      +      +      +A     +      +      +
 2.511E+04 1.97E+01 +      +      +      +      +      +A     +      +      +
 3.162E+04 1.97E+01 +      +      +      +      +      +A     +      +      +
 3.981E+04 1.97E+01 +      +      +      +      +      +A     +      +      +
 5.011E+04 1.97E+01 +      +      +      +      +      +A     +      +      +
 6.309E+04 1.97E+01 +      +      +      +      +      +A     +      +      +
 7.943E+04 1.97E+01 +      +      +      +      +      +A     +      +      +
 1.000E+05 1.97E+01-+------+------+------+------+------+A-----+------+------+-
 1.258E+05 1.97E+01 +      +      +      +      +      +A     +      +      +
 1.584E+05 1.97E+01 +      +      +      +      +      +A     +      +      +
 1.995E+05 1.97E+01 +      +      +      +      +      +A     +      +      +
 2.511E+05 1.97E+01 +      +      +      +      +      +A     +      +      +
 3.162E+05 1.97E+01 +      +      +      +      +      +A     +      +      +
 3.981E+05 1.97E+01 +      +      +      +      +      +A     +      +      +
 5.011E+05 1.97E+01 +      +      +      +      +      +A     +      +      +
 6.309E+05 1.97E+01 +      +      +      +      +      +A     +      +      +
 7.943E+05 1.97E+01 +      +      +      +      +      +A     +      +      +
 1.000E+06 1.97E+01-+------+------+------+------+------+A-----+------+------+-
 1.258E+06 1.97E+01 +      +      +      +      +      +A     +      +      +
 1.584E+06 1.97E+01 +      +      +      +      +      +A     +      +      +
 1.995E+06 1.97E+01 +      +      +      +      +      +A     +      +      +
 2.511E+06 1.97E+01 +      +      +      +      +      +A     +      +      +
 3.162E+06 1.97E+01 +      +      +      +      +      +A     +      +      +
 3.981E+06 1.97E+01 +      +      +      +      +      +A     +      +      +
 5.011E+06 1.97E+01 +      +      +      +      +      +A     +      +      +
 6.309E+06 1.97E+01 +      +      +      +      +      + A    +      +      +
 7.943E+06 1.97E+01 +      +      +      +      +      + A    +      +      +
 1.000E+07 1.97E+01-+------+------+------+------+------+-A----+------+------+-
 1.258E+07 1.97E+01 +      +      +      +      +      + A    +      +      +
 1.584E+07 1.97E+01 +      +      +      +      +      + A    +      +      +
 1.995E+07 1.97E+01 +      +      +      +      +      +  A   +      +      +
 2.511E+07 1.97E+01 +      +      +      +      +      +   A  +      +      +
 3.162E+07 1.97E+01 +      +      +      +      +      +    A +      +      +
 3.981E+07 1.97E+01 +      +      +      +      +      +     A+      +      +
 5.011E+07 1.98E+01 +      +      +      +      +      +      A      +      +
 6.309E+07 1.97E+01 +      +      +      +      +      +     A+      +      +
 7.943E+07 1.96E+01 +      +      +      +      +     A+      +      +      +
 1.000E+08 1.93E+01-+------+--A---+------+------+------+------+------+------+-
                    +             +             +             +             +

     FREQ       VP(3,4)
 (A        )    1.200E+02     1.400E+02     1.600E+02     1.800E+02     2.000E+02
                    +             +             +             +             +
 9.999E+03 1.80E+02-+------+------+------+------+------+------A------+------+-
 1.258E+04 1.80E+02 +      +      +      +      +      +      A      +      +
 1.584E+04 1.80E+02 +      +      +      +      +      +      A      +      +
 1.995E+04 1.80E+02 +      +      +      +      +      +      A      +      +
 2.511E+04 1.80E+02 +      +      +      +      +      +      A      +      +
 3.162E+04 1.80E+02 +      +      +      +      +      +      A      +      +
 3.981E+04 1.80E+02 +      +      +      +      +      -      A      +      +
 5.011E+04 1.80E+02 +      +      +      +      +      +      A      +      +
 6.309E+04 1.80E+02 +      +      +      +      +      +      A      +      +
 7.943E+04 1.80E+02 +      +      +      +      +      +      A      +      +
 1.000E+05 1.80E+02-+------+------+------+------+------+------A------+------+-
 1.258E+05 1.79E+02 +      +      +      +      +      +      A      +      +
 1.584E+05 1.79E+02 +      +      +      +      +      +      A      +      +
 1.995E+05 1.79E+02 +      +      +      +      +      +      A      +      +
 2.511E+05 1.79E+02 +      +      +      +      +      +      A      +      +
 3.162E+05 1.79E+02 +      +      +      +      +      +      A      +      +
 3.981E+05 1.79E+02 +      +      +      +      +      -      A      +      +
 5.011E+05 1.79E+02 +      +      +      +      +      +      A      +      +
 6.309E+05 1.79E+02 +      +      +      +      +      +      A      +      +
 7.943E+05 1.79E+02 +      +      +      +      +      +      A      +      +
 1.000E+06 1.79E+02-+------+------+------+------+------+------A------+------+-
 1.259E+06 1.79E+02 +      +      +      +      +      +      A      +      +
 1.584E+06 1.79E+02 +      +      +      +      +      +      A      +      +
 1.995E+06 1.79E+02 +      +      +      +      +      +     A+      +      +
 2.511E+06 1.79E+02 +      +      +      +      +      +     A+      +      +
 3.162E+06 1.78E+02 +      +      +      +      +      +     A+      +      +
 3.981E+06 1.78E+02 +      +      +      +      +      +     A+      +      +
 5.011E+06 1.78E+02 +      +      +      +      +      +     A+      +      +
 6.309E+06 1.77E+02 +      +      +      +      +      +    A +      +      +
 7.943E+06 1.76E+02 +      +      +      +      +      +    A +      +      +
 1.000E+07 1.75E+02-+------+------+------+------+------+---A--+------+------+-
 1.258E+07 1.74E+02 +      +      +      +      +      +  A   +      +      +
 1.584E+07 1.73E+02 +      +      +      +      +      + A    +      +      +
 1.995E+07 1.71E+02 +      +      +      +      +      +A     +      +      +
 2.511E+07 1.69E+02 +      +      +      +      +      A      +      +      +
 3.162E+07 1.66E+02 +      +      +      +      +    A +      +      +      +
 3.981E+07 1.63E+02 +      +      +      +      + A    +      +      +      +
 5.011E+07 1.58E+02 +      +      +      +     A+      +      +      +      +
 6.309E+07 1.51E+02 +      +      +      +A     +      +      +      +      +
 7.943E+07 1.43E+02 +      +      + A    +      +      +      +      +      +
 1.000E+08 1.31E+02-+------+A-----+------+------+------+------+------+------+-
                    +             +             +             +             +
```

7.33





$$i_o = g_{m2} v_{i2} = g_{m2} \times i_i \frac{1}{g_{m1}} = \frac{g_{m2}}{g_{m1}} i_i$$

$$= \frac{\sqrt{2k_n'(W/L)_2 I_{D2}}}{\sqrt{2k_n'(W/L)_1 I_{D1}}} i_i = \sqrt{\frac{(W/L)_2}{(W/L)_1} \frac{I_{D2}}{I_{D1}}}\, i_i = 4 i_i$$

$$g_{m1} = \frac{2I_{D1}}{V_{ov1}} = \frac{2 \times 1 \times 10^{-3}}{0.3} = 6.7 \times 10^{-3}\, A/V$$

$$(C_{gs1} + C_{db1} + C_{gs2} + C_{gd2}) \frac{1}{g_{m1}}$$

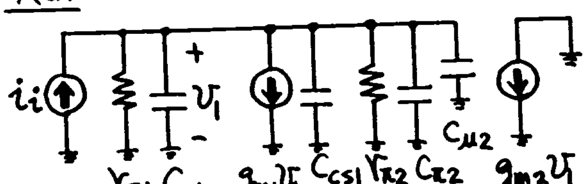
$$= (0.2 + 0.09 + 0.8 + 0.2) \times 10^{-12} \times \frac{1}{6.7 \times 10^{-3}}$$

$$= 1.9 \times 10^{-10} s$$

$$f_{-3dB} = \frac{1}{2\pi} \frac{1}{1.9 \times 10^{-10}} = 8.3 \times 10^{8} Hz$$

$$t_r = \frac{0.35}{f_{-3dB}} = 4.2 \times 10^{-10} s$$

7.34



$$v_1 = i_i \left(r_{\pi1} \| \frac{1}{g_{m1}} \| r_{\pi 2}\right)$$

$$r_{\pi1} = \frac{\beta}{g_{m1}} = 200 \times 26 = 5.2 K\Omega$$

$$\frac{1}{g_{m1}} = 26\Omega$$

$$r_{\pi2} = \frac{\beta}{g_{m2}} = 200 \times \frac{26}{4} = 1.3 K\Omega$$

$$\therefore v_1 = i_i \times 25.37\Omega$$

$$i_o = g_{m2} v_1 = \frac{4}{26} v_1$$

$$\therefore \frac{i_o}{i_i} = \frac{4}{26} \times 25.37 = 3.90$$

For Q_1 $C_b = \tau_F g_{m1}$

$$= 0.2 \times \frac{1}{26} \times 10^{-9} = 7.7 pF$$

$$\therefore C_{\pi1} = 8.7 pF$$

For Q_2 $C_b = 0.2 \times \frac{4}{26} \times 10^{-9} = 30.8 pF$

$$\therefore C_{\pi2} = 34.8 pF$$

Total shunt C

$$= C_{\pi1} + C_{cs1} + C_{\pi2} + C_{\mu2}$$

$$= 8.7 + 1 + 34.8 + 0.8 = 45.3 pF$$

$$r_{\pi1} \| \frac{1}{g_{m1}} \| r_{\pi2} = 25.4\ \Omega$$

$\therefore$ Time constant $= 45.3 \times 25.4 = 1.15$ ns

$\therefore f_{-3dB} = 138$ MHZ

$$t_r(10\text{-}90\%) = \frac{0.35}{f_{-3dB}} = 2.5 ns$$

7.35

Bias $I_{C6} = \frac{5.4}{6} = 0.9 mA$

$$\therefore I_{C5} \simeq \frac{1}{2} \times 0.9 = 0.45 mA$$

$$\therefore I_{C1} = I_{C2} = 0.22\ mA$$

$$\therefore V_{C1} = V_{C2} = 6 - 2.2 = 3.8 V$$

$$\therefore I_{C3} = I_{C4} = \frac{1}{2} \frac{3.2}{5} = 0.32 mA$$

$$\therefore V_{C3} = V_{C4} = 6 - 5 \times 0.32 = 4.4V$$

7-38

Parameters

Q_1: $r_{\pi 1} = \frac{\beta}{g_{m1}} = 200 \times \frac{26}{0.22} = 23.6\,k\Omega$

$C_\pi + C_\mu = \frac{g_{m1}}{2\pi f_T} = \frac{1}{2\pi \times 26 \times 600 \times 10^6}$

$= 10.2\,pF$ at $I_C = 1\,mA$

$\therefore C_\pi = 10\,pF$

$\therefore C_b = 8\,pF$ at $I_c = 1\,mA$

$= 1.8\,pF$ at $I_c = 0.22\,mA$

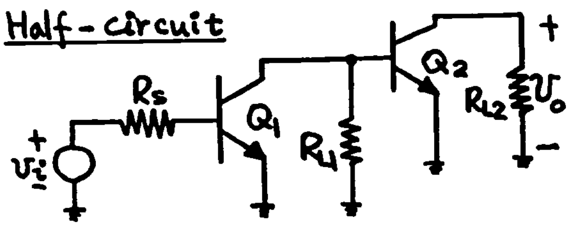
$\therefore C_{\pi 1} = 3.8\,pF$

Q_2: $r_{\pi 2} = 200 \times \frac{26}{0.32} = 16.3\,k\Omega$

$C_b = 2.6\,pF$ at $0.32\,mA$

$C_{\pi 2} = 4.6\,pF$

Half-circuit



$$\frac{v_o}{v_i} = \frac{r_{\pi 1}}{R_s + r_{\pi 1}} g_{m1} \frac{R_{L1} r_{\pi 2}}{R_{L1} + r_{\pi 2}} g_{m2} R_{L2}$$

$$= \frac{23.6}{43.6} \frac{0.22}{26} \frac{10 \times 16.3}{26.3} \times 1000 \times \frac{0.32}{26} \times 5000$$

$$= 1747$$

$\therefore$ Circuit gain $= \frac{1}{2} \times 1747 = 873$

$R_{\pi 01} = R_s \| r_{\pi 1} = 20k \| 23.6k = 10.8\,k\Omega$

$C_{\pi 1} R_{\pi 01} = 3.8 \times 10.8 = 41.1\,ns$

$R_{\mu 01} = R_{\pi 01} + R_1 + g_{m1} R_{\pi 01} R_1$

$R_1 = R_{L1} \| r_{\pi 2} = 10 \| 16.3 = 6.2\,k\Omega$

$\therefore R_{\mu 01} = 10.8 + 6.2 + \frac{0.22}{26} \times 6200 \times 10.8$

$= 584\,k\Omega$

$\therefore C_{\mu 1} R_{\mu 01} = 0.2 \times 584 = 117\,ns$

$C_{cs1} R_1 = 1 \times 6.2 = 6.2\,ns$

$R_{\pi 02} = R_1 = 6.2\,k\Omega$

$\therefore C_{\pi 2} R_{\pi 02} = 4.6 \times 6.2 = 28.5\,ns$

$R_{\mu 02} = R_{\pi 02} + R_{L2} + g_{m2} R_{L2} R_{\pi 02}$

$= 6.2 + 5 + \frac{0.32}{26} \times 5000 \times 6.2$

$= 393\,k\Omega$

$\therefore C_{\mu 2} R_{\mu 02} = 0.2 \times 393 = 79\,ns$

$C_{cs2} R_{L2} = 1 \times 5 = 5\,ns$

$\therefore \Sigma T_o = 41.1 + 117 + 6.2 + 28.5 + 79 + 5$

$= 276\,ns$

$\therefore f_{-3dB} = \frac{1}{2\pi \Sigma T_o} = 576\,kHz$

$t_r(10\text{-}90\%) = \frac{0.35}{f_{-3dB}} = 608\,ns$

7-39

```
TWO-STAGE AMPLIFIER
VCC 1 0 6V
VEE 2 0 -6V
RL1 1 3 10K
RL2 1 4 10K
Q1 3 5 7 NPN
Q2 4 6 7 NPN
RS1 8 5 20K
RS2 6 0 20K
RL3 1 13 5K
RL4 1 14 5K
Q3 13 3 12 NPN
Q4 14 4 12 NPN
REE34 12 0 5K
Q5 7 11 9 NPN
Q6 11 11 10 NPN
RE5 9 2 2K
RE6 10 2 1K
RBIAS 11 0 5K
VI 8 0 0V AC
.PLOT AC VDB(14)
.PLOT AC VP(14)
.AC DEC 10 10K 100MEG
.MODEL NPN NPN IS=1E-16A BF=200 RB=0
+ CJE=2PF CJC=0.3PF CJS=3PF TF=213PS
+ MJE=0.5 MJC=0.5 MJS=0.5 VJE=0.55 VJC=0.55 VJS=0.55
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END
```

```
****** OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000

+0:1       = 6.000E+00 0:2      =-6.000E+00 0:3      = 3.789E+00
+0:4       = 3.789E+00 0:5      =-2.196E-02 0:6      =-2.196E-02
+0:7       =-7.570E-01 0:8      =   0.      0:9      =-5.112E+00
+0:10      =-5.130E+00 0:11     =-4.359E+00 0:12     = 3.045E+00
+0:13      = 4.484E+00 0:14     = 4.484E+00
```

**** BIPOLAR JUNCTION TRANSISTORS

ELEMENT	0:Q1	0:Q2	0:Q3	0:Q4	0:Q5	0:Q6
MODEL	0:NPN	0:NPN	0:NPN	0:NPN	0:NPN	0:NPN
IB	1.098E-06	1.098E-06	1.515E-06	1.515E-06	2.207E-06	4.327E-06
IC	2.196E-04	2.196E-04	3.030E-04	3.030E-04	4.414E-04	8.654E-04
VBE	7.350E-01	7.350E-01	7.433E-01	7.433E-01	7.531E-01	7.705E-01
VCE	4.545E+00	4.545E+00	1.439E+00	1.439E+00	4.355E+00	7.705E-01
VBC	-3.810E+00	-3.810E+00	-6.958E-01	-6.958E-01	-3.602E+00	0.
VS	-3.789E+00	-3.789E+00	-4.484E+00	-4.484E+00	7.570E-01	4.359E+00
POWER	9.990E-04	9.990E-04	4.373E-04	4.373E-04	1.924E-03	6.701E-04
BETAD	2.000E+02	2.000E+02	2.000E+02	2.000E+02	2.000E+02	2.000E+02
GM	8.490E-03	8.490E-03	1.172E-02	1.172E-02	1.707E-02	3.346E-02
RPI	2.355E+04	2.355E+04	1.706E+04	1.706E+04	1.172E+04	5.977E+03
RX	0.	0.	0.	0.	0.	0.
RO	3.810E+16	3.810E+16	6.958E+15	6.958E+15	3.602E+16	2.586E+14
CPI	7.002E-12	7.002E-12	7.733E-12	7.733E-12	8.922E-12	1.250E-11
CMU	1.065E-13	1.065E-13	1.993E-13	1.993E-13	1.092E-13	3.000E-13
CBX	0.	0.	0.	0.	0.	0.
CCS	1.068E-12	1.068E-12	9.915E-13	9.915E-13	5.064E-12	1.489E-11
BETAAC	2.000E+02	2.000E+02	2.000E+02	2.000E+02	2.000E+02	2.000E+02
FT	1.900E+08	1.900E+08	2.351E+08	2.351E+08	3.007E+08	4.159E+08

```
****** AC ANALYSIS                 TNOM=  27.000 TEMP=  27.000

     FREQ      VDB(14)
(A        )    -2.000E+01      0.        2.000E+01    4.000E+01    6.000E+01

 9.999E+03  5.85E+01
 1.258E+04  5.85E+01
 1.584E+04  5.85E+01
 1.995E+04  5.85E+01
 2.511E+04  5.85E+01
 3.162E+04  5.85E+01
 3.981E+04  5.85E+01
 5.011E+04  5.85E+01
 6.309E+04  5.85E+01
 7.943E+04  5.85E+01
 1.000E+05  5.84E+01
 1.258E+05  5.84E+01
 1.584E+05  5.83E+01
 1.995E+05  5.82E+01
 2.511E+05  5.80E+01
 3.162E+05  5.77E+01
 3.981E+05  5.73E+01
 5.011E+05  5.66E+01
 6.309E+05  5.58E+01
 7.943E+05  5.47E+01
 1.000E+06  5.34E+01
 1.258E+06  5.17E+01
 1.584E+06  4.98E+01
 1.995E+06  4.77E+01
 2.511E+06  4.52E+01
 3.162E+06  4.26E+01
 3.981E+06  3.96E+01
 5.011E+06  3.64E+01
 6.309E+06  3.30E+01
 7.943E+06  2.94E+01
 1.000E+07  2.57E+01
 1.258E+07  2.18E+01
 1.584E+07  1.78E+01
 1.995E+07  1.35E+01
 2.511E+07  8.88E+00
 3.162E+07  4.35E+00
 3.981E+07 -9.98E-02
 5.011E+07 -4.65E+00
 6.309E+07 -9.41E+00
 7.943E+07 -1.44E+01
 1.000E+08 -1.96E+01
```

```
     FREQ      VP(14)
(A        )    -1.000E+02      0.        1.000E+02    2.000E+02    3.000E+02

 9.999E+03  1.79E+02
 1.258E+04  1.78E+02
 1.584E+04  1.78E+02
 1.995E+04  1.78E+02
 2.511E+04  1.77E+02
 3.162E+04  1.76E+02
 3.981E+04  1.76E+02
 5.011E+04  1.75E+02
 6.309E+04  1.73E+02
 7.943E+04  1.72E+02
 1.000E+05  1.70E+02
 1.258E+05  1.67E+02
 1.584E+05  1.64E+02
 1.995E+05  1.60E+02
 2.511E+05  1.55E+02
 3.162E+05  1.50E+02
 3.981E+05  1.43E+02
 5.011E+05  1.35E+02
 6.309E+05  1.27E+02
 7.943E+05  1.17E+02
 1.000E+06  1.07E+02
 1.258E+06  9.77E+01
 1.584E+06  8.75E+01
 1.995E+06  7.72E+01
 2.511E+06  6.70E+01
 3.162E+06  5.68E+01
 3.981E+06  4.70E+01
 5.011E+06  3.77E+01
 6.309E+06  2.90E+01
 7.943E+06  2.10E+01
 1.000E+07  1.35E+01
 1.258E+07  5.98E+00
 1.584E+07 -2.16E+00
 1.995E+07 -1.02E+01
 2.511E+07 -1.61E+01
 3.162E+07 -2.06E+01
 3.981E+07 -2.56E+01
 5.011E+07 -3.15E+01
 6.309E+07 -3.79E+01
 7.943E+07 -4.44E+01
 1.000E+08 -5.05E+01
```

7.36

Bias $I_{C5} = \frac{5.4}{11} = 0.49\ mA$

$\therefore I_{C4} \simeq \frac{0.49}{2.5} = 196\ \mu A$

$\therefore I_{C1} = I_{C2} = 98\ \mu A$

$\therefore V_{C2} \simeq 6 - 0.098 \times 12.5 = 4.77\ V$

$\therefore I_{C3} = \frac{1.227 - 0.6}{1} = 0.627\ mA$

$I_{B3} = 6\ \mu A$

Recalculate

$V_{C2} = 6 - 0.092 \times 12.5 = 4.85\ V$

$\therefore I_{C3} = \frac{1.15 - 0.6}{1} = 0.55\ mA$

Parameters

Q_1 $r_{\pi 1} = \frac{\beta}{g_{m1}} = 200 \times \frac{26}{0.098} = 53.1\ k\Omega$

$C_\pi + C_\mu = \frac{g_{m1}}{2\pi f_T} = \frac{1}{2\pi \times 26 \times 400 \times 10^6}$

$= 15.3\ pF$ at $1 mA$

$\therefore C_\pi = 15\ pF$ at $1 mA$

$C_b = 12 pF$ at $1 mA$

$= 1.2\ pF$ at $0.098\ mA$

$\therefore C_{\pi 1} = 4.2\ pF$

Q_3 $r_{\pi 3} = \frac{\beta}{g_{m3}} = 100 \times \frac{26}{0.55} = 4.7 k\Omega$

$C_{bs} + C_\pi + C_\mu = \frac{g_{m3}}{2\pi f_T}$

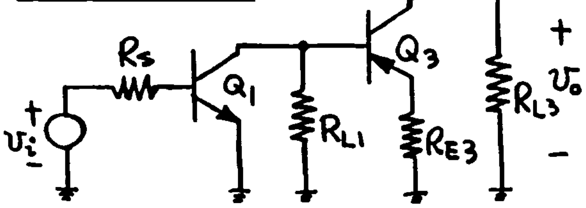
$= \frac{0.5}{2\pi \times 26 \times 6 \times 10^6} = 510\ pF$

$\therefore C_b = 505\ pF$ at $0.5\ mA$

$= 555\ pF$ at $0.55\ mA$

$\therefore C_{\pi 3} = 558\ pF$

Half-circuit



$\frac{v_o}{v_i} = \frac{r_{\pi 1}}{r_{\pi 1} + R_s} g_{m1} \frac{R_{L1} R_{i3}}{R_{L1} + R_{i3}} G_{m3} R_{L3}$

$R_{i3} = r_{\pi 3}(1 + g_{m3} R_{E3})$

$= 4.7\left(1 + \frac{0.55}{26} \times 1000\right) = 104\ k\Omega$

$G_{m3} = \frac{g_{m3}}{1 + g_{m3} R_{E3}} = \frac{0.55}{26} \cdot \frac{1}{22.2}$

$= 0.953\ mA/V$

$\therefore \frac{v_o}{v_i} = \frac{53.1}{63.1} \times \frac{0.098}{26} \frac{12.5 \times 104}{116.5} \times 1000 \times 0.953 \times 10$

$= 337$

Actual gain $= \frac{1}{2} \times 337 = 169$

$R_{\pi o1} = R_s \| r_{\pi 1} = 10 \| 53.1 = 8.42 k\Omega$

$\therefore C_{\pi 1} R_{\pi o1} = 4.2 \times 8.42 = 35.4\ ns$

$R_{\mu o1} = R_{\pi o1} + R_1 + g_{m1} R_{\pi o1} R_1$

$R_1 = R_{L1} \| R_{i3} = 12.5 \| 104 = 11.2 k\Omega$

$\therefore R_{\mu o1} = 8.42 + 11.2 + \frac{0.098}{26} \times 8420 \times 11.2$

$= 375\ k\Omega$

$\therefore C_{\mu 1} R_{\mu o1} = 0.3 \times 375 = 112\ ns$

$C_{cs1} R_1 = 1.5 \times 11.2 = 16.8\ ns$

$C_{bs3} R_1 = 1.5 \times 11.2 = 16.8\ ns$

$R_{\pi o3} = r_{\pi 3} \| \frac{R_{L1} + R_{E3}}{1 + g_{m3} R_{E3}} = 4.7^k \| \frac{12.6^k}{22.2}$

$= 4.7k \| 608 = 538\ \Omega$

$\therefore C_{\pi 3} R_{\pi o3} = 558 \times 0.538 = 300\ ns$

$R_{\mu o3} = R_1 + R_{L3} + G_m R_1 R_{L3}$

$R_1 = R_{L1} \| R_{i3} = 11.2 k\Omega$

$\therefore R_{\mu o3} = 11.2 + 10 + 0.953 \times 10 \times 11.2$

$= 128\ k\Omega$

$\therefore C_{\mu 3} R_{\mu o3} = 0.3 \times 128 = 38.4\ ns$

$\therefore \sum T_o = 35.4 + 112 + 16.8 \times 2 + 300 + 38.4$

$= 519\ ns$

$\therefore f_{-3dB} = \frac{1}{2\pi \sum T_o} = 306\ kHz$

7-41

```
TWO-STAGE AMPLIFIER
VCC 1 0 6V
VEE 2 0 -6V
RL1 1 3 12.5K
RL2 1 4 12.5K
Q1 3 5 7 NPN
Q2 4 6 7 NPN
RS1 8 5 10K
RS2 6 0 10K
Q4 7 9 10 NPN
RQ4 10 2 2.5K
Q5 9 9 11 NPN
RQ5 11 2 1K
RBIAS 9 0 10K
Q3 12 4 13 PNP
RQ3 1 13 1K
RL3 12 2 10K
VI 8 0 0V AC
.PLOT AC VDB(12)
.PLOT AC VP(12)
.AC DEC 10 10K 100MEG
.MODEL NPN NPN IS=9.31E-15A BF=200 RB=0
+ CJE=3PF CJC=0.58PF CJS=1.5PF TF=318PS
.MODEL PNP PNP IS=52.3E-15A BF=100 RB=0
+ CJE=3PF CJC=0.58PF CJS=1.5PF TF=26.2PS
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END
```

```
 ******  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000

+0:1        = 6.000E+00 0:2       =-6.000E+00 0:3       = 4.740E+00
+0:4        = 4.812E+00 0:5       =-5.040E-03 0:6       =-5.040E-03
+0:7        =-6.026E-01 0:8       =    0.     0:9       =-4.875E+00
+0:10       =-5.491E+00 0:11      =-5.513E+00 0:12      =-1.707E-01
+0:13       = 5.411E+00
```

**** BIPOLAR JUNCTION TRANSISTORS

ELEMENT	0:Q1	0:Q2	0:Q4	0:Q5	0:Q3
MODEL	0:NPN	0:NPN	0:NPN	0:NPN	0:PNP
IB	5.040E-07	5.040E-07	1.013E-06	2.420E-06	-5.829E-06
IC	1.008E-04	1.008E-04	2.026E-04	4.841E-04	-5.829E-04
VBE	5.976E-01	5.976E-01	6.157E-01	6.382E-01	-5.984E-01
VCE	5.342E+00	5.415E+00	4.888E+00	6.382E-01	-5.581E+00
VBC	-4.745E+00	-4.817E+00	-4.272E+00	0.	4.983E+00
VS	-4.740E+00	-4.812E+00	6.026E-01	4.875E+00	-4.812E+00
POWER	5.388E-04	5.462E-04	9.910E-04	3.105E-04	3.257E-03
BETAD	2.000E+02	2.000E+02	2.000E+02	2.000E+02	1.000E+02
GM	3.897E-03	3.897E-03	7.833E-03	1.872E-02	2.254E-02
RPI	5.131E+04	5.131E+04	2.553E+04	1.068E+04	4.436E+03
RX	0.	0.	0.	0.	0.
RO	5.096E+14	5.175E+14	4.589E+14	2.778E+12	9.528E+13
CPI	5.749E-12	5.749E-12	7.061E-12	1.060E-11	5.103E-12
CMU	3.006E-13	2.993E-13	3.097E-13	5.800E-13	2.964E-13
CBX	0.	0.	0.	0.	0.
CCS	1.500E-12	1.500E-12	1.500E-12	1.500E-12	1.500E-12
BETAAC	2.000E+02	2.000E+02	2.000E+02	2.000E+02	9.999E+01
FT	1.025E+08	1.025E+08	1.691E+08	2.665E+08	6.643E+08

```
******  AC ANALYSIS                          TNOM=  27.000 TEMP=  27.000

    FREQ       VDB(12)
(A        )    -1.000E+02    -5.000E+01     0.           5.000E+01     1.000E+02
                    +             +             +             +             +
9.999E+03  4.47E+01-+------+------+------+------+------+-----A+------+------+-
1.258E+04  4.47E+01 +      +      +      +      +      +     A+      +      +
1.584E+04  4.47E+01 +      +      +      +      +      +     A+      +      +
1.995E+04  4.47E+01 +      +      +      +      +      +     A+      +      +
2.511E+04  4.47E+01 +      +      +      +      +      +     A+      +      +
3.162E+04  4.47E+01 +      +      +      +      +      +     A+      +      +
3.981E+04  4.47E+01 +      +      +      +      +      +     A+      +      +
5.011E+04  4.47E+01 +      +      +      +      +      +     A+      +      +
6.309E+04  4.47E+01 +      +      +      +      +      +     A+      +      +
7.943E+04  4.47E+01 +      +      +      +      +      +     A+      +      +
1.000E+05  4.46E+01-+------+------+------+------+------+-----A+------+------+-
1.258E+05  4.46E+01 +      +      +      +      +      +    A +      +      +
1.584E+05  4.45E+01 +      +      +      +      +      +    A +      +      +
1.995E+05  4.44E+01 +      +      +      +      +      +    A +      +      +
2.511E+05  4.43E+01 +      +      +      +      +      +    A +      +      +
3.162E+05  4.40E+01 +      +      +      +      +      +    A +      +      +
3.981E+05  4.36E+01 +      +      +      +      +      +    A +      +      +
5.011E+05  4.31E+01 +      +      +      +      +      +    A +      +      +
6.309E+05  4.24E+01 +      +      +      +      +      +    A +      +      +
7.943E+05  4.14E+01 +      +      +      +      +      +    A +      +      +
1.000E+06  4.01E+01-+------+------+------+------+------+---A--+------+------+-
1.258E+06  3.86E+01 +      +      +      +      +      +   A  +      +      +
1.584E+06  3.68E+01 +      +      +      +      +      +  A   +      +      +
1.995E+06  3.47E+01 +      +      +      +      +      +  A   +      +      +
2.511E+06  3.24E+01 +      +      +      +      +      + A    +      +      +
3.162E+06  2.99E+01 +      +      +      +      +      +A     +      +      +
3.981E+06  2.73E+01 +      +      +      +      +      +A     +      +      +
5.011E+06  2.45E+01 +      +      +      +      +      A      +      +      +
6.309E+06  2.16E+01 +      +      +      +      +     A+      +      +      +
7.943E+06  1.88E+01 +      +      +      +      +    A +      +      +      +
1.000E+07  1.60E+01-+------+------+------+------+---A--+------+------+------+-
1.258E+07  1.31E+01 +      +      +      +      +   A  +      +      +      +
1.584E+07  1.02E+01 +      +      +      +      +  A   +      +      +      +
1.995E+07  7.04E+00 +      +      +      +      + A    +      +      +      +
2.511E+07  3.43E+00 +      +      +      +      +A     +      +      +      +
3.162E+07 -9.39E-01 +      +      +      +      A      +      +      +      +
3.981E+07 -6.30E+00 +      +      +      +    A +      +      +      +      +
5.011E+07 -1.24E+01 +      +      +      +   A  +      +      +      +      +
6.309E+07 -1.87E+01 +      +      +      + A    +      +      +      +      +
7.943E+07 -2.44E+01 +      +      +      A      +      +      +      +      +
1.000E+08 -2.94E+01-+------+------+-----A+------+------+------+------+------+-
                    +             +             +             +             +
```

```
    FREQ       VP(12)
(A        )    -1.000E+02     0.           1.000E+02     2.000E+02     3.000E+02
                    +             +             +             +             +
9.999E+03  1.79E+02-+------+------+------+------+------+---A--+------+------+-
1.258E+04  1.78E+02 +      +      +      +      +      +   A  +      +      +
1.584E+04  1.78E+02 +      +      +      +      +      +   A  +      +      +
1.995E+04  1.78E+02 +      +      +      +      +      +   A  +      +      +
2.511E+04  1.77E+02 +      +      +      +      +      +   A  +      +      +
3.162E+04  1.77E+02 +      +      +      +      +      +   A  +      +      +
3.981E+04  1.76E+02 +      +      +      +      +      +   A  +      +      +
5.011E+04  1.75E+02 +      +      +      +      +      +   A  +      +      +
6.309E+04  1.74E+02 +      +      +      +      +      +  A   +      +      +
7.943E+04  1.73E+02 +      +      +      +      +      +  A   +      +      +
1.000E+05  1.71E+02-+------+------+------+------+------+--A---+------+------+-
1.258E+05  1.69E+02 +      +      +      +      +      +  A   +      +      +
1.584E+05  1.66E+02 +      +      +      +      +      + A    +      +      +
1.995E+05  1.62E+02 +      +      +      +      +      + A    +      +      +
2.511E+05  1.58E+02 +      +      +      +      +      +A     +      +      +
3.162E+05  1.53E+02 +      +      +      +      +      A      +      +      +
3.981E+05  1.47E+02 +      +      +      +      +      A      +      +      +
5.011E+05  1.40E+02 +      +      +      +      +     A+      +      +      +
6.309E+05  1.32E+02 +      +      +      +      +    A +      +      +      +
7.943E+05  1.23E+02 +      +      +      +      +  A   +      +      +      +
1.000E+06  1.14E+02-+------+------+------+------+-A----+------+------+------+-
1.258E+06  1.05E+02 +      +      +      +      +A     +      +      +      +
1.584E+06  9.57E+01 +      +      +      +     A+      +      +      +      +
1.995E+06  8.67E+01 +      +      +      +    A +      +      +      +      +
2.511E+06  7.81E+01 +      +      +      +   A  +      +      +      +      +
3.162E+06  7.02E+01 +      +      +      +  A   +      +      +      +      +
3.981E+06  6.30E+01 +      +      +      + A    +      +      +      +      +
5.011E+06  5.65E+01 +      +      +      +A     +      +      +      +      +
6.309E+06  5.05E+01 +      +      +      A      +      +      +      +      +
7.943E+06  4.45E+01 +      +      +     A+      +      +      +      +      +
1.000E+07  3.80E+01-+------+------+----A-+------+------+------+------+------+-
1.258E+07  3.04E+01 +      +      +   A  +      +      +      +      +      +
1.584E+07  2.08E+01 +      +      +  A   +      +      +      +      +      +
1.995E+07  9.01E+00 +      +      +A     +      +      +      +      +      +
2.511E+07 -5.51E+00 +      +     A+      +      +      +      +      +      +
3.162E+07 -2.18E+01 +      +   A  +      +      +      +      +      +      +
3.981E+07 -3.71E+01 +      + A    +      +      +      +      +      +      +
5.011E+07 -4.73E+01 +      A      +      +      +      +      +      +      +
6.309E+07 -5.07E+01 +      A      +      +      +      +      +      +      +
7.943E+07 -4.89E+01 +      A      +      +      +      +      +      +      +
1.000E+08 -4.53E+01-+------+A-----+------+------+------+------+------+------+-
                    +             +             +             +             +
```

7.37 (a)

$V_o = 2.5\,V$ dc

$V_{GS_2} = 2.5\,V$

$V_{t_2} = V_{t_0} + \gamma(\sqrt{2\phi_f + V_{SB}} - \sqrt{2\phi_f}$

$= 0.7 + 0.4(\sqrt{0.6+2.5} - \sqrt{0.6})$

$= 1.09\,V$

$I_D = \frac{\mu_n C_{ox}}{2}\left(\frac{W}{L}\right)_2 (V_{GS_2} - V_{t_2})^2$

$= \frac{60\mu}{2}\,\frac{4}{1}(2.5 - 1.09)^2$

$= 237\,\mu A$

$\frac{V_o}{V_i} = \frac{-g_{m_1}}{g_{m_2} + g_{mb_2}} = \frac{-1.69m}{337\mu + 38.3\mu}$

$= -4.5$

$g_{m_1} = \sqrt{2 I_D \mu C_{ox} \frac{W}{L}}$

$= \sqrt{2(237\mu)(60\mu)(100)}$

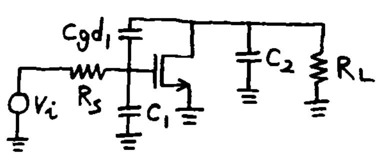
$= 1.69\,mA/V$

$g_{m_2} = \sqrt{2(237\mu)(60\mu)(4)}$

$= 337\,\mu A/V$

$g_{mb_2} = \frac{g_{m_2}\gamma}{2\sqrt{2\phi_f + V_{SB}}} = \frac{g_{m_2}\,0.4}{2\sqrt{0.6+2.5}}$

$= 38.3\,\mu A/V$



$C_{ox} = 1.73\,\frac{fF}{\mu^2}$

$C_{gs1} = \frac{2}{3} WL\,C_{ox} + C_{ol} W$

$= 115\,fF + 30\,fF = 145\,fF$

$C_{gs2} = \frac{2}{3} WL\,C_{ox} + C_{ol} W$

$= 4.61\,fF + 1.2\,fF$

$= 5.8\,fF$

$C_{db_1} = \frac{0.8\,(100)}{\sqrt{1 + \frac{2.5}{0.6}}} = 35.2\,fF$

$C_{gd_1} = C_{ol} W = 30\,fF$

$C_{sb_2} = \frac{0.8\,(4)}{\sqrt{1 + \frac{2.5}{0.6}}} = 1.41\,fF$

$C_1 = C_{gs1} = 145\,fF$

$C_2 = C_{db_1} + C_{sb_2} + C_{gs_2} + C_L$

$= 142\,fF$

$C_1 R_S = 145\,ps$

$C_2 R_L = 142\,fF\,(2665\,\Omega)$

$= 378\,ps$

$C_{gd_1}(R_S + R_L + g_m R_S R_L)$

$= 30(1k + 2665 + 1.69m(1k)(2665))\,f$

$= 245\,ps$

$f_{-3dB} = \frac{1}{2\pi}\,\frac{10^{12}}{145 + 378 + 245}$

$= 207\,MHz$

(b)

$R_{SX} = \frac{1}{\mathcal{E}_c\,\mu C_{ox} W}$

$m1\ R_{SX} = \frac{1}{1.5M\ \ 60\mu\ \ 100\mu}$

$= 111\,\Omega$

m2 $R_{SX} = \frac{1}{1.5M\ 60\mu\ 4\mu}$

$= 2.78\,k$

$R_L' = R_{SX2} + \frac{1}{g_{m2} + g_{mb2}}$

$= 2.78\,k + 2.66\,k$

$= 5.44\,k$

$g_{m1}' = \frac{g_{m1}}{1 + g_{m1} R_{SX1}}$

$= 1.42\,m\,A/V$

$\frac{V_o}{V_i} = -g_{m1}' R_L' = -7.74$

$C_1 R_S = 145\,ps$ unchanged

$C_2 R_L' = C_2 R_L \frac{R_L'}{R_L}$

$= 378\,ps\,(2.04)$

$= 772\,ps$

$C_{gd1}(R_S + R_L' + g_{m1}' R_L' R_S)$

$= 30f\,(1k + 5.44k + 1.42m(5.44k)(1k))$

$= 425\,ps$

$f_{-3dB} = \frac{1}{2\pi} \frac{10^{12}}{145 + 772 + 425}$

$= 119\,MHz$

```
NMOS AMP
VDD 1 0 5V
M2 1 1 2 0 NMOS2 W=4U L=1U
M1 2 3 0 0 NMOS W=100U L=1U
CLOAD 2 0 100FF
RS 4 3 1K
VI 4 0 0.981V AC
.PLOT AC VDB(2)
.PLOT AC VP(2)
.AC DEC 15 1MEG 2GIG
.MODEL NMOS NMOS KP=60U VTO=0.7 LAMBDA=0 LD=0 GAMMA=0.4
+ TOX=20NM CGSO=300PF CGDO=300PF CBD=80FF CBS=80FF
.MODEL NMOS2 NMOS KP=60U VTO=0.7 LAMBDA=0 LD=0 GAMMA=0.4
+ TOX=20NM CGSO=300PF CGDO=300PF CBD=3.2FF CBS=3.2FF
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END
 ******  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
+0:1        = 5.000E+00 0:2        = 2.500E+00 0:3        = 9.810E-01
+0:4        = 9.810E-01
**** MOSFETS
ELEMENT  0:M2       0:M1
MODEL    0:NMOS2    0:NMOS
 ID       2.369E-04  2.369E-04
 IBS     -2.501E-14   0.
 IBD     -5.000E-14 -2.501E-14
 VGS      2.499E+00  9.810E-01
 VDS      2.499E+00  2.500E+00
 VBS     -2.500E+00   0.
 VTH      1.094E+00  7.000E-01
 VDSAT    1.405E+00  2.810E-01
 BETA     2.400E-04  6.000E-03
 GAM EFF  4.000E-01  4.000E-01
 GM       3.372E-04  1.686E-03
 GMB      3.830E-05  4.353E-04
 CDTOT    2.411E-15  6.996E-14
 CGTOT    7.037E-15  1.780E-13
 CSTOT    7.380E-15  2.251E-13
 CBTOT    2.774E-15  1.217E-13
 CGS      5.804E-15  1.451E-13
 CGD      1.223E-15  3.058E-14
 ******  AC ANALYSIS                            TNOM=  27.000 TEMP=  27.000
   FREQ      VDB(2)
(A       )   -2.000E+01   -1.000E+01       0.        1.000E+01    2.000E+01
1.000E+06  1.30E+01
1.165E+06  1.30E+01
1.359E+06  1.30E+01
1.584E+06  1.30E+01
1.847E+06  1.30E+01
2.154E+06  1.30E+01
2.511E+06  1.30E+01
2.929E+06  1.30E+01
3.414E+06  1.30E+01
3.981E+06  1.30E+01
4.641E+06  1.30E+01
5.411E+06  1.30E+01
6.309E+06  1.30E+01
7.356E+06  1.30E+01
8.577E+06  1.30E+01
1.000E+07  1.30E+01
1.165E+07  1.30E+01
1.359E+07  1.30E+01
1.584E+07  1.30E+01
1.847E+07  1.30E+01
2.154E+07  1.30E+01
2.512E+07  1.30E+01
2.929E+07  1.29E+01
3.414E+07  1.29E+01
3.981E+07  1.29E+01
4.641E+07  1.28E+01
5.411E+07  1.28E+01
6.309E+07  1.27E+01
7.356E+07  1.26E+01
8.577E+07  1.25E+01
1.000E+08  1.23E+01
1.165E+08  1.20E+01
1.359E+08  1.17E+01
1.584E+08  1.14E+01
1.847E+08  1.09E+01
2.154E+08  1.03E+01
2.511E+08  9.66E+00
2.929E+08  8.86E+00
3.414E+08  7.93E+00
3.981E+08  6.90E+00
4.641E+08  5.75E+00
5.411E+08  4.50E+00
6.309E+08  3.14E+00
7.356E+08  1.67E+00
8.577E+08  9.97E-02
1.000E+09 -1.58E+00
1.165E+09 -3.38E+00
1.359E+09 -5.28E+00
1.584E+09 -7.30E+00
1.847E+09 -9.40E+00
2.154E+09 -1.15E+01
```

```
   FREQ      VP(2)
(A       )    0.        5.000E+01   1.000E+02   1.500E+02   2.000E+02
1.000E+06  1.79E+02
1.165E+06  1.79E+02
1.359E+06  1.79E+02
1.584E+06  1.79E+02
1.847E+06  1.79E+02
2.154E+06  1.79E+02
2.511E+06  1.79E+02
2.928E+06  1.79E+02
3.414E+06  1.79E+02
3.981E+06  1.78E+02
4.641E+06  1.78E+02
5.411E+06  1.78E+02
6.309E+06  1.78E+02
7.356E+06  1.77E+02
8.577E+06  1.77E+02
1.000E+07  1.77E+02
1.165E+07  1.76E+02
1.359E+07  1.76E+02
1.584E+07  1.75E+02
1.847E+07  1.74E+02
2.154E+07  1.73E+02
2.511E+07  1.72E+02
2.928E+07  1.71E+02
3.414E+07  1.70E+02
3.981E+07  1.68E+02
4.641E+07  1.66E+02
5.411E+07  1.64E+02
6.309E+07  1.62E+02
7.356E+07  1.59E+02
8.577E+07  1.55E+02
1.000E+08  1.52E+02
1.165E+08  1.48E+02
1.359E+08  1.43E+02
1.584E+08  1.38E+02
1.847E+08  1.33E+02
2.154E+08  1.27E+02
2.511E+08  1.21E+02
2.928E+08  1.14E+02
3.414E+08  1.08E+02
3.981E+08  1.01E+02
4.641E+08  9.45E+01
5.411E+08  8.76E+01
6.309E+08  8.07E+01
7.356E+08  7.36E+01
8.577E+08  6.65E+01
1.000E+09  5.93E+01
1.165E+09  5.20E+01
1.359E+09  4.48E+01
1.584E+09  3.76E+01
1.847E+09  3.05E+01
2.154E+09  2.35E+01
```

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```
******

NMOS AMP, EXAMINE SMALL SIGNAL BANDWIDTH AS DC VIN VARIES
VDD 1 0 5V
M2 1 1 2 0 NMOS2 W=4U L=1U
M1 2 3 0 0 NMOS W=100U L=1U
CLOAD 2 0 100FF
RS 4 3 1K
VI 4 0 0.5V AC
.PLOT AC VDB(2)
.PLOT AC VP(2)
.AC DEC 15 1MEG 2GIG
.MODEL NMOS NMOS KP=60U VTO=0.7 LAMBDA=0 LD=0 GAMMA=0.4
+ TOX=20NM CGSO=300PF CGDO=300PF CBD=80FF CBS=80FF
.MODEL NMOS2 NMOS KP=60U VTO=0.7 LAMBDA=0 LD=0 GAMMA=0.4
+ TOX=20NM CGSO=300PF CGDO=300PF CBD=3.2FF CBS=3.2FF
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

******  AC ANALYSIS                         TNOM=  27.000 TEMP=  27.000

    FREQ       VDB(2)
(A         )   -2.000E+01    -1.800E+01    -1.600E+01    -1.400E+01    -1.200E+01
                    +             +             +             +             +

3.981E+07 -1.50E+01 +      +      +      +      +     A+      +      +      +
4.641E+07 -1.50E+01 +      +      +      +      +     A+      +      +      +
5.411E+07 -1.50E+01 +      +      +      +      +     A+      +      +      +
6.309E+07 -1.50E+01 +      +      +      +      +     A+      +      +      +
7.356E+07 -1.50E+01 +      +      +      +      +     A+      +      +      +
8.577E+07 -1.50E+01 +      +      +      +      +     A+      +      +      +
1.000E+08 -1.51E+01-+------+------+------+------+-----A+------+------+------+-
1.165E+08 -1.51E+01 +      +      +      +      +     A+      +      +      +
1.359E+08 -1.51E+01 +      +      +      +      +     A+      +      +      +
1.584E+08 -1.51E+01 +      +      +      +      +     A+      +      +      +
1.847E+08 -1.51E+01 +      +      +      +      +     A+      +      +      +
2.154E+08 -1.51E+01 +      +      +      +      +     A+      +      +      +
2.511E+08 -1.52E+01 +      +      +      +      +     A+      +      +      +
2.928E+08 -1.52E+01 +      +      +      +      +    A +      +      +      +
3.414E+08 -1.52E+01 +      +      +      +      +    A +      +      +      +
3.981E+08 -1.53E+01 +      +      +      +      +   A  +      +      +      +
4.641E+08 -1.54E+01-+------+------+------+------+---A--+------+------+------+-
5.411E+08 -1.56E+01 +      +      +      +      + A    +      +      +      +
6.309E+08 -1.57E+01 +      +      +      +      +A     +      +      +      +
7.356E+08 -1.60E+01 +      +      +      +      A      +      +      +      +
8.577E+08 -1.62E+01 +      +      +      +    A +      +      +      +      +
1.000E+09 -1.66E+01 +      +      +      + A    +      +      +      +      +
1.165E+09 -1.71E+01 +      +      +     A+      +      +      +      +      +
```

```
*****

NMOS AMP
VDD 1 0 5V
M2 1 1 2 0 NMOS2 W=4U L=1U
M1 2 3 0 0 NMOS W=100U L=1U
CLOAD 2 0 100FF
RS 4 3 1K
VI 4 0 1.5V AC
.PLOT AC VDB(2)
.PLOT AC VP(2)
.AC DEC 15 1MEG 2GIG
.MODEL NMOS NMOS KP=60U VTO=0.7 LAMBDA=0 LD=0 GAMMA=0.4
+ TOX=20NM CGSO=300PF CGDO=300PF CBD=80FF CBS=80FF
.MODEL NMOS2 NMOS KP=60U VTO=0.7 LAMBDA=0 LD=0 GAMMA=0.4
+ TOX=20NM CGSO=300PF CGDO=300PF CBD=3.2FF CBS=3.2FF
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

******  AC ANALYSIS                         TNOM=  27.000 TEMP=  27.000

    FREQ       VDB(2)
(A         )    -1.500E+01    -1.000E+01    -5.000E+00    0.            5.000E+00
                     +             +             +             +             +

2.928E+06  2.29E-01 +      +      +      +      +      +      +A     +      +
3.414E+06  2.29E-01 +      +      +      +      +      +      +A     +      +
3.981E+06  2.29E-01 +      +      +      +      +      +      +A     +      +
4.641E+06  2.28E-01-+------+------+------+------+------+------+A-----+------+-
5.411E+06  2.28E-01 +      +      +      +      +      +      +A     +      +
6.309E+06  2.28E-01 +      +      +      +      +      +      +A     +      +
7.356E+06  2.28E-01 +      +      +      +      +      +      +A     +      +
8.577E+06  2.27E-01 +      +      +      +      +      +      +A     +      +
1.000E+07  2.27E-01 +      +      +      +      +      +      +A     +      +
1.165E+07  2.26E-01 +      +      +      +      +      +      +A     +      +
1.359E+07  2.25E-01 +      +      +      +      +      +      +A     +      +
1.584E+07  2.24E-01 +      +      +      +      +      +      +A     +      +
1.847E+07  2.22E-01 +      +      +      +      +      +      +A     +      +
2.154E+07  2.19E-01-+------+------+------+------+------+------+A-----+------+-
2.511E+07  2.16E-01 +      +      +      +      +      +      +A     +      +
2.928E+07  2.11E-01 +      +      +      +      +      +      +A     +      +
3.414E+07  2.04E-01 +      +      +      +      +      +      +A     +      +
3.981E+07  1.96E-01 +      +      +      +      +      +      +A     +      +
4.641E+07  1.84E-01 +      +      +      +      +      +      +A     +      +
5.411E+07  1.68E-01 +      +      +      +      +      +      A      +      +
6.309E+07  1.46E-01 +      +      +      +      +      +      A      +      +
7.356E+07  1.16E-01 +      +      +      +      +      +      A      +      +
8.577E+07  7.64E-02 +      +      +      +      +      +      A      +      +
1.000E+08  2.29E-02-+------+------+------+------+------+------A------+------+-
1.165E+08 -4.89E-02 +      +      +      +      +      +      A      +      +
1.359E+08 -1.45E-01 +      +      +      +      +      +      A      +      +
1.584E+08 -2.72E-01 +      +      +      +      +      +     A+      +      +
1.847E+08 -4.39E-01 +      +      +      +      +      +     A+      +      +
2.154E+08 -6.56E-01 +      +      +      +      +      +    A +      +      +
2.511E+08 -9.36E-01 +      +      +      +      +      +   A  +      +      +
2.928E+08 -1.29E+00 +      +      +      +      +      +  A   +      +      +
3.414E+08 -1.73E+00 +      +      +      +      +      + A    +      +      +
3.981E+08 -2.26E+00 +      +      +      +      +      +A     +      +      +
4.641E+08 -2.91E+00-+------+------+------+------+-----A+------+------+------+-
```

7-46

```
*****

NMOS AMP
VDD 1 0 5V
M2 1 1 2 0 NMOS2 W=4U L=1U
M1 2 3 0 0 NMOS W=100U L=1U
CLOAD 2 0 100FF
RS 4 3 1K
VI 4 0 2V AC
.PLOT AC VDB(2)
.PLOT AC VP(2)
.AC DEC 15 1MEG 2GIG
.MODEL NMOS NMOS KP=60U VTO=0.7 LAMBDA=0 LD=0 GAMMA=0.4
+ TOX=20NM CGSO=300PF CGDO=300PF CBD=80FF CBS=80FF
.MODEL NMOS2 NMOS KP=60U VTO=0.7 LAMBDA=0 LD=0 GAMMA=0.4
+ TOX=20NM CGSO=300PF CGDO=300PF CBD=3.2FF CBS=3.2FF
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

******  AC ANALYSIS                                TNOM=  27.000 TEMP=  27.000

      FREQ      VDB(2)
(A         )   -2.500E+01      -2.000E+01      -1.500E+01      -1.000E+01      -5.000E+00
                    +               +               +               +               +
2.511E+07 -1.31E+01 +       +       +       +       +     A +       +       +       +
2.928E+07 -1.31E+01 +       +       +       +       +     A +       +       +       +
3.414E+07 -1.31E+01 +       +       +       +       +     A +       +       +       +
3.981E+07 -1.31E+01 +       +       +       +       +     A +       +       +       +
4.641E+07 -1.31E+01 +       +       +       +       +     A +       +       +       +
5.411E+07 -1.31E+01 +       +       +       +       +     A +       +       +       +
6.309E+07 -1.31E+01 +       +       +       +       +     A +       +       +       +
7.356E+07 -1.31E+01 +       +       +       +       +     A +       +       +       +
8.577E+07 -1.32E+01 +       +       +       +       +     A +       +       +       +
1.000E+08 -1.32E+01-+-------+-------+-------+-------+-----A-+-------+-------+-------+-
1.165E+08 -1.32E+01 +       +       +       +       +     A +       +       +       +
1.359E+08 -1.33E+01 +       +       +       +       +     A +       +       +       +
1.584E+08 -1.34E+01 +       +       +       +       +    A  +       +       +       +
1.847E+08 -1.34E+01 +       +       +       +       +    A  +       +       +       +
2.154E+08 -1.36E+01 +       +       +       +       +    A  +       +       +       +
2.511E+08 -1.37E+01 +       +       +       +       +   A   +       +       +       +
2.928E+08 -1.40E+01 +       +       +       +       +   A   +       +       +       +
3.414E+08 -1.42E+01 +       +       +       +       +  A    +       +       +       +
3.981E+08 -1.46E+01 +       +       +       +       +A      +       +       +       +
4.641E+08 -1.50E+01-+-------+-------+-------+-------A-------+-------+-------+-------+-
5.411E+08 -1.55E+01 +       +       +       +     A +       +       +       +       +
6.309E+08 -1.61E+01 +       +       +       +    A  +       +       +       +       +
7.356E+08 -1.68E+01 +       +       +       +  A    +       +       +       +       +
```

```
*****

NMOS AMP
VDD 1 0 5V
M2 1 1 2 0 NMOS2 W=4U L=1U
M1 2 3 0 0 NMOS W=100U L=1U
CLOAD 2 0 100FF
RS 4 3 1K
VI 4 0 3V AC
.PLOT AC VDB(2)
.PLOT AC VP(2)
.AC DEC 15 1MEG 2GIG
.MODEL NMOS NMOS KP=60U VTO=0.7 LAMBDA=0 LD=0 GAMMA=0.4
+ TOX=20NM CGSO=300PF CGDO=300PF CBD=80FF CBS=80FF
.MODEL NMOS2 NMOS KP=60U VTO=0.7 LAMBDA=0 LD=0 GAMMA=0.4
+ TOX=20NM CGSO=300PF CGDO=300PF CBD=3.2FF CBS=3.2FF
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

******  AC ANALYSIS                                TNOM=  27.000 TEMP=  27.000

      FREQ      VDB(2)
(A         )   -3.000E+01      -2.800E+01      -2.600E+01      -2.400E+01      -2.200E+01
                    +               +               +               +               +
4.641E+07 -2.38E+01 +       +       +       +       +       +       +A      +       +
5.411E+07 -2.38E+01 +       +       +       +       +       +       +A      +       +
6.309E+07 -2.38E+01 +       +       +       +       +       +       +A      +       +
7.356E+07 -2.38E+01 +       +       +       +       +       +       +A      +       +
8.577E+07 -2.38E+01 +       +       +       +       +       +       +A      +       +
1.000E+08 -2.38E+01-+-------+-------+-------+-------+-------+-------+A------+-------+-
1.165E+08 -2.38E+01 +       +       +       +       +       +       +A      +       +
1.359E+08 -2.39E+01 +       +       +       +       +       +       +A      +       +
1.584E+08 -2.39E+01 +       +       +       +       +       +       A       +       +
1.847E+08 -2.40E+01 +       +       +       +       +       +       A       +       +
2.154E+08 -2.41E+01 +       +       +       +       +       +      A+       +       +
2.511E+08 -2.42E+01 +       +       +       +       +       +     A +       +       +
2.928E+08 -2.43E+01 +       +       +       +       +       +    A  +       +       +
3.414E+08 -2.45E+01 +       +       +       +       +       +  A    +       +       +
3.981E+08 -2.47E+01 +       +       +       +       +       + A     +       +       +
4.641E+08 -2.50E+01-+-------+-------+-------+-------+-------A-------+-------+-------+-
5.411E+08 -2.53E+01 +       +       +       +       +    A  +       +       +       +
6.309E+08 -2.57E+01 +       +       +       +       + A     +       +       +       +
7.356E+08 -2.61E+01 +       +       +       +      A+       +       +       +       +
8.577E+08 -2.65E+01 +       +       +       +  A    +       +       +       +       +
1.000E+09 -2.70E+01 +       +       +       A       +       +       +       +       +
```

```
*****

NMOS AMP
VDD 1 0 5V
M2 1 1 2 0 NMOS2 W=4U L=1U
M1 2 3 0 0 NMOS W=100U L=1U
CLOAD 2 0 100FF
RS 4 3 1K
VI 4 0 4V AC
.PLOT AC VDB(2)
.PLOT AC VP(2)
.AC DEC 15 1MEG 2GIG
.MODEL NMOS NMOS KP=60U VTO=0.7 LAMBDA=0 LD=0 GAMMA=0.4
+ TOX=20NM CGSO=300PF CGDO=300PF CBD=80FF CBS=80FF
.MODEL NMOS2 NMOS KP=60U VTO=0.7 LAMBDA=0 LD=0 GAMMA=0.4
+ TOX=20NM CGSO=300PF CGDO=300PF CBD=3.2FF CBS=3.2FF
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

******  AC ANALYSIS                          TNOM=  27.000 TEMP=  27.000

    FREQ       VDB(2)
(A        )    -3.800E+01    -3.600E+01    -3.400E+01    -3.200E+01    -3.000E+01
                     +             +             +             +             +
4.641E+07 -3.00E+01  +      +      +      +      +      +      +      +      A
5.411E+07 -3.00E+01  +      +      +      +      +      +      +      +      A
6.309E+07 -3.00E+01  +      +      +      +      +      +      +      +      A
7.356E+07 -3.00E+01  +      +      +      +      +      +      +      +      A
8.577E+07 -3.00E+01  +      +      +      +      +      +      +      +     A+
1.000E+08 -3.00E+01 -+------+------+------+------+------+------+------+-----A+-
1.165E+08 -3.01E+01  +      +      +      +      +      +      +      +     A+
1.359E+08 -3.01E+01  +      +      +      +      +      +      +      +     A+
1.584E+08 -3.01E+01  +      +      +      +      +      +      +      +     A+
1.847E+08 -3.01E+01  +      +      +      +      +      +      +      +     A+
2.154E+08 -3.02E+01  +      +      +      +      +      +      +      +    A +
2.511E+08 -3.02E+01  +      +      +      +      +      +      +      +    A +
2.928E+08 -3.03E+01  +      +      +      +      +      +      +      +   A  +
3.414E+08 -3.04E+01  +      +      +      +      +      +      +      +   A  +
3.981E+08 -3.05E+01  +      +      +      +      +      +      +      +  A   +
4.641E+08 -3.07E+01 -+------+------+------+------+------+------+------+-A----+-
5.411E+08 -3.08E+01  +      +      +      +      +      +      +      +A     +
6.309E+08 -3.10E+01  +      +      +      +      +      +      +      A      +
7.356E+08 -3.12E+01  +      +      +      +      +      +      +    A +      +
8.577E+08 -3.14E+01  +      +      +      +      +      +      +   A  +      +
1.000E+09 -3.16E+01  +      +      +      +      +      +      +  A   +      +
1.165E+09 -3.18E+01  +      +      +      +      +      +      +A     +      +
1.359E+09 -3.19E+01  +      +      +      +      +      +      A      +      +
1.584E+09 -3.21E+01  +      +      +      +      +      +     A+      +      +
1.847E+09 -3.22E+01  +      +      +      +      +      +    A +      +      +
2.154E+09 -3.23E+01 -+------+------+------+------+------+---A--+------+------+-
2.511E+09 -3.24E+01  +      +      +      +      +      +   A  +      +      +
2.928E+09 -3.25E+01  +      +      +      +      +      +  A   +      +      +
3.414E+09 -3.26E+01  +      +      +      +      +      + A    +      +      +
3.981E+09 -3.28E+01  +      +      +      +      +      +A     +      +      +
4.641E+09 -3.29E+01  +      +      +      +      +      A      +      +      +
5.411E+09 -3.31E+01  +      +      +      +      +     A+      +      +      +
6.309E+09 -3.33E+01  +      +      +      +      +    A +      +      +      +
7.356E+09 -3.36E+01  +      +      +      +      +  A   +      +      +      +
```

```
*****

NMOS AMP
VDD 1 0 5V
M2 1 1 2 0 NMOS2 W=4U L=1U
M1 2 3 0 0 NMOS W=100U L=1U
CLOAD 2 0 100FF
RS 4 3 1K
VI 4 0 5V AC
.PLOT AC VDB(2)
.PLOT AC VP(2)
.AC DEC 15 1MEG 2GIG
.MODEL NMOS NMOS KP=60U VTO=0.7 LAMBDA=0 LD=0 GAMMA=0.4
+ TOX=20NM CGSO=300PF CGDO=300PF CBD=80FF CBS=80FF
.MODEL NMOS2 NMOS KP=60U VTO=0.7 LAMBDA=0 LD=0 GAMMA=0.4
+ TOX=20NM CGSO=300PF CGDO=300PF CBD=3.2FF CBS=3.2FF
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

******  AC ANALYSIS                          TNOM=  27.000 TEMP=  27.000

    FREQ       VDB(2)
(A        )    -6.000E+01    -5.000E+01    -4.000E+01    -3.000E+01    -2.000E+01
                     +             +             +             +             +
3.414E+08 -3.46E+01  +      +      +      +      +      +A     +      +      +
3.981E+08 -3.46E+01  +      +      +      +      +      +A     +      +      +
4.641E+08 -3.46E+01 -+------+------+------+------+------+A-----+------+------+-
5.411E+08 -3.46E+01  +      +      +      +      +      +A     +      +      +
6.309E+08 -3.46E+01  +      +      +      +      +      A      +      +      +
7.356E+08 -3.46E+01  +      +      +      +      +      A      +      +      +
8.577E+08 -3.46E+01  +      +      +      +      +      A      +      +      +
1.000E+09 -3.46E+01  +      +      +      +      +      A      +      +      +
1.165E+09 -3.47E+01  +      +      +      +      +      A      +      +      +
1.359E+09 -3.47E+01  +      +      +      +      +      A      +      +      +
1.584E+09 -3.47E+01  +      +      +      +      +      A      +      +      +
1.847E+09 -3.47E+01  +      +      +      +      +      A      +      +      +
2.154E+09 -3.47E+01 -+------+------+------+------+------A------+------+------+-
2.511E+09 -3.47E+01  +      +      +      +      +      A      +      +      +
2.928E+09 -3.48E+01  +      +      +      +      +      A      +      +      +
3.414E+09 -3.48E+01  +      +      +      +      +      A      +      +      +
3.981E+09 -3.49E+01  +      +      +      +      +      A      +      +      +
4.641E+09 -3.50E+01  +      +      +      +      +      A      +      +      +
5.411E+09 -3.51E+01  +      +      +      +      +      A      +      +      +
6.309E+09 -3.52E+01  +      +      +      +      +      A      +      +      +
7.356E+09 -3.54E+01  +      +      +      +      +     A+      +      +      +
8.577E+09 -3.56E+01  +      +      +      +      +     A+      +      +      +
1.000E+10 -3.59E+01 -+------+------+------+------+-----A+------+------+------+-
1.165E+10 -3.62E+01  +      +      +      +      +    A +      +      +      +
1.359E+10 -3.67E+01  +      +      +      +      +    A +      +      +      +
1.584E+10 -3.72E+01  +      +      +      +      +   A  +      +      +      +
1.847E+10 -3.79E+01  +      +      +      +      +  A   +      +      +      +
2.154E+10 -3.86E+01  +      +      +      +      + A    +      +      +      +
2.511E+10 -3.95E+01  +      +      +      +      +A     +      +      +      +
```

7.38

$m_3, m_4 \quad I_D = \frac{\mu C_{ox}}{2}\frac{W}{L}(V_{GS}-V_t)^2$

$100\mu = 15\mu\, 50\,(V_{GS}-V_t)^2$

$V_{GS} = -1.065\text{ V}$

m_2, m_6, m_7

$100\mu = 30\mu\, 50\,(V_{GS}-V_t)^2$

$V_{GS} = 0.958\text{V}$

$V_{GS_5} = 5 - 1.065 - 0.958$

$= 2.977\text{ V}$

$100\mu = 15\mu \frac{W}{L}(2.977-0.7)^2$

$m_5 \ \frac{W}{L} = 1.286 = \frac{2.57\mu}{2\mu}$

$2.5 = V_{GS_1} + V_{GS_2}$

$2.5 - 0.958 = 1.542\text{ V} = V_{GS_1}$

$V_{t_1} = V_{t_0} + \gamma\left(\sqrt{2\phi_f + V_{SB}} - \sqrt{2\phi_f}\right)$

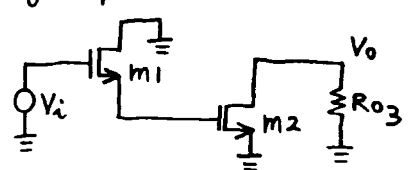
$= 0.7 + 0.4\left(\sqrt{0.6+0.958} - \sqrt{0.6}\right)$

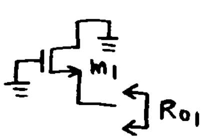
$= 0.89$

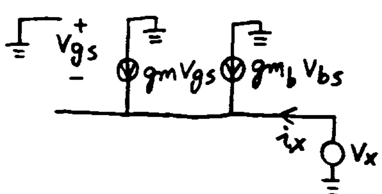
$I_{D_1} = 100\mu = 30\mu\left(\frac{W}{L}\right)_1(1.542-0.89)^2$

$\left(\frac{W}{L}\right)_1 = 7.83 = \frac{15.7\mu}{2\mu}$

signal path







$V_{gs} = -V_x = V_{bs}$

$i_x = g_m V_x + g_{mb} V_x$

$R_{o1} = \frac{V_x}{i_x} = \frac{1}{g_m + g_{mb}}$

$r_{o2} = r_{o3} = \frac{1}{0.03\,(100\mu)} = 333\text{k}$

$R_{o3} = r_{o2} \| r_{o3} = 167\text{k}$

$g_{m1} = \sqrt{2 I_D \mu C_{ox} \frac{W}{L}}$

$= \sqrt{200\mu\ 60\mu\ 7.83}$

$= 307\ \mu A/V$

$g_{mb1} = g_{m1}\frac{\gamma}{2\sqrt{2\phi_f + V_{SB}}}$

$= 307\mu \frac{0.4}{2\sqrt{0.6+0.958}}$

$= 49.2\ \mu A/V$

$R_{o1} = 2811\ \Omega$

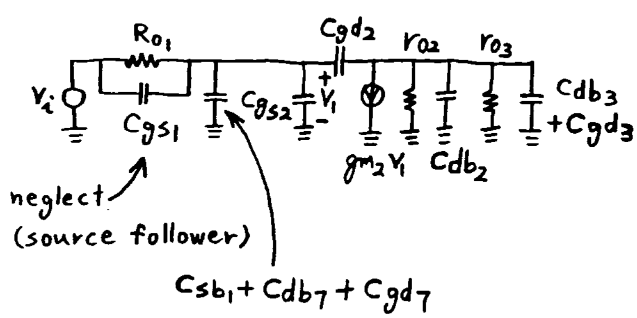
$g_{m2} = \sqrt{200\mu\ 60\mu\ 50}$

$= 775\ \mu A/V$

gain

$\frac{V_o}{V_i} = -g_{m1} R_{o1}\, g_{m2} R_{o3}$

$= -112$



$$C_{sb_1} = \frac{C_{sbo}}{\sqrt{1+\frac{V_{SB}}{\psi_0}}}$$

$$= \frac{0.8\,f(7.83)}{\sqrt{1+\frac{0.958}{0.6}}} = 3.89\,fF$$

$$C_{db_7} = \frac{0.8\,f(100)}{\sqrt{1+\frac{0.958}{0.6}}} = 49.6\,fF$$

$$C_{gd_7} = 0.3\,(100\mu) = 30\,fF = C_{gd_2}$$

$$C_{gs_2} = \tfrac{2}{3} WL\, C_{ox} + 30\,fF$$

$$= 231 + 30$$
$$= 261\ fF$$

$$C_{db_2} = \frac{C_{sbo}}{\sqrt{1+\frac{V_{SB}}{\psi_0}}}$$

$$= \frac{0.8\,f\ (100)}{\sqrt{1+\frac{2.5}{0.6}}}$$

$$= 35.2\,fF = C_{db_3}$$

$$R_{o_1}(C_{sb_1} + C_{db_7} + C_{gd_7} + C_{gs_2})$$
$$= 2811(3.89 + 49.6 + 30 + 261)\,f$$
$$= 0.968\,ns$$

$$(r_{o_2} \| r_{o_3})(C_{db_2} + C_{db_3} + C_{gd_3})$$
$$= 167k\ (35.2 + 35.2 + 30)\,f$$
$$= 16.8\ ns$$

$$C_{gd_2}(R_{o_1} + R_{o_3} + g_{m_2} R_{o_1} R_{o_3})$$
$$= 30f(2811 + 167k + 775\mu\ 167k\ 2811)$$
$$= 16\ ns$$

$$f_{-3dB} = \frac{1}{2\pi}\,\frac{10^9}{0.968 + 16.8 + 16} = 4.71\ MHz$$

7-50

```
CMOS AMP
VDD 1 0 5V
M1 2 8 6 0 NMOS1 W=15.7U L=2U
M2 7 6 0 0 NMOS W=100U L=2U
M3 7 2 1 1 PMOS W=100U L=2U
M4 2 2 1 1 PMOS W=100U L=2U
M5 5 5 2 2 PMOS5 W=2.57U L=2U
M6 5 5 0 0 NMOS W=100U L=2U
M7 6 5 0 0 NMOS W=100U L=2U
VI 8 0 2.5746V AC
.PLOT AC VDB(7)
.AC DEC 20 100K 100MEG
.MODEL NMOS NMOS KP=60U VTO=0.7 LAMBDA=0.03 LD=0 GAMMA=0.4
+ TOX=20NM CGSO=300PF CGDO=300PF CBD=80FF CBS=80FF
.MODEL NMOS1 NMOS KP=60U VTO=0.7 LAMBDA=0.03 LD=0 GAMMA=0.4
+ TOX=20NM CGSO=300PF CGDO=300PF CBD=12.6FF CBS=12.6FF
.MODEL PMOS PMOS KP=30U VTO=-0.7 LAMBDA=0.03 LD=0 GAMMA=0.4
+ TOX=20NM CGSO=300PF CGDO=300PF CBD=80FF CBS=80FF
.MODEL PMOS5 PMOS KP=30U VTO=-0.7 LAMBDA=0.03 LD=0 GAMMA=0.4
+ TOX=20NM CGSO=300PF CGDO=300PF CBD=2.06FF CBS=2.06FF
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END
```

```
 ******  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000

+0:1       = 5.000E+00 0:2       = 3.800E+00 0:5       = 9.504E-01
+0:6       = 1.053E+00 0:7       = 2.493E+00 0:8       = 2.574E+00
```

**** MOSFETS

ELEMENT	0:M1	0:M2	0:M3	0:M4	0:M5	0:M6
MODEL	0:NMOS1	0:NMOS	0:PMOS	0:PMOS	0:PMOS5	0:NMOS
ID	9.703E-05	2.011E-04	-2.011E-04	-1.938E-04	-9.674E-05	9.674E-05
IBS	-1.053E-14	0.	0.	0.	0.	0.
IBD	-3.801E-14	-2.493E-14	2.507E-14	1.199E-14	2.850E-14	-9.504E-15
VGS	1.521E+00	1.053E+00	-1.199E+00	-1.199E+00	-2.850E+00	9.504E-01
VDS	2.747E+00	2.493E+00	-2.507E+00	-1.199E+00	-2.850E+00	9.504E-01
VBS	-1.053E+00	0.	0.	0.	0.	0.
VTH	9.045E-01	7.000E-01	-7.000E-01	-7.000E-01	-7.000E-01	7.000E-01
VDSAT	6.170E-01	3.532E-01	-4.994E-01	-4.994E-01	-2.150E+00	2.504E-01
BETA	5.098E-04	3.224E-03	1.613E-03	1.554E-03	4.185E-05	3.086E-03
GAM EFF	4.000E-01	4.000E-01	4.000E-01	4.000E-01	4.000E-01	4.000E-01
GM	3.145E-04	1.139E-03	8.054E-04	7.760E-04	8.998E-05	7.726E-04
GDS	2.689E-06	5.613E-06	5.611E-06	5.611E-06	2.673E-06	2.822E-06
GMB	4.893E-05	2.940E-04	2.080E-04	2.004E-04	2.323E-05	1.995E-04
CDTOT	1.016E-14	7.058E-14	7.050E-14	8.116E-14	1.769E-15	8.452E-14
CGTOT	4.599E-14	2.952E-13	2.941E-13	2.935E-13	7.509E-15	2.959E-13
CSTOT	4.913E-14	3.402E-13	3.402E-13	3.402E-13	8.747E-15	3.402E-13
CBTOT	1.376E-14	1.232E-13	1.221E-13	1.333E-13	3.041E-15	1.393E-13
CGS	4.085E-14	2.602E-13	2.602E-13	2.602E-13	6.687E-15	2.602E-13
CGD	4.909E-15	3.115E-14	3.115E-14	3.055E-14	8.047E-16	3.044E-14

ELEMENT	0:M7
MODEL	0:NMOS
ID	9.703E-05
IBS	0.
IBD	-1.053E-14
VGS	9.504E-01
VDS	1.053E+00
VBS	0.
VTH	7.000E-01
VDSAT	2.504E-01
BETA	3.095E-03
GAM EFF	4.000E-01
GM	7.750E-04
GDS	2.822E-06
GMB	2.001E-04
CDTOT	8.305E-14
CGTOT	2.959E-13
CSTOT	3.402E-13
CBTOT	1.378E-13
CGS	2.602E-13
CGD	3.048E-14

```
******  AC ANALYSIS                                TNOM=  27.000 TEMP=  27.000

     FREQ      VDB(7)
(A        )    1.000E+01     2.000E+01     3.000E+01     4.000E+01     5.000E+01
                   +             +             +             +             +
1.000E+05 3.87E+01-+------+------+------+------+------+----A-+------+------+-
1.122E+05 3.87E+01 +      +      +      +      +      +    A +      +      +
1.258E+05 3.87E+01 +      +      +      +      +      +    A +      +      +
1.412E+05 3.87E+01 +      +      +      +      +      +    A +      +      +
1.584E+05 3.87E+01 +      +      +      +      +      +    A +      +      +
1.778E+05 3.87E+01 +      +      +      +      +      +    A +      +      +
1.995E+05 3.87E+01 +      +      +      +      +      +    A +      +      +
2.238E+05 3.87E+01 +      +      +      +      +      +    A +      +      +
2.511E+05 3.87E+01 +      +      +      +      +      +    A +      +      +
2.818E+05 3.87E+01 +      +      +      +      +      +    A +      +      +
3.162E+05 3.87E+01-+------+------+------+------+------+----A-+------+------+-
3.548E+05 3.87E+01 +      +      +      +      +      +    A +      +      +
3.981E+05 3.87E+01 +      +      +      +      +      +    A +      +      +
4.466E+05 3.87E+01 +      +      +      +      +      +    A +      +      +
5.011E+05 3.87E+01 +      +      +      +      +      +    A +      +      +
5.623E+05 3.86E+01 +      +      +      +      +      +    A +      +      +
6.309E+05 3.86E+01 +      +      +      +      +      +    A +      +      +
7.079E+05 3.86E+01 +      +      +      +      +      +    A +      +      +
7.943E+05 3.86E+01 +      +      +      +      +      +    A +      +      +
8.912E+05 3.86E+01 +      +      +      +      +      +    A +      +      +
9.999E+05 3.86E+01-+------+------+------+------+------+----A-+------+------+-
1.122E+06 3.85E+01 +      +      +      +      +      +    A +      +      +
1.258E+06 3.85E+01 +      +      +      +      +      +    A +      +      +
1.412E+06 3.85E+01 +      +      +      +      +      +    A +      +      +
1.584E+06 3.84E+01 +      +      +      +      +      +    A +      +      +
1.778E+06 3.84E+01 +      +      +      +      +      +    A +      +      +
1.995E+06 3.83E+01 +      +      +      +      +      +    A +      +      +
2.238E+06 3.82E+01 +      +      +      +      +      +    A +      +      +
2.511E+06 3.81E+01 +      +      +      +      +      +   A  +      +      +
2.818E+06 3.79E+01 +      +      +      +      +      +   A  +      +      +
3.162E+06 3.77E+01-+------+------+------+------+------+---A--+------+------+-
3.548E+06 3.75E+01 +      +      +      +      +      +   A  +      +      +
3.981E+06 3.73E+01 +      +      +      +      +      +  A   +      +      +
4.466E+06 3.70E+01 +      +      +      +      +      +  A   +      +      +
5.011E+06 3.66E+01 +      +      +      +      +      + A    +      +      +
5.623E+06 3.62E+01 +      +      +      +      +      + A    +      +      +
6.309E+06 3.57E+01 +      +      +      +      +      +A     +      +      +
7.079E+06 3.52E+01 +      +      +      +      +      A      +      +      +
7.943E+06 3.46E+01 +      +      +      +      +      A      +      +      +
8.912E+06 3.40E+01 +      +      +      +      +     A+      +      +      +
9.999E+06 3.33E+01-+------+---- -+------+------+----A-+------+------+------+-
1.122E+07 3.26E+01 +      +      +      +      +   A  +      +      +      +
1.258E+07 3.18E+01 +      +      +      +      + A    +      +      +      +
1.412E+07 3.10E+01 +      +      +      +      +A     +      +      +      +
1.584E+07 3.01E+01 +      +      +      +      A      +      +      +      +
1.778E+07 2.92E+01 +      +      +      +     A+      +      +      +      +
1.995E+07 2.83E+01 +      +      +      +    A +      +      +      +      +
2.238E+07 2.74E+01 +      +      +      +  A   +      +      +      +      +
2.511E+07 2.64E+01 +      +      +      + A    +      +      +      +      +
2.818E+07 2.55E+01 +      +      +      +A     +      +      +      +      +
3.162E+07 2.45E+01-+------+---- -+-----A+------+------+------+------+------+-
3.548E+07 2.35E+01 +      +      +    A +      +      +      +      +      +
3.981E+07 2.24E+01 +      +      +  A   +      +      +      +      +      +
4.466E+07 2.14E+01 +      +      + A    +      +      +      +      +      +
5.011E+07 2.03E+01 +      +      +A     +      +      +      +      +      +
5.623E+07 1.93E+01 +      +     A+      +      +      +      +      +      +
6.309E+07 1.82E+01 +      +   A  +      +      +      +      +      +      +
7.079E+07 1.70E+01 +      +  A   +      +      +      +      +      +      +
7.943E+07 1.58E+01 +      +A     +      +      +      +      +      +      +
8.912E+07 1.46E+01 +      A      +      +      +      +      +      +      +
9.999E+07 1.34E+01-+----A-+---- -+------+------+------+------+------+------+-
                   +             +             +             +             +
```

7.39

$I_{C1} = 261\,\mu A$

$V_{C1} = 5 - 2.61 = 2.39$

$V_{B1} = V_{GS2} + V_{BE2}$

$= 1.47 + 0.8 = 2.27$

$V_{BC1} \simeq 0$

$\therefore C_{\mu 1} = 5\,fF$

$C_{\pi 1} = C_{je} + \tau_F g_m$

$= 2(5f) + 10p\,\frac{0.261m}{V_T}$

$= 110\,fF$

$C_{cs1} = \frac{20f}{\left(1 + \frac{2.39}{0.6}\right)^{0.33}}$

$= 11.8\,fF$

$I_{C3} = 1.59\,mA$

$C_{\pi 3} = 10f + 10p\,\frac{1.59}{26}$

$= 622\,fF$

$V_{CB3} = 2.61\,V$

$C_{\mu 3} = \frac{5f}{\left(1 + \frac{2.61}{0.6}\right)^{0.33}}$

$= 2.87\,fF$

$R_{\pi o3} = r_{\pi 3} \,||\, \frac{R_S + r_{b3} + R_{E3}}{1 + g_{m3} R_{E3}}$

$r_{\pi 3} = \frac{\beta}{g_m} = 1.96\,k$

$R_S = R_{L2} = 10k$

$r_{b3} = 400$

$R_{E3} = 1k \,||\, 30k = 968$

$R_{\pi o3} = 1.96\,k \,||\, 189$

$= 172\,\Omega$

$R_{\pi o3} C_{\pi 3} = 172\,(622f) = 107\,ps$

@ Q_1 collector

$C_1 = C_{\mu 1} + C_{\mu 3} + C_{cs1}$

$= 5 + 2.87 + 11.8$

$= 19.7\,fF$

$R_1 = R_{L2} \,||\, R_{i3}$

$= 10k \,||\, r_{\pi 3}(1 + g_{m3} R_{E3})$

$= 10k \,||\, 118\,k$

$= 9.22\,k$

$R_1 C_1 = 182\,ps$

dominant pole

$|P_1| = \frac{1}{182p + 107p} = 3.46\,G\,rad/s$

$\hookrightarrow$ 551 MHz

@ m1 drain

$C_2 = C_{db1} + C_{gd1} + C_{\pi 1}$

$= 200 + 90 + 110$

$= 400\,fF$

$R_2 = R_{L1} \,||\, \left(\frac{1}{g_{m1}} + \frac{R_{S1}}{\beta} + r_{e1}\right)$

$g_{m Q2} = \frac{273\mu}{26\,m} = 10.5\,mA/V$

$g_{m\,m2} = \sqrt{2(273\mu)(40\mu)(30)}$

$= 809\,\mu A/V$

$R_{S1} = 10k \,||\, \left(\frac{1}{g_{m Q2}} + \frac{1}{g_{m\,m2}}\right)$

$= 1.17\,k$

$R_2 = 1k \,||\, \left(99.6 + \frac{1.17k}{120} + 40\right)$

$= 130$

second pole $|P_2| = \frac{1}{R_2 C_2} = 19.2\,G\,rad/s$

$\rightarrow$ 3.06 GHz

7-52

```
BICMOS AMP
VCC 1 0 5V
RL1 1 4 1K
M1 4 2 0 0 NMOS W=300U L=1U
VI 2 0 1.59V AC
.TF V(7) VI
RF 2 7 30K
RE 7 0 1K
RL2 1 3 10K
RBIAS 1 5 10K
Q1 3 5 4 NPN
Q2 5 5 6 NPN
Q3 1 3 7 NPN
M2 6 6 0 0 NMOS2 W=30U L=1U
.MODEL NMOS NMOS KP=40U VTO=0.8 LAMBDA=0 LD=0 GAMMA=0
+ TOX=34.5NM CBD=340FF CBS=200FF CGSO=300PF CGDO=300PF
.MODEL NMOS2 NMOS KP=40U VTO=0.8 LAMBDA=0 LD=0 GAMMA=0
+ TOX=34.5NM CBD=34FF CBS=20FF CGSO=300PF CGDO=300PF
.MODEL NPN NPN IS=6E-18 BF=120 RB=400 VAF=35V
+ CJE=5FF CJC=5FF CJS=20FF TF=10PS
+ MJE=0.4 MJC=0.33 MJS=0.33 RE=40
+ VJE=0.8 VJC=0.6 VJS=0.6 RC=100
.AC DEC 20 10MEG 10GIG
.PLOT AC VP(7)
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END
```

****** OPERATING POINT INFORMATION   TNOM= 27.000 TEMP= 27.000

+0:1	= 5.000E+00	0:2	= 1.590E+00	0:3	= 2.669E+00
+0:4	= 1.476E+00	0:5	= 2.293E+00	0:6	= 1.469E+00
+0:7	= 1.734E+00				

**** BIPOLAR JUNCTION TRANSISTORS

ELEMENT	0:Q1	0:Q2	0:Q3
MODEL	0:NPN	0:NPN	0:NPN
IB	1.811E-06	2.223E-06	1.355E-05
IC	2.195E-04	2.666E-04	1.726E-03
VBE	8.171E-01	8.244E-01	9.346E-01
VCE	1.192E+00	8.244E-01	3.265E+00
VBC	-3.757E-01	0.	-2.330E+00
VS	-2.647E+00	-2.267E+00	-4.827E+00
POWER	2.633E-04	2.216E-04	5.649E-03
BETAD	1.212E+02	1.199E+02	1.274E+02
GM	8.480E-03	1.030E-02	6.670E-02
RPI	1.428E+04	1.163E+04	1.909E+03
RX	4.000E+02	4.000E+02	4.000E+02
RO	1.610E+05	1.311E+05	2.152E+04
CPI	9.415E-14	1.124E-13	6.771E-13
CMU	4.290E-15	5.073E-15	3.021E-15
CBX	0.	0.	0.
CCS	1.146E-14	1.194E-14	9.670E-15
BETAAC	1.211E+02	1.198E+02	1.273E+02
FT	1.371E+10	1.395E+10	1.560E+10

**** MOSFETS

ELEMENT	0:M1	0:M2
MODEL	0:NMOS	0:NMOS2
ID	3.745E-03	2.688E-04
IBS	0.	0.
IBD	-1.477E-14	-1.469E-14
VGS	1.590E+00	1.469E+00
VDS	1.476E+00	1.469E+00
VBS	0.	0.
VTH	8.000E-01	8.000E-01
VDSAT	7.900E-01	6.693E-01
BETA	1.200E-02	1.200E-03
GAM EFF	0.	0.
GM	9.480E-03	8.032E-04
GDS	0.	0.
GMB	0.	0.
CDTOT	2.921E-13	2.925E-14
CGTOT	3.863E-13	3.875E-14
CSTOT	4.902E-13	4.902E-14
CBTOT	4.071E-13	4.086E-14
CGS	2.902E-13	2.902E-14
CGD	9.059E-14	9.059E-15

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(7)/VI		= -6.966E+01
INPUT RESISTANCE AT	VI	= 4.245E+02
OUTPUT RESISTANCE AT V(7)		= 1.187E+02

****** AC ANALYSIS   TNOM= 27.000 TEMP= 27.000

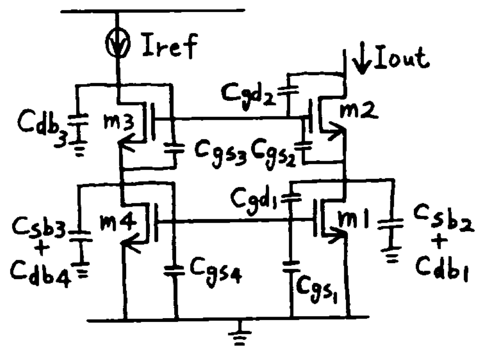
Plot scale: -1.000E+02, 0., 1.000E+02, 2.000E+02, 3.000E+02

FREQ	VP(7)
1.000E+07	1.78E+02
1.122E+07	1.78E+02
1.258E+07	1.78E+02
1.412E+07	1.77E+02
1.584E+07	1.77E+02
1.778E+07	1.77E+02
1.995E+07	1.77E+02
2.238E+07	1.76E+02
2.511E+07	1.76E+02
2.818E+07	1.75E+02
3.162E+07	1.75E+02
3.548E+07	1.74E+02
3.981E+07	1.74E+02
4.466E+07	1.73E+02
5.011E+07	1.72E+02
5.623E+07	1.71E+02
6.309E+07	1.70E+02
7.079E+07	1.69E+02
7.943E+07	1.68E+02
8.912E+07	1.67E+02
9.999E+07	1.65E+02
1.122E+08	1.63E+02
1.258E+08	1.61E+02
1.412E+08	1.59E+02
1.584E+08	1.57E+02
1.778E+08	1.54E+02
1.995E+08	1.51E+02
2.239E+08	1.48E+02
2.511E+08	1.44E+02
2.818E+08	1.41E+02
3.162E+08	1.36E+02
3.548E+08	1.32E+02
3.981E+08	1.27E+02
4.466E+08	1.21E+02
5.011E+08	1.16E+02
5.623E+08	1.10E+02
6.309E+08	1.04E+02
7.079E+08	9.78E+01
7.943E+08	9.13E+01
8.912E+08	8.47E+01
9.999E+08	7.79E+01
1.122E+09	7.12E+01
1.258E+09	6.44E+01
1.412E+09	5.77E+01
1.584E+09	5.11E+01
1.778E+09	4.45E+01
1.995E+09	3.79E+01
2.238E+09	3.14E+01
2.511E+09	2.49E+01
2.818E+09	1.85E+01
3.162E+09	1.20E+01
3.548E+09	5.49E+00
3.981E+09	-1.11E+00
4.466E+09	-7.82E+00
5.011E+09	-1.46E+01
5.623E+09	-2.15E+01
6.309E+09	-2.85E+01
7.079E+09	-3.55E+01
7.943E+09	-4.24E+01
8.912E+09	-4.89E+01
9.999E+09	-5.49E+01

dominant pole at 135° phase = 316 MHz

Second pole at 45° phase = 1.8 GHz

7.40



All $I_D = 100\mu A$

sum time constants

$T_1 = (C_{gs4} + C_{gs1}) \frac{1}{g_{m4}}$

$g_{m4} = \sqrt{2 I_D \mu C_{ox} \frac{W}{L}}$

$= \sqrt{200\mu \, 60\mu \, 10}$

$= 346\mu$

$T_1 = 40f \; 2887$

$= 115 \, ps$

drain of m4

$T_2 = (C_{db4} + C_{sb3}) \frac{1}{g_{m4}}$

$= (10fF + 10fF) \, 2887$

$= 57.7 \, ps$

drain of m3

$T_3 = (C_{db3} + C_{gd2})\left(\frac{1}{g_{m3}} + \frac{1}{g_{m4}}\right)$

$= (10 + 3) f \, (2)(2887)$

$= 75.1 \, ps$

gate – source of m3

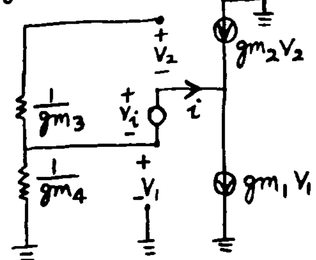
$T_4 = C_{gs3} \frac{1}{g_{m3}}$

$= 20f \; 2887$

$= 57.7 \, ps$

7-53

gate – drain of m1



$g_{m2}V_2 + i = g_{m1}V_1 = -\frac{g_{m1}}{g_{m4}} i$

$V_1 = \frac{-i}{g_{m4}}$

$g_{m2}V_2 + 2i = 0$

$V_2 = -V_i$

$-g_{m2}V_i + 2i = 0$

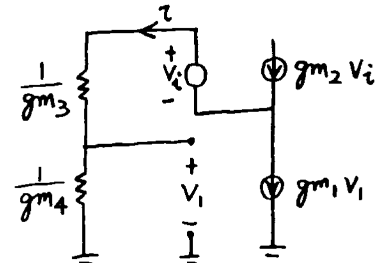
$R_i = \frac{V_i}{i} = \frac{2}{g_{m2}}$

$T_5 = C_{gd1} \frac{2}{g_m}$

$= 3f \, (2)(2887)$

$= 17.3 \, ps$

gate – source of m_2



$V_1 = \frac{i}{g_{m4}}$

$i = g_{m2}V_i - g_{m1}V_1$

$= g_m V_i - i$

$2i = g_m V_i$

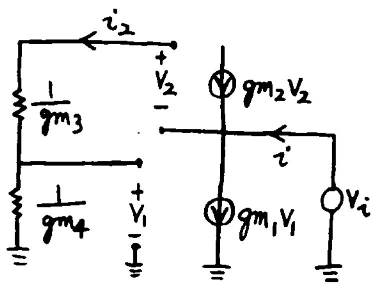
$R_i = \frac{V_i}{i} = \frac{2}{g_m}$

$T_6 = C_{gs_2} \frac{2}{g_m}$

$= 20f(2)(2887)$

$= 115\,ps$

drain of m_1



$i = g_{m_1}V_1 - g_{m_2}V_2$

$V_1 = V_i + V_2$

$i_2 = 0$

$V_1 = 0$

$0 = V_i + V_2$

$i = -g_{m_2}(-V_i)$

$R_i = \frac{V_i}{i} = \frac{1}{g_{m_2}}$

$T_7 = 20f\ 2887$

$= 57.7\,ps$

$T_0 = \sum_{n=1}^{7} T_n = 496\,ps$

dominant pole

$|P_1| = \frac{1}{T_0} = 2.02\,G\,rad/s$

$\hookrightarrow 321\,MHz$

device f_T

$f_T = \frac{1}{2\pi} \frac{g_m}{C_{gs} + C_{gd}}$

$= \frac{1}{2\pi} \frac{1}{2887} \frac{1}{23f}$

$= 2.4\,GHz$

```
MOS CASCODE CURRENT MIRROR
VCC 1 0 5V
IREF 1 2 100UA AC
M1 4 3 0 0 NMOS W=10U L=1U
M2 5 2 4 4 NMOS W=10U L=1U
M3 2 2 3 3 NMOS W=10U L=1U
M4 3 3 0 0 NMOS W=10U L=1U
VOUT 5 0 2.5547V
.MODEL NMOS NMOS KP=60U VTO=0.7 LAMBDA=0 LD=0 GAMMA=0
+ TOX=11.5NM CBD=16.1FF CBS=10FF CGSO=300PF CGDO=300PF
.AC DEC 30 10MEG 1GIG
.PLOT AC IDB(VOUT)
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END
```

****** OPERATING POINT INFORMATION   TNOM= 27.000 TEMP= 27.000

```
+0:1        = 5.000E+00 0:2        = 2.554E+00 0:3        = 1.277E+00
+0:4        = 1.277E+00 0:5        = 2.554E+00
```

**** MOSFETS

ELEMENT	0:M1	0:M2	0:M3	0:M4
MODEL	0:NMOS	0:NMOS	0:NMOS	0:NMOS
ID	1.000E-04	1.000E-04	1.000E-04	1.000E-04
IBS	0.	0.	0.	0.
IBD	-1.277E-14	-1.277E-14	-1.277E-14	-1.277E-14
VGS	1.277E+00	1.277E+00	1.277E+00	1.277E+00
VDS	1.277E+00	1.277E+00	1.277E+00	1.277E+00
VBS	0.	0.	0.	0.
VTH	7.000E-01	7.000E-01	7.000E-01	7.000E-01
VDSAT	5.774E-01	5.774E-01	5.774E-01	5.774E-01
BETA	6.000E-04	6.000E-04	6.000E-04	6.000E-04
GAM EFF	0.	0.	0.	0.
GM	3.464E-04	3.464E-04	3.464E-04	3.464E-04
GDS	0.	0.	0.	0.
GMB	0.	0.	0.	0.
CDTOT	1.304E-14	1.304E-14	1.304E-14	1.304E-14
CGTOT	2.687E-14	2.687E-14	2.687E-14	2.687E-14
CSTOT	3.302E-14	3.302E-14	3.302E-14	3.302E-14
CBTOT	2.079E-14	2.079E-14	2.079E-14	2.079E-14
CGS	2.302E-14	2.302E-14	2.302E-14	2.302E-14
CGD	3.051E-15	3.051E-15	3.051E-15	3.051E-15

****** AC ANALYSIS   TNOM= 27.000 TEMP= 27.000

```
     FREQ      IDB(VOUT)
(A        )    -6.000E+00    -4.000E+00    -2.000E+00    0.            2.000E+00
                    +             +             +             +             +
1.000E+07 -1.19E-03-+------+------+------+------+------+------A------+------+-
1.079E+07 -1.37E-03 +      +      +      +      +      +      A      +      +
1.165E+07 -1.60E-03 +      +      +      +      +      +      A      +      +
1.258E+07 -1.86E-03 +      +      +      +      +      +      A      +      +
1.359E+07 -2.17E-03 +      +      +      +      +      +      A      +      +
1.467E+07 -2.53E-03 +      +      +      +      +      +      A      +      +
1.584E+07 -2.95E-03 +      +      +      +      +      +      A      +      +
1.711E+07 -3.44E-03 +      +      +      +      +      +      A      +      +
1.847E+07 -4.01E-03 +      +      +      +      +      +      A      +      +
1.995E+07 -4.68E-03 +      +      +      +      +      +      A      +      +
2.154E+07 -5.46E-03-+------+------+------+------+------+------A------+------+-
2.326E+07 -6.36E-03 +      +      +      +      +      +      A      +      +
2.511E+07 -7.41E-03 +      +      +      +      +      +      A      +      +
2.712E+07 -8.64E-03 +      +      +      +      +      +      A      +      +
2.928E+07 -1.01E-02 +      +      +      +      +      +      A      +      +
3.162E+07 -1.17E-02 +      +      +      +      +      +      A      +      +
3.414E+07 -1.37E-02 +      +      +      +      +      +      A      +      +
3.686E+07 -1.60E-02 +      +      +      +      +      +      A      +      +
3.981E+07 -1.86E-02 +      +      +      +      +      +      A      +      +
4.298E+07 -2.17E-02 +      +      +      +      +      +      A      +      +
4.641E+07 -2.53E-02-+------+------+------+------+------+------A------+------+-
5.011E+07 -2.94E-02 +      +      +      +      +      +      A      +      +
5.411E+07 -3.43E-02 +      +      +      +      +      +      A      +      +
5.843E+07 -3.99E-02 +      +      +      +      +      +      A      +      +
6.309E+07 -4.65E-02 +      +      +      +      +      +      A      +      +
6.812E+07 -5.42E-02 +      +      +      +      +      +      A      +      +
7.356E+07 -6.31E-02 +      +      +      +      +      +      A      +      +
7.943E+07 -7.35E-02 +      +      +      +      +      +     A+      +      +
8.577E+07 -8.55E-02 +      +      +      +      +      +     A+      +      +
9.261E+07 -9.95E-02 +      +      +      +      +      +     A+      +      +
1.000E+08 -1.16E-01-+------+------+------+------+------+-----A+------+------+-
1.079E+08 -1.35E-01 +      +      +      +      +      +     A+      +      +
1.165E+08 -1.56E-01 +      +      +      +      +      +     A+      +      +
1.258E+08 -1.82E-01 +      +      +      +      +      +     A+      +      +
1.359E+08 -2.11E-01 +      +      +      +      +      +     A+      +      +
1.467E+08 -2.45E-01 +      +      +      +      +      +    A +      +      +
1.584E+08 -2.84E-01 +      +      +      +      +      +    A +      +      +
1.711E+08 -3.29E-01 +      +      +      +      +      +    A +      +      +
1.847E+08 -3.81E-01 +      +      +      +      +      +   A  +      +      +
1.995E+08 -4.40E-01 +      +      +      +      +      +   A  +      +      +
2.154E+08 -5.08E-01-+------+------+------+------+------+--A---+------+------+-
2.326E+08 -5.86E-01 +      +      +      +      +      +  A   +      +      +
2.511E+08 -6.74E-01 +      +      +      +      +      + A    +      +      +
2.712E+08 -7.75E-01 +      +      +      +      +      + A    +      +      +
2.928E+08 -8.88E-01 +      +      +      +      +      +A     +      +      +
3.162E+08 -1.01E+00 +      +      +      +      +      A      +      +      +
3.414E+08 -1.16E+00 +      +      +      +      +     A+      +      +      +
3.686E+08 -1.32E+00 +      +      +      +      +    A +      +      +      +
3.981E+08 -1.49E+00 +      +      +      +      +   A  +      +      +      +
4.298E+08 -1.69E+00 +      +      +      +      + A    +      +      +      +
4.641E+08 -1.90E+00-+------+------+------+------+A-----+------+------+------+-
5.011E+08 -2.14E+00 +      +      +      +     A+      +      +      +      +
5.411E+08 -2.39E+00 +      +      +      +   A  +      +      +      +      +
5.843E+08 -2.66E+00 +      +      +      + A    +      +      +      +      +
6.309E+08 -2.95E+00 +      +      +      A      +      +      +      +      +
6.812E+08 -3.26E+00 +      +      +    A +      +      +      +      +      +
7.356E+08 -3.58E+00 +      +      +  A   +      +      +      +      +      +
7.943E+08 -3.91E+00 +      +      +A     +      +      +      +      +      +
8.577E+08 -4.26E+00 +      +    A +      +      +      +      +      +      +
9.261E+08 -4.62E+00 +      +  A   +      +      +      +      +      +      +
1.000E+09 -4.99E+00-+------A------+------+------+------+------+------+------+-
                    +             +             +             +             +
```

*****
BANDWIDTH = 680 MEGAHERTZ

*****

```
MOS CASCODE CURRENT MIRROR
VCC 1 0 5V
IREF 1 2 50UA AC
M1 4 3 0 0 NMOS W=10U L=1U
M2 5 2 4 4 NMOS W=10U L=1U
M3 2 2 3 3 NMOS W=10U L=1U
M4 3 3 0 0 NMOS W=10U L=1U
VOUT 5 0 2.2165V
.MODEL NMOS NMOS KP=60U VTO=0.7 LAMBDA=0 LD=0 GAMMA=0
+ TOX=11.5NM CBD=16.1FF CBS=10FF CGSO=300PF CGDO=300PF
.AC DEC 30 10MEG 1GIG
.PLOT AC IDB(VOUT)
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END
```

*****
BANDWIDTH = 460 MEGAHERTZ

```
*****
MOS CASCODE CURRENT MIRROR
VCC 1 0 5V
IREF 1 2 200UA AC
M1 4 3 0 0 NMOS W=10U L=1U
M2 5 2 4 4 NMOS W=10U L=1U
M3 2 2 3 3 NMOS W=10U L=1U
M4 3 3 0 0 NMOS W=10U L=1U
VOUT 5 0 3.0330V
.MODEL NMOS NMOS KP=60U VTO=0.7 LAMBDA=0 LD=0 GAMMA=0
+ TOX=11.5NM CBD=16.1FF CBS=10FF CGSO=300PF CGDO=300PF
.AC DEC 30 10MEG 1GIG
.PLOT AC IDB(VOUT)
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

*****
BANDWIDTH = 930 MEGAHERTZ
```

7.41

all $I_D = 100\mu A$

$$R_{SX} = \frac{1}{\mathcal{E}_c \, \mu C_{ox} W}$$

$$= \frac{1}{1.5M \; 60\mu \; 10\mu}$$

$$= 1111\,\Omega$$

m_3, m_4

$$\frac{1}{g_m} + R_{SX} = 2887 + 1111 = 4k$$

m_1, m_2

$$G_m = \frac{g_m}{1 + g_m R_{SX}} = \frac{\frac{1}{2887}}{1 + \frac{1111}{2887}}$$

$$= 250\mu$$

$$\frac{1}{G_m} = \frac{1 + g_m R_{SX}}{g_m} = \frac{1}{g_m} + R_{SX}$$

$$\frac{1}{G_m} = 4k \quad \text{also}$$

$\therefore$ all time constants increase by $\frac{4000}{2887}$

dominant pole @ $321 \, \frac{2887}{4000} M$

$$= 232 \text{ MHz}$$

device $f_T = \frac{1}{2\pi} \frac{1}{4000} \frac{1}{23f}$

$$= 1.73 \text{ GHz}$$

```
CMOS CASCODE CURRENT MIRROR, SHORT CHANNEL EFFECTS
VCC 1 0 5V
IREF 1 2 100UA AC
M1 8 4 9 9 NMOS W=10U L=1U
RSX1 9 0 1111
CGS1 4 0 20FF
M2 6 2 7 7 NMOS W=10U L=1U
RSX2 7 8 1111
CGS2 2 8 20FF
M3 2 2 3 3 NMOS W=10U L=1U
RSX3 3 4 1111
CGS3 2 4 20FF
M4 4 4 5 5 NMOS W=10U L=1U
RSX4 5 0 1111
CGS4 4 0 20FF
CSB3 4 0 10FF
CSB2 8 0 10FF
CDB1 8 0 10FF
CDB3 2 0 10FF
CDB4 4 0 10FF
VOUT 6 0 2.7769V
.MODEL NMOS NMOS KP=60U VTO=0.7 LAMBDA=0 LD=0 GAMMA=0
+ TOX=11.5NM CGSO=300PF CGDO=300PF
.AC DEC 30 10MEG 1GIG
.PLOT AC IDB(VOUT)
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END
```

```
****** OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000

+0:1     = 5.000E+00 0:2     = 2.776E+00 0:3     = 1.499E+00
+0:4     = 1.388E+00 0:5     = 1.111E-01 0:6     = 2.776E+00
+0:7     = 1.499E+00 0:8     = 1.388E+00 0:9     = 1.111E-01
```

**** MOSFETS

ELEMENT	0:M1	0:M2	0:M3	0:M4
MODEL	0:NMOS	0:NMOS	0:NMOS	0:NMOS
ID	1.000E-04	1.000E-04	1.000E-04	1.000E-04
IBS	0.	0.	0.	0.
IBD	-1.277E-14	-1.277E-14	-1.277E-14	-1.277E-14
VGS	1.277E+00	1.277E+00	1.277E+00	1.277E+00
VDS	1.277E+00	1.277E+00	1.277E+00	1.277E+00
VBS	0.	0.	0.	0.
VTH	7.000E-01	7.000E-01	7.000E-01	7.000E-01
VDSAT	5.774E-01	5.774E-01	5.774E-01	5.774E-01
BETA	6.000E-04	6.000E-04	6.000E-04	6.000E-04
GAM EFF	0.	0.	0.	0.
GM	3.464E-04	3.464E-04	3.464E-04	3.464E-04
GDS	0.	0.	0.	0.
GMB	0.	0.	0.	0.
CDTOT	3.051E-15	3.051E-15	3.051E-15	3.051E-15
CGTOT	2.687E-14	2.687E-14	2.687E-14	2.687E-14
CSTOT	2.302E-14	2.302E-14	2.302E-14	2.302E-14
CBTOT	8.005E-16	8.005E-16	8.005E-16	8.005E-16
CGS	2.302E-14	2.302E-14	2.302E-14	2.302E-14
CGD	3.051E-15	3.051E-15	3.051E-15	3.051E-15

```
****** AC ANALYSIS                                   TNOM=  27.000 TEMP=  27.000

     FREQ        IDB(VOUT)
 (A        )     -1.500E+01  -1.000E+01  -5.000E+00      0.      5.000E+00
                    +           +           +           +           +
 1.000E+07 -7.63E-03-+-----+-----+-----+-----+-----+-----A-----+-----+-
 1.079E+07 -8.89E-03 +     +     +     +     +     +     A     +     +
 1.165E+07 -1.04E-02 +     +     +     +     +     +     A     +     +
 1.258E+07 -1.21E-02 +     +     +     +     +     +     A     +     +
 1.359E+07 -1.41E-02 +     +     +     +     +     +     A     +     +
 1.467E+07 -1.64E-02 +     +     +     +     +     +     A     +     +
 1.584E+07 -1.91E-02 +     +     +     +     +     +     A     +     +
 1.711E+07 -2.23E-02 +     +     +     +     +     +     A     +     +
 1.847E+07 -2.60E-02 +     +     +     +     +     +     A     +     +
 1.995E+07 -3.03E-02 +     +     +     +     +     +     A     +     +
 2.154E+07 -3.53E-02-+-----+-----+-----+-----+-----+-----A-----+-----+-
 2.326E+07 -4.11E-02 +     +     +     +     +     +     A     +     +
 2.511E+07 -4.79E-02 +     +     +     +     +     +     A     +     +
 2.712E+07 -5.58E-02 +     +     +     +     +     +     A     +     +
 2.928E+07 -6.50E-02 +     +     +     +     +     +     A     +     +
 3.162E+07 -7.57E-02 +     +     +     +     +     +     A     +     +
 3.414E+07 -8.82E-02 +     +     +     +     +     +     A     +     +
 3.686E+07 -1.03E-01 +     +     +     +     +     +     A     +     +
 3.981E+07 -1.20E-01 +     +     +     +     +     +     A     +     +
 4.298E+07 -1.39E-01 +     +     +     +     +     +     A     +     +
 4.641E+07 -1.62E-01-+-----+-----+-----+-----+-----+-----A-----+-----+-
 5.011E+07 -1.88E-01 +     +     +     +     +     +    A+     +     +
 5.411E+07 -2.19E-01 +     +     +     +     +     +    A+     +     +
 5.843E+07 -2.54E-01 +     +     +     +     +     +    A+     +     +
 6.309E+07 -2.95E-01 +     +     +     +     +     +    A+     +     +
 6.812E+07 -3.42E-01 +     +     +     +     +     +    A+     +     +
 7.356E+07 -3.97E-01 +     +     +     +     +     +    A+     +     +
 7.943E+07 -4.60E-01 +     +     +     +     +     +    A+     +     +
 8.577E+07 -5.32E-01 +     +     +     +     +     +    A+     +     +
 9.261E+07 -6.15E-01 +     +     +     +     +     +   A +     +     +
 1.000E+08 -7.10E-01-+-----+-----+-----+-----+-----+---A-+-----+-----+-
 1.079E+08 -8.19E-01 +     +     +     +     +     +   A +     +     +
 1.165E+08 -9.43E-01 +     +     +     +     +     +  A  +     +     +
 1.258E+08 -1.08E+00 +     +     +     +     +     +  A  +     +     +
 1.359E+08 -1.24E+00 +     +     +     +     +     +  A  +     +     +
 1.467E+08 -1.42E+00 +     +     +     +     +     + A   +     +     +
 1.584E+08 -1.62E+00 +     +     +     +     +     + A   +     +     +
 1.711E+08 -1.84E+00 +     +     +     +     +     + A   +     +     +
 1.847E+08 -2.09E+00 +     +     +     +     +     +A    +     +     +
 1.995E+08 -2.37E+00 +     +     +     +     +     A     +     +     +
 2.154E+08 -2.68E+00-+-----+-----+-----+-----+----A+-----+-----+-----+-
 2.326E+08 -3.01E+00 +     +     +     +     +    A+     +     +     +
 2.511E+08 -3.38E+00 +     +     +     +     +   A +     +     +     +
 2.712E+08 -3.77E+00 +     +     +     +     +  A  +     +     +     +
 2.928E+08 -4.20E+00 +     +     +     +     + A   +     +     +     +
 3.162E+08 -4.65E+00 +     +     +     +     +A    +     +     +     +
 3.414E+08 -5.13E+00 +     +     +     +     A     +     +     +     +
 3.686E+08 -5.64E+00 +     +     +     +   A +     +     +     +     +
 3.981E+08 -6.18E+00 +     +     +     +  A  +     +     +     +     +
 4.298E+08 -6.73E+00 +     +     +     + A   +     +     +     +     +
 4.641E+08 -7.30E+00-+-----+-----+-----+A----+-----+-----+-----+-----+-
 5.011E+08 -7.89E+00 +     +     +    A+     +     +     +     +     +
 5.411E+08 -8.48E+00 +     +     +  A  +     +     +     +     +     +
 5.843E+08 -9.07E+00 +     +     + A   +     +     +     +     +     +
 6.309E+08 -9.65E+00 +     +     +A    +     +     +     +     +     +
 6.812E+08 -1.02E+01 +     +    A+     +     +     +     +     +     +
 7.356E+08 -1.07E+01 +     +   A +     +     +     +     +     +     +
 7.943E+08 -1.13E+01 +     +  A  +     +     +     +     +     +     +
 8.577E+08 -1.18E+01 +     + A   +     +     +     +     +     +     +
 9.261E+08 -1.23E+01 +     +A    +     +     +     +     +     +     +
 1.000E+09 -1.27E+01-+----A+-----+-----+-----+-----+-----+-----+-----+-
                     +           +           +           +           +
```

*****

BANDWIDTH = 230 MEGAHERTZ

******

```
CMOS CASCODE CURRENT MIRROR, SHORT CHANNEL EFFECTS
VCC 1 0 5V
IREF 1 2 50UA AC
M1 8 4 9 9 NMOS W=10U L=1U
RSX1 9 0 1111
CGS1 4 0 20FF
M2 6 2 7 7 NMOS W=10U L=1U
RSX2 7 8 1111
CGS2 2 8 20FF
M3 2 2 3 3 NMOS W=10U L=1U
RSX3 3 4 1111
CGS3 2 4 20FF
M4 4 4 5 5 NMOS W=10U L=1U
RSX4 5 0 1111
CGS4 4 0 20FF
CSB3 4 0 10FF
CSB2 8 0 10FF
CDB1 8 0 10FF
CDB3 2 0 10FF
CDB4 4 0 10FF
VOUT 6 0 2.3276V
.MODEL NMOS NMOS KP=60U VTO=0.7 LAMBDA=0 LD=0 GAMMA=0
+ TOX=11.5NM CGSO=300PF CGDO=300PF
.AC DEC 30 10MEG 1GIG
```

```
.PLOT AC IDB(VOUT)
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

*****
BANDWIDTH = 170 MEGAHERTZ

******

CMOS CASCODE CURRENT MIRROR, SHORT CHANNEL EFFECTS
VCC 1 0 5V
IREF 1 2 200UA AC
M1 8 4 9 9 NMOS W=10U L=1U
RSX1 9 0 1111
CGS1 4 0 20FF
M2 6 2 7 7 NMOS W=10U L=1U
RSX2 7 8 1111
CGS2 2 8 20FF
M3 2 2 3 3 NMOS W=10U L=1U
RSX3 3 4 1111
CGS3 2 4 20FF
M4 4 4 5 5 NMOS W=10U L=1U
RSX4 5 0 1111
CGS4 4 0 20FF
CSB3 4 0 10FF
CSB2 8 0 10FF
CDB1 8 0 10FF
CDB3 2 0 10FF
CDB4 4 0 10FF
VOUT 6 0 3.4774V
.MODEL NMOS NMOS KP=60U VTO=0.7 LAMBDA=0 LD=0 GAMMA=0
+ TOX=11.5NM CGSO=300PF CGDO=300PF
.AC DEC 30 10MEG 1GIG
.PLOT AC IDB(VOUT)
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

*****
BANDWIDTH = 320 MEGAHERTZ
```

7.42

$m_3 \quad I_D = 100\mu A$

$g_m = \sqrt{2 I_D \mu_n C_{ox} \frac{W}{L}}$

$= \sqrt{200\mu \; 60\mu \; 10}$

$= 346\mu \frac{A}{V}$

$= \frac{1}{2890} \Omega$

use $\frac{1}{2}$ circuit

$T_o = \frac{1}{g_{m_3}}(C_{gs_3} + C_{sb_3} + C_{gd_{10}} + C_{db_{10}} + C_{db_1} + C_{gd_1})$

$= 2890(20 + 10 + 6 + 20 + 10 + 3) f$

$= 199 \text{ ps}$

non-dominant pole

$\frac{1}{2\pi T_o} = 799 \text{MHz}$

ss gain

$\frac{V_o}{V_i} = g_{m_1} \frac{1}{j\omega C_L}$

$\omega_1 = \frac{g_{m_1}}{C_L} \; @ \; \left|\frac{V_o}{V_i}\right| = 1$

$= \frac{245\mu}{1p}$

$= 245 \text{ M rad/s}$

↳ 39 MHz

$g_{m_1} = \sqrt{2 I_D \mu_p C_{ox} \frac{W}{L}}$

$= 245 \; \mu A/V$

7-59

from input to source of m_3

transfer function $= \frac{K}{1 + \frac{j\omega}{2\pi \, 799M}}$

$@ \; \omega = \omega_1 = 245 \text{ M rad/s}$

phase from non-dominant pole

$= -\arctan \frac{245M}{2\pi \; 799M}$

$= -2.79°$

```
PART OF FOLDED CASCODE
VDD 1 0 3V
VSS 2 0 -3V
M11 8 3 1 1 PMOS W=10U L=1U
V3 3 0 1.1453V
M1 17 9 8 8 PMOS W=10U L=1U
M2 18 10 8 8 PMOS W=10U L=1U
M3 15 11 17 2 NMOS W=10U L=1U
M4 16 11 18 2 NMOS W=10U L=1U
V11 11 0 -0.44565V
M9 18 12 2 2 NMOS2 W=20U L=1U
M10 17 12 2 2 NMOS2 W=20U L=1U
V12 12 0 -1.72265V
VOUT15 15 0 0V
VOUT16 16 0 0V
.MODEL NMOS NMOS KP=60U VTO=0.7 LAMBDA=0 LD=0 GAMMA=0
+ TOX=11.5NM CBD=16.1FF CBS=10FF CGSO=300PF CGDO=300PF
.MODEL NMOS2 NMOS KP=60U VTO=0.7 LAMBDA=0 LD=0 GAMMA=0
+ TOX=11.5NM CBD=32FF CBS=20FF CGSO=300PF CGDO=300PF
.MODEL PMOS PMOS KP=30U VTO=-0.7 LAMBDA=0 LD=0 GAMMA=0
+ TOX=11.5NM CBD=16.1FF CBS=10FF CGSO=300PF CGDO=300PF
VI1 9 0 0V AC
VI2 10 0 0V
.AC DEC 20 10MEG 2GIG
.PLOT AC IDB(VOUT15)
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END
```

```
 ******  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000

+0:1        = 3.000E+00 0:2       =-3.000E+00 0:3       = 1.145E+00
+0:8        = 1.516E+00 0:9       =   0.      0:10      =   0.
+0:11       =-4.457E-01 0:12      =-1.722E+00 0:15      =   0.
+0:16       =   0.      0:17      =-1.723E+00 0:18      =-1.723E+00
```

**** MOSFETS

ELEMENT	0:M11	0:M1	0:M2	0:M3	0:M4	0:M9
MODEL	0:PMOS	0:PMOS	0:PMOS	0:NMOS	0:NMOS	0:NMOS2
ID	-2.000E-04	-1.000E-04	-1.000E-04	1.000E-04	1.000E-04	2.000E-04
IBS	0.	0.	0.	-1.277E-14	-1.277E-14	0.
IBD	1.484E-14	3.239E-14	3.239E-14	-3.000E-14	-3.000E-14	-1.277E-14
VGS	-1.854E+00	-1.516E+00	-1.516E+00	1.277E+00	1.277E+00	1.277E+00
VDS	-1.483E+00	-3.239E+00	-3.239E+00	1.723E+00	1.723E+00	1.277E+00
VBS	0.	0.	0.	-1.277E+00	-1.277E+00	0.
VTH	-7.000E-01	-7.000E-01	-7.000E-01	7.000E-01	7.000E-01	7.000E-01
VDSAT	-1.154E+00	-8.165E-01	-8.165E-01	5.774E-01	5.774E-01	5.773E-01
BETA	3.000E-04	3.000E-04	3.000E-04	6.000E-04	6.000E-04	1.200E-03
GAM EFF	0.	0.	0.	0.	0.	0.
GM	3.464E-04	2.449E-04	2.449E-04	3.464E-04	3.464E-04	6.928E-04
GDS	0.	0.	0.	0.	0.	0.
GMB	0.	0.	0.	0.	0.	0.
CDTOT	1.259E-14	1.029E-14	1.029E-14	1.046E-14	1.046E-14	2.596E-14
CGTOT	2.643E-14	2.668E-14	2.668E-14	2.689E-14	2.689E-14	5.374E-14
CSTOT	3.302E-14	3.302E-14	3.302E-14	2.922E-14	2.922E-14	6.604E-14
CBTOT	1.988E-14	1.770E-14	1.770E-14	1.439E-14	1.439E-14	4.146E-14
CGS	2.302E-14	2.302E-14	2.302E-14	2.302E-14	2.302E-14	4.604E-14
CGD	3.059E-15	3.130E-15	3.130E-15	3.069E-15	3.069E-15	6.102E-15

ELEMENT	0:M10
MODEL	0:NMOS2
ID	2.000E-04
IBS	0.
IBD	-1.277E-14
VGS	1.277E+00
VDS	1.277E+00
VBS	0.
VTH	7.000E-01
VDSAT	5.773E-01
BETA	1.200E-03
GAM EFF	0.
GM	6.928E-04
GDS	0.
GMB	0.
CDTOT	2.596E-14
CGTOT	5.374E-14
CSTOT	6.604E-14
CBTOT	4.146E-14
CGS	4.604E-14
CGD	6.102E-15

```
 ******  AC ANALYSIS                                 TNOM=  27.000 TEMP=  27.000
   FREQ        IDB(VOUT15)
(A       )     -8.600E+01    -8.400E+01    -8.200E+01    -8.000E+01    -7.800E+01
                    +             +             +             +             +
1.000E+07 -7.82E+01-+------+------+------+------+------+------+------+----A-+-
1.122E+07 -7.82E+01 +      +      +      +      +      +      +      +    A +
1.258E+07 -7.82E+01 +      +      +      +      +      +      +      +    A +
1.412E+07 -7.82E+01 +      +      +      +      +      +      +      +    A +
1.584E+07 -7.82E+01 +      +      +      +      +      +      +      +    A +
1.778E+07 -7.82E+01 +      +      +      +      +      +      +      +    A +
1.995E+07 -7.82E+01 +      +      +      +      +      +      +      +    A +
2.238E+07 -7.82E+01 +      +      +      +      +      +      +      +    A +
2.511E+07 -7.82E+01 +      +      +      +      +      +      +      +    A +
2.818E+07 -7.82E+01 +      +      +      +      +      +      +      +    A +
3.162E+07 -7.82E+01-+------+------+------+------+------+------+------+----A-+-
3.548E+07 -7.82E+01 +      +      +      +      +      +      +      +    A +
3.981E+07 -7.82E+01 +      +      +      +      +      +      +      +    A +
4.466E+07 -7.82E+01 +      +      +      +      +      +      +      +    A +
5.011E+07 -7.82E+01 +      +      +      +      +      +      +      +    A +
5.623E+07 -7.82E+01 +      +      +      +      +      +      +      +    A +
6.309E+07 -7.82E+01 +      +      +      +      +      +      +      +    A +
7.079E+07 -7.82E+01 +      +      +      +      +      +      +      +    A +
7.943E+07 -7.82E+01 +      +      +      +      +      +      +      +    A +
8.912E+07 -7.82E+01 +      +      +      +      +      +      +      +    A +
9.999E+07 -7.82E+01-+------+------+------+------+------+------+------+----A-+-
1.122E+08 -7.82E+01 +      +      +      +      +      +      +      +    A +
1.258E+08 -7.83E+01 +      +      +      +      +      +      +      +    A +
1.412E+08 -7.83E+01 +      +      +      +      +      +      +      +    A +
1.584E+08 -7.83E+01 +      +      +      +      +      +      +      +    A +
1.778E+08 -7.83E+01 +      +      +      +      +      +      +      +   A  +
1.995E+08 -7.83E+01 +      +      +      +      +      +      +      +   A  +
2.238E+08 -7.84E+01 +      +      +      +      +      +      +      +   A  +
2.511E+08 -7.84E+01 +      +      +      +      +      +      +      +   A  +
2.818E+08 -7.85E+01 +      +      +      +      +      +      +      +  A   +
3.162E+08 -7.86E+01-+------+------+------+------+------+------+------+--A---+-
3.548E+08 -7.86E+01 +      +      +      +      +      +      +      + A    +
3.981E+08 -7.88E+01 +      +      +      +      +      +      +      +A     +
4.466E+08 -7.89E+01 +      +      +      +      +      +      +      +A     +
5.011E+08 -7.90E+01 +      +      +      +      +      +      +     A+      +
5.623E+08 -7.92E+01 +      +      +      +      +      +      +    A +      +
6.309E+08 -7.94E+01 +      +      +      +      +      +      +   A  +      +
7.079E+08 -7.97E+01 +      +      +      +      +      +      + A    +      +
7.943E+08 -8.00E+01 +      +      +      +      +      +      A      +      +
8.912E+08 -8.04E+01 +      +      +      +      +      +   A  +      +      +
9.999E+08 -8.08E+01-+------+------+------+------+------+A-----+------+------+-
1.122E+09 -8.12E+01 +      +      +      +      +    A +      +      +      +
1.258E+09 -8.17E+01 +      +      +      +      + A    +      +      +      +
1.412E+09 -8.22E+01 +      +      +      +    A +      +      +      +      +
1.584E+09 -8.28E+01 +      +      +      +A     +      +      +      +      +
1.778E+09 -8.34E+01 +      +      +   A  +      +      +      +      +      +
1.995E+09 -8.40E+01 +      +      A      +      +      +      +      +      +
2.238E+09 -8.46E+01 +      + A    +      +      +      +      +      +      +
                    +             +             +             +             +

 *****
BANDWIDTH = 1.12 GIGAHERTZ
```

```
FOLDED CASCODE
VDD 1 0 3V
VSS 2 0 -3V
M11 8 3 1 1 PMOS W=10U L=1U
V3 3 0 1.1453V
M1 17 9 8 8 PMOS W=10U L=1U
M2 18 10 8 8 PMOS W=10U L=1U
M3 15 11 17 2 NMOS W=10U L=1U
M4 16 11 18 2 NMOS W=10U L=1U
M5 14 13 1 1 PMOS W=10U L=1U
M6 13 13 1 1 PMOS W=10U L=1U
M7 16 15 14 14 PMOS W=10U L=1U
M8 15 15 13 13 PMOS W=10U L=1U
V11 11 0 -0.44565V
M9 18 12 2 2 NMOS2 W=20U L=1U
M10 17 12 2 2 NMOS2 W=20U L=1U
V12 12 0 -1.72265V
CL 16 0 1PF
.MODEL NMOS NMOS KP=60U VTO=0.7 LAMBDA=0 LD=0 GAMMA=0
+ TOX=11.5NM CBD=16.1FF CBS=10FF CGSO=300PF CGDO=300PF
.MODEL NMOS2 NMOS KP=60U VTO=0.7 LAMBDA=0 LD=0 GAMMA=0
+ TOX=11.5NM CBD=32FF CBS=20FF CGSO=300PF CGDO=300PF
.MODEL PMOS PMOS KP=30U VTO=-0.7 LAMBDA=0 LD=0 GAMMA=0
+ TOX=11.5NM CBD=16.1FF CBS=10FF CGSO=300PF CGDO=300PF
VI1 9 0 0V AC
VI2 10 0 0V
.AC DEC 40 10MEG 100MEG
.TF V(16) VI1
.PLOT AC V(16)
.PLOT AC VP(16)
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END
```

```
 ******  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
+0:1        = 3.000E+00 0:2       =-3.000E+00 0:3       = 1.145E+00
+0:8        = 1.516E+00 0:9       =   0.      0:10      =   0.
+0:11       =-4.457E-01 0:12      =-1.722E+00 0:13      = 1.483E+00
```

```
+0:14       = 1.483E+00 0:15       =-3.299E-02 0:16       =-3.299E-02
+0:17       =-1.723E+00 0:18       =-1.723E+00

**** MOSFETS
ELEMENT  0:M11      0:M1       0:M2       0:M3       0:M4       0:M5
MODEL    0:PMOS     0:PMOS     0:PMOS     0:NMOS     0:NMOS     0:PMOS
 ID      -2.000E-04 -1.000E-04 -1.000E-04  1.000E-04  1.000E-04 -1.000E-04
 IBS       0.         0.         0.       -1.277E-14 -1.277E-14   0.
 IBD      1.484E-14  3.239E-14  3.239E-14 -2.967E-14 -2.967E-14  1.516E-14
 VGS     -1.854E+00 -1.516E+00 -1.516E+00  1.277E+00  1.277E+00 -1.516E+00
 VDS     -1.483E+00 -3.239E+00 -3.239E+00  1.690E+00  1.690E+00 -1.516E+00
 VBS       0.         0.         0.       -1.277E+00 -1.277E+00   0.
 VTH     -7.000E-01 -7.000E-01 -7.000E-01  7.000E-01  7.000E-01 -7.000E-01
 VDSAT   -1.154E+00 -8.165E-01 -8.165E-01  5.774E-01  5.774E-01 -8.165E-01
 BETA     3.000E-04  3.000E-04  3.000E-04  6.000E-04  6.000E-04  3.000E-04
 GAM EFF   0.         0.         0.         0.         0.         0.
 GM       3.464E-04  2.449E-04  2.449E-04  3.464E-04  3.464E-04  2.449E-04
 GDS       0.         0.         0.         0.         0.         0.
 GMB       0.         0.         0.         0.         0.         0.
 CDTOT    1.259E-14  1.029E-14  1.029E-14  1.049E-14  1.049E-14  1.252E-14
 CGTOT    2.643E-14  2.668E-14  2.668E-14  2.689E-14  2.689E-14  2.661E-14
 CSTOT    3.302E-14  3.302E-14  3.302E-14  2.922E-14  2.922E-14  3.302E-14
 CBTOT    1.988E-14  1.770E-14  1.770E-14  1.443E-14  1.443E-14  1.999E-14
 CGS      2.302E-14  2.302E-14  2.302E-14  2.302E-14  2.302E-14  2.302E-14
 CGD      3.059E-15  3.130E-15  3.130E-15  3.068E-15  3.068E-15  3.061E-15

ELEMENT  0:M6       0:M7       0:M8       0:M9       0:M10
MODEL    0:PMOS     0:PMOS     0:PMOS     0:NMOS2    0:NMOS2
 ID      -1.000E-04 -1.000E-04 -1.000E-04  2.000E-04  2.000E-04
 IBS       0.         0.         0.         0.         0.
 IBD      1.516E-14  1.516E-14  1.516E-14 -1.277E-14 -1.277E-14
 VGS     -1.516E+00 -1.516E+00 -1.516E+00  1.277E+00  1.277E+00
 VDS     -1.516E+00 -1.516E+00 -1.516E+00  1.277E+00  1.277E+00
 VBS       0.         0.         0.         0.         0.
 VTH     -7.000E-01 -7.000E-01 -7.000E-01  7.000E-01  7.000E-01
 VDSAT   -8.165E-01 -8.165E-01 -8.165E-01  5.773E-01  5.773E-01
 BETA     3.000E-04  3.000E-04  3.000E-04  1.200E-03  1.200E-03
 GAM EFF   0.         0.         0.         0.         0.
 GM       2.449E-04  2.449E-04  2.449E-04  6.928E-04  6.928E-04
 GDS       0.         0.         0.         0.         0.
 GMB       0.         0.         0.         0.         0.
 CDTOT    1.252E-14  1.252E-14  1.252E-14  2.596E-14  2.596E-14
 CGTOT    2.661E-14  2.661E-14  2.661E-14  5.374E-14  5.374E-14
 CSTOT    3.302E-14  3.302E-14  3.302E-14  6.604E-14  6.604E-14
 CBTOT    1.999E-14  1.999E-14  1.999E-14  4.146E-14  4.146E-14
 CGS      2.302E-14  2.302E-14  2.302E-14  4.604E-14  4.604E-14
 CGD      3.061E-15  3.061E-15  3.061E-15  6.102E-15  6.102E-15

****      SMALL-SIGNAL TRANSFER CHARACTERISTICS
     V(16)/VI1                                  =  2.425E+08
     INPUT RESISTANCE AT          VI1           =  9.999E+19
     OUTPUT RESISTANCE AT V(16)                 =  9.901E+11
 ****** AC ANALYSIS                          TNOM=  27.000 TEMP=  27.000
```

```
    FREQ       V(16)
(A        )     0.        1.000E-00     2.000E+00     3.000E+00     4.000E+00
                   +             +             +             +             +

 1.000E+07  3.83E+00-+------+------+------+------+------+------+------+----A-+
 1.059E+07  3.61E+00 +      +      +      +      +      +      +      + A    +
 1.122E+07  3.41E+00 +      +      +      +      +      +      +     A+      +
 1.188E+07  3.22E+00 +      +      +      +      +      +      +  A   +      +
 1.258E+07  3.04E+00 +      +      +      +      +      +      +A     +      +
 1.333E+07  2.87E+00 +      +      +      +      +      +    A +      +      +
 1.412E+07  2.71E+00 +      +      +      +      +      +  A   +      +      +
 1.496E+07  2.56E+00 +      +      +      +      +      +A     +      +      +
 1.584E+07  2.41E+00 +      +      +      +      +     A+      +      +      +
 1.678E+07  2.28E+00 +      +      +      +      +   A  +      +      +      +
 1.778E+07  2.15E+00-+------+------+------+------+-A----+------+------+------+
 1.883E+07  2.03E+00 +      +      +      +      A      +      +      +      +
 1.995E+07  1.91E+00 +      +      +      +     A+      +      +      +      +
 2.113E+07  1.81E+00 +      +      +      +   A  +      +      +      +      +
 2.238E+07  1.71E+00 +      +      +      +  A   +      +      +      +      +
 2.371E+07  1.61E+00 +      +      +      + A    +      +      +      +      +
 2.511E+07  1.52E+00 +      +      +      A      +      +      +      +      +
 2.660E+07  1.43E+00 +      +      +     A+      +      +      +      +      +
 2.818E+07  1.35E+00 +      +      +    A +      +      +      +      +      +
 2.985E+07  1.28E+00 +      +      +   A  +      +      +      +      +      +
 3.162E+07  1.20E+00-+------+------+--A---+------+------+------+------+------+
 3.349E+07  1.14E+00 +      +      + A    +      +      +      +      +      +
 3.548E+07  1.07E+00 +      +      +A     +      +      +      +      +      +
 3.758E+07  1.01E+00 +      +      A      +      +      +      +      +      +
 3.981E+07  9.57E-01 +      +     A+      +      +      +      +      +      +
 4.217E+07  9.03E-01 +      +     A+      +      +      +      +      +      +
 4.466E+07  8.52E-01 +      +    A +      +      +      +      +      +      +
 4.731E+07  8.04E-01 +      +   A  +      +      +      +      +      +      +
 5.011E+07  7.58E-01 +      +   A  +      +      +      +      +      +      +
 5.308E+07  7.15E-01 +      +  A   +      +      +      +      +      +      +
 5.623E+07  6.74E-01-+------+-A----+------+------+------+------+------+------+
 5.956E+07  6.35E-01 +      + A    +      +      +      +      +      +      +
 6.309E+07  5.99E-01 +      +A     +      +      +      +      +      +      +
 6.683E+07  5.64E-01 +      +A     +      +      +      +      +      +      +
 7.079E+07  5.32E-01 +      A      +      +      +      +      +      +      +
 7.498E+07  5.01E-01 +      A      +      +      +      +      +      +      +
 7.943E+07  4.72E-01 +      A      +      +      +      +      +      +      +
 8.414E+07  4.44E-01 +     A+      +      +      +      +      +      +      +
 8.912E+07  4.18E-01 +     A+      +      +      +      +      +      +      +
 9.440E+07  3.93E-01 +     A+      +      +      +      +      +      +      +
 1.000E+08  3.70E-01-+----A-+------+------+------+------+------+------+------+
                   +             +             +             +             +
```

```
    FREQ       VP(16)
(A        )  -1.100E+02    -1.050E+02    -1.000E+02    -9.500E+01    -9.000E+01
                   +             +             +             +             +

 1.000E+07 -9.16E+01-+------+------+------+------+------+------+------+--A---+
 1.059E+07 -9.17E+01 +      +      +      +      +      +      +      + A    +
 1.122E+07 -9.18E+01 +      +      +      +      +      +      +      + A    +
 1.189E+07 -9.19E+01 +      +      +      +      +      +      +      +A     +
 1.258E+07 -9.21E+01 +      +      +      +      +      +      +      +A     +
 1.333E+07 -9.22E+01 +      +      +      +      +      +      +      +A     +
 1.412E+07 -9.23E+01 +      +      +      +      +      +      +      A      +
 1.496E+07 -9.24E+01 +      +      +      +      +      +      +      A      +
 1.584E+07 -9.26E+01 +      +      +      +      +      +      +      A      +
 1.678E+07 -9.27E+01 +      +      +      +      +      +      +     A+      +
 1.778E+07 -9.29E+01-+------+------+------+------+------+------+-----A+------+
 1.883E+07 -9.31E+01 +      +      +      +      +      +      +    A +      +
 1.995E+07 -9.33E+01 +      +      +      +      +      +      +    A +      +
 2.113E+07 -9.35E+01 +      +      +      +      +      +      +   A  +      +
 2.238E+07 -9.37E+01 +      +      +      +      +      +      +   A  +      +
 2.371E+07 -9.39E+01 +      +      +      +      +      +      +  A   +      +
 2.511E+07 -9.41E+01 +      +      +      +      +      +      + A    +      +
 2.660E+07 -9.44E+01 +      +      +      +      +      +      + A    +      +
 2.818E+07 -9.46E+01 +      +      +      +      +      +      +A     +      +
 2.985E+07 -9.49E+01 +      +      +      +      +      +      A      +      +
 3.162E+07 -9.52E+01-+------+------+------+------+------+-----A+------+------+
 3.349E+07 -9.55E+01 +      +      +      +      +      +    A +      +      +
 3.548E+07 -9.58E+01 +      +      +      +      +      +   A  +      +      +
 3.758E+07 -9.62E+01 +      +      +      +      +      +   A  +      +      +
 3.981E+07 -9.66E+01 +      +      +      +      +      +  A   +      +      +
 4.217E+07 -9.70E+01 +      +      +      +      +      +A     +      +      +
 4.466E+07 -9.74E+01 +      +      +      +      +      A      +      +      +
 4.731E+07 -9.78E+01 +      +      +      +      +     A+      +      +      +
 5.011E+07 -9.83E+01 +      +      +      +      +    A +      +      +      +
 5.308E+07 -9.87E+01 +      +      +      +      +  A   +      +      +      +
 5.623E+07 -9.93E+01-+------+------+------+------+-A----+------+------+------+
 5.956E+07 -9.98E+01 +      +      +      +      A      +      +      +      +
 6.309E+07 -1.00E+02 +      +      +      +     A+      +      +      +      +
 6.683E+07 -1.01E+02 +      +      +      +   A  +      +      +      +      +
 7.079E+07 -1.01E+02 +      +      +      + A    +      +      +      +      +
 7.498E+07 -1.02E+02 +      +      +      A      +      +      +      +      +
 7.943E+07 -1.03E+02 +      +      +    A +      +      +      +      +      +
 8.414E+07 -1.03E+02 +      +      +  A   +      +      +      +      +      +
 8.912E+07 -1.04E+02 +      +      +A     +      +      +      +      +      +
 9.440E+07 -1.05E+02 +      +     A+      +      +      +      +      +      +
 1.000E+08 -1.06E+02-+------+--A---+------+------+------+------+------+------+
                   +             +             +             +             +
```

```
*****
UNITY GAIN FREQUENCY = 37.58 MEGAHERTZ
PHASE = -96.2 DEGREES @ 37.58 MEGAHERTZ

FOLDED CASCODE
* TAKE AWAY ALL CAPACITANCES CONTRIBUTING TO
* THE NON-DOMINANT POLE
VDD 1 0 3V
VSS 2 0 -3V
M11 8 3 1 1 PMOS W=10U L=1U
V3 3 0 1.1453V
M1 17 9 8 8 P_NOCAP W=10U L=1U
M2 18 10 8 8 P_NOCAP W=10U L=1U
M3 15 11 17 2 N_NOCAP W=10U L=1U
M4 16 11 18 2 N_NOCAP W=10U L=1U
M5 14 13 1 1 PMOS W=10U L=1U
M6 13 13 1 1 PMOS W=10U L=1U
M7 16 15 14 14 PMOS W=10U L=1U
M8 15 15 13 13 PMOS W=10U L=1U
V11 11 0 -0.44565V
M9 18 12 2 2 N_NOCAP W=20U L=1U
M10 17 12 2 2 N_NOCAP W=20U L=1U
V12 12 0 -1.72265V
CL 16 0 1PF
.MODEL N_NOCAP NMOS KP=60U VTO=0.7 TOX=10M
.MODEL P_NOCAP PMOS KP=30U VTO=-0.7 TOX=10M
.MODEL NMOS NMOS KP=60U VTO=0.7
+ TOX=11.5NM CBD=16.1FF CBS=10FF CGSO=300PF CGDO=300PF
.MODEL PMOS PMOS KP=30U VTO=-0.7
+ TOX=11.5NM CBD=16.1FF CBS=10FF CGSO=300PF CGDO=300PF
VI1 9 0 0V AC
VI2 10 0 0V
.AC DEC 40 10MEG 100MEG
.TF V(16) VI1
.PLOT AC V(16)
.PLOT AC VP(16)
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

 ******  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000

+0:1        = 3.000E+00 0:2        =-3.000E+00 0:3        = 1.145E+00
+0:8        = 1.516E+00 0:9        =  0.       0:10       =  0.
+0:11       =-4.457E-01 0:12       =-1.722E+00 0:13       = 1.483E+00
+0:14       = 1.483E+00 0:15       =-3.299E-02 0:16       =-3.299E-02
+0:17       =-1.723E+00 0:18       =-1.723E+00

**** MOSFETS
```

ELEMENT	0:M11	0:M1	0:M2	0:M3	0:M4	0:M5
MODEL	0:PMOS	0:P_NOCAP	0:P_NOCAP	0:N_NOCAP	0:N_NOCAP	0:PMOS
ID	-2.000E-04	-1.000E-04	-1.000E-04	1.000E-04	1.000E-04	-1.000E-04
IBS	0.	0.	0.	-1.277E-14	-1.277E-14	0.
IBD	1.484E-14	3.239E-14	3.239E-14	-2.967E-14	-2.967E-14	1.516E-14
VGS	-1.854E+00	-1.516E+00	-1.516E+00	1.277E+00	1.277E+00	-1.516E+00
VDS	-1.483E+00	-3.239E+00	-3.239E+00	1.690E+00	1.690E+00	-1.516E+00
VBS	0.	0.	0.	-1.277E+00	-1.277E+00	0.
VTH	-7.000E-01	-7.000E-01	-7.000E-01	7.000E-01	7.000E-01	-7.000E-01
VDSAT	-1.154E+00	-8.165E-01	-8.165E-01	5.774E-01	5.774E-01	-8.165E-01
BETA	3.000E-04	3.000E-04	3.000E-04	6.000E-04	6.000E-04	3.000E-04
GAM EFF	0.	0.	0.	0.	0.	0.
GM	3.464E-04	2.449E-04	2.449E-04	3.464E-04	3.464E-04	2.449E-04
GDS	0.	0.	0.	0.	0.	0.
GMB	0.	0.	0.	0.	0.	0.
CDTOT	1.259E-14	1.492E-22	1.492E-22	7.781E-23	7.781E-23	1.252E-14
CGTOT	2.643E-14	2.378E-20	2.378E-20	2.402E-20	2.402E-20	2.661E-14
CSTOT	3.302E-14	2.302E-20	2.302E-20	2.302E-20	2.302E-20	3.302E-14
CBTOT	1.988E-14	6.126E-22	6.126E-22	9.206E-22	9.206E-22	1.999E-14
CGS	2.302E-14	2.302E-20	2.302E-20	2.302E-20	2.302E-20	2.302E-14
CGD	3.059E-15	1.492E-22	1.492E-22	7.781E-23	7.781E-23	3.061E-15

ELEMENT	0:M6	0:M7	0:M8	0:M9	0:M10
MODEL	0:PMOS	0:PMOS	0:PMOS	0:N_NOCAP	0:N_NOCAP
ID	-1.000E-04	-1.000E-04	-1.000E-04	2.000E-04	2.000E-04
IBS	0.	0.	0.	0.	0.
IBD	1.516E-14	1.516E-14	1.516E-14	-1.277E-14	-1.277E-14
VGS	-1.516E+00	-1.516E+00	-1.516E+00	1.277E+00	1.277E+00
VDS	-1.516E+00	-1.516E+00	-1.516E+00	1.277E+00	1.277E+00
VBS	0.	0.	0.	0.	0.
VTH	-7.000E-01	-7.000E-01	-7.000E-01	7.000E-01	7.000E-01
VDSAT	-8.165E-01	-8.165E-01	-8.165E-01	5.773E-01	5.773E-01
BETA	3.000E-04	3.000E-04	3.000E-04	1.200E-03	1.200E-03
GAM EFF	0.	0.	0.	0.	0.
GM	2.449E-04	2.449E-04	2.449E-04	6.928E-04	6.928E-04
GDS	0.	0.	0.	0.	0.
GMB	0.	0.	0.	0.	0.
CDTOT	1.252E-14	1.252E-14	1.252E-14	1.176E-22	1.176E-22
CGTOT	2.661E-14	2.661E-14	2.661E-14	4.800E-20	4.800E-20
CSTOT	3.302E-14	3.302E-14	3.302E-14	4.604E-20	4.604E-20
CBTOT	1.999E-14	1.999E-14	1.999E-14	1.841E-21	1.841E-21
CGS	2.302E-14	2.302E-14	2.302E-14	4.604E-20	4.604E-20
CGD	3.061E-15	3.061E-15	3.061E-15	1.176E-22	1.176E-22

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

```
     V(16)/VI1                                 =  2.425E+08
     INPUT RESISTANCE AT          VI1          =  9.999E+19
     OUTPUT RESISTANCE AT V(16)                =  9.901E+11
```

****** AC ANALYSIS   TNOM= 27.000 TEMP= 27.000

```
     FREQ       V(16)
(A         )    0.           1.000E-00     2.000E+00     3.000E+00     4.000E+00
                    +             +             +             +             +
 1.000E+07  3.87E+00-+------+------+------+------+------+------+------+----A-+-
 1.059E+07  3.65E+00 +      +      +      +      +      +      +      + A    +
 1.122E+07  3.45E+00 +      +      +      +      +      +      +     A+      +
 1.188E+07  3.25E+00 +      +      +      +      +      +      +  A   +      +
 1.258E+07  3.07E+00 +      +      +      +      +      +      +A     +      +
 1.333E+07  2.90E+00 +      +      +      +      +      +     A+      +      +
 1.412E+07  2.74E+00 +      +      +      +      +      +  A   +      +      +
 1.496E+07  2.58E+00 +      +      +      +      +      +A     +      +      +
 1.584E+07  2.44E+00 +      +      +      +      +     A+      +      +      +
 1.678E+07  2.30E+00 +      +      +      +      +   A  +      +      +      +
 1.778E+07  2.17E+00-+------+------+------+------+-A----+------+------+------+-
 1.883E+07  2.05E+00 +      +      +      +      +A     +      +      +      +
 1.995E+07  1.94E+00 +      +      +      +     A+      +      +      +      +
 2.113E+07  1.83E+00 +      +      +      +    A +      +      +      +      +
 2.238E+07  1.72E+00 +      +      +      +  A   +      +      +      +      +
 2.371E+07  1.63E+00 +      +      +      + A    +      +      +      +      +
 2.511E+07  1.54E+00 +      +      +      +A     +      +      +      +      +
 2.660E+07  1.45E+00 +      +      +     A+      +      +      +      +      +
 2.818E+07  1.37E+00 +      +      +    A +      +      +      +      +      +
 2.985E+07  1.29E+00 +      +      +   A  +      +      +      +      +      +
 3.162E+07  1.22E+00-+------+------+--A---+------+------+------+------+------+-
 3.349E+07  1.15E+00 +      +      + A    +      +      +      +      +      +
 3.548E+07  1.08E+00 +      +      +A     +      +      +      +      +      +
 3.758E+07  1.02E+00 +      +      A      +      +      +      +      +      +
 3.981E+07  9.70E-01 +      +      A      +      +      +      +      +      +
 4.217E+07  9.16E-01 +      +     A+      +      +      +      +      +      +
 4.466E+07  8.64E-01 +      +    A +      +      +      +      +      +      +
 4.731E+07  8.15E-01 +      +   A  +      +      +      +      +      +      +
 5.011E+07  7.69E-01 +      +   A  +      +      +      +      +      +      +
 5.308E+07  7.26E-01 +      +  A   +      +      +      +      +      +      +
 5.623E+07  6.85E-01-+------+--A---+------+------+------+------+------+------+-
 5.956E+07  6.46E-01 +      + A    +      +      +      +      +      +      +
 6.309E+07  6.09E-01 +      + A    +      +      +      +      +      +      +
 6.683E+07  5.75E-01 +      +A     +      +      +      +      +      +      +
 7.079E+07  5.42E-01 +      +A     +      +      +      +      +      +      +
 7.498E+07  5.11E-01 +      A      +      +      +      +      +      +      +
 7.943E+07  4.82E-01 +      A      +      +      +      +      +      +      +
 8.414E+07  4.54E-01 +     A+      +      +      +      +      +      +      +
 8.912E+07  4.29E-01 +     A+      +      +      +      +      +      +      +
 9.440E+07  4.03E-01 +     A+      +      +      +      +      +      +      +
 1.000E+08  3.80E-01-+----A-+------+------+------+------+------+------+------+-
                    +             +             +             +             +
```

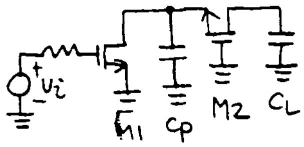
```
     FREQ       VP(16)
(A         )   -9.800E+01    -9.600E+01    -9.400E+01    -9.200E+01    -9.000E+01
                    +             +             +             +             +
 1.000E+07 -9.07E+01-+------+------+------+------+------+------+------+A-----+-
 1.059E+07 -9.08E+01 +      +      +      +      +      +      +      +A     +
 1.122E+07 -9.08E+01 +      +      +      +      +      +      +      +A     +
 1.188E+07 -9.09E+01 +      +      +      +      +      +      +      A      +
 1.258E+07 -9.09E+01 +      +      +      +      +      +      +      A      +
 1.333E+07 -9.10E+01 +      +      +      +      +      +      +      A      +
 1.412E+07 -9.11E+01 +      +      +      +      +      +      +     A+      +
 1.496E+07 -9.11E+01 +      +      +      +      +      +      +     A+      +
 1.584E+07 -9.12E+01 +      +      +      +      +      +      +    A +      +
 1.678E+07 -9.13E+01 +      +      +      +      +      +      +    A +      +
 1.778E+07 -9.14E+01-+------+------+------+------+------+------+---A--+------+-
 1.883E+07 -9.14E+01 +      +      +      +      +      +      +   A  +      +
 1.995E+07 -9.15E+01 +      +      +      +      +      +      +  A   +      +
 2.113E+07 -9.16E+01 +      +      +      +      +      +      + A    +      +
 2.238E+07 -9.17E+01 +      +      +      +      +      +      + A    +      +
 2.371E+07 -9.18E+01 +      +      +      +      +      +      +A     +      +
 2.511E+07 -9.19E+01 +      +      +      +      +      +      A      +      +
 2.660E+07 -9.20E+01 +      +      +      +      +      +     A+      +      +
 2.818E+07 -9.22E+01 +      +      +      +      +      +     A+      +      +
 2.985E+07 -9.23E+01 +      +      +      +      +      +    A +      +      +
 3.162E+07 -9.24E+01-+------+------+------+------+------+---A--+------+------+-
 3.349E+07 -9.26E+01 +      +      +      +      +      + A    +      +      +
 3.548E+07 -9.27E+01 +      +      +      +      +      +A     +      +      +
 3.758E+07 -9.29E+01 +      +      +      +      +      A      +      +      +
 3.981E+07 -9.31E+01 +      +      +      +      +     A+      +      +      +
 4.217E+07 -9.33E+01 +      +      +      +      +    A +      +      +      +
 4.466E+07 -9.34E+01 +      +      +      +      +   A  +      +      +      +
 4.731E+07 -9.37E+01 +      +      +      +      + A    +      +      +      +
 5.011E+07 -9.39E+01 +      +      +      +      +A     +      +      +      +
 5.308E+07 -9.41E+01 +      +      +      +     A+      +      +      +      +
 5.623E+07 -9.43E+01-+------+------+------+----A-+------+------+------+------+-
 5.956E+07 -9.46E+01 +      +      +      +  A   +      +      +      +      +
 6.309E+07 -9.49E+01 +      +      +      +A     +      +      +      +      +
 6.683E+07 -9.51E+01 +      +      +     A+      +      +      +      +      +
 7.079E+07 -9.54E+01 +      +      +   A  +      +      +      +      +      +
 7.498E+07 -9.58E+01 +      +      +A     +      +      +      +      +      +
 7.943E+07 -9.61E+01 +      +     A+      +      +      +      +      +      +
 8.414E+07 -9.64E+01 +      +   A  +      +      +      +      +      +      +
 8.912E+07 -9.68E+01 +      +A     +      +      +      +      +      +      +
 9.440E+07 -9.72E+01 +     A+      +      +      +      +      +      +      +
 1.000E+08 -9.76E+01-+-A----+------+------+------+------+------+------+------+-
                    +             +             +             +             +
```

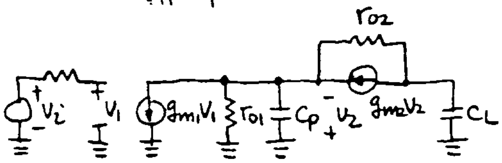
*****

UNITY GAIN FREQUENCY = 37.58 MEGAHERTZ

PHASE = -92.9 DEGREES @ 37.58 MEGAHERTZ

7.43





$$g_{m2} = \sqrt{2k'\frac{W}{L}I_D} = \sqrt{2\times 180\times 10^{-6}\times\frac{20}{0.5}\times 100\times 10^{-6}}$$

$$= 1.2\times 10^{-3}\,A/V$$

$$r_{o1} = \frac{1}{\lambda I_D} = \frac{1}{0.04\times 100\times 10^{-6}} = 2.5\times 10^5\,\Omega = r_{o2}$$

(a) With C_L open

$$C_P r_{o1} = 0.2\times 10^{-12}\times 2.5\times 10^5 = 5\times 10^{-8}\,s$$

With Cp open

$$C_L(r_{o1}+r_{o2}+g_{m2}r_{o1}r_{o2})$$

$$= 2\times 10^{-12}(2.5\times 10^5 + 2.5\times 10^5 + 1.2\times 10^{-3}\times 2.5\times 10^5 \times 2.5\times 10^5)$$

$$= 1.5\times 10^{-4}\,s$$

$$P_1 = -\frac{1}{5\times 10^{-8} + 1.5\times 10^{-4}} = -6.6\times 10^3\,rad/s$$

(b) With Cp short

$$C_L r_{o2} = 2\times 10^{-12}\times 2.5\times 10^5 = 5\times 10^{-7}\,s$$

With C_L short

$$C_P\left(\frac{1}{g_{m2}} \| r_{o1} \| r_{o2}\right) \approx \frac{C_P}{g_{m2}} = \frac{0.2\times 10^{-12}}{1.2\times 10^{-3}}$$

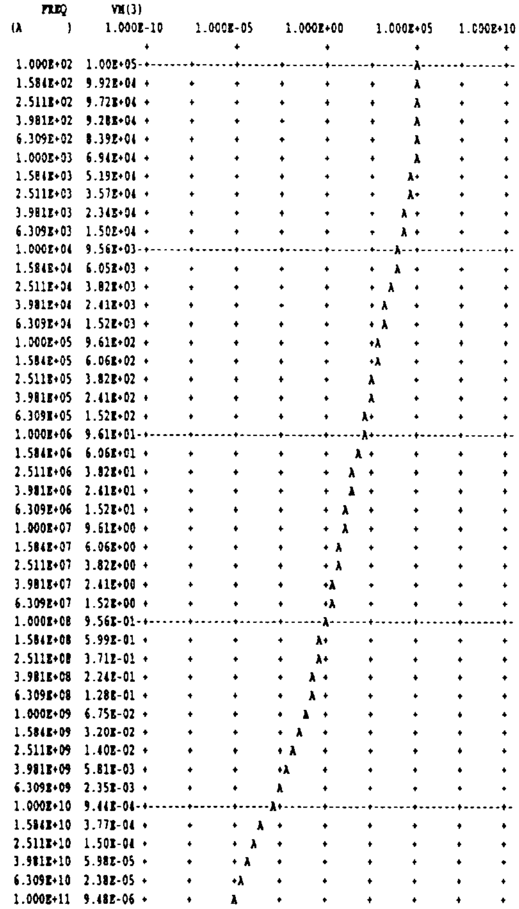
$$= 1.7\times 10^{-10}\,s$$

$$P_2 = -\left(\frac{1}{5\times 10^{-7}} + \frac{1}{1.7\times 10^{-10}}\right) \approx -6\times 10^9\,rad/s$$

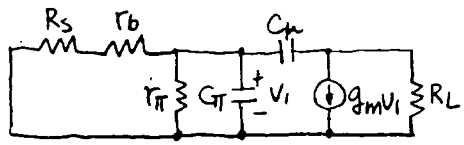
7-63

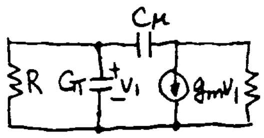
```
MOS CASCODE STAGE
VI   1   0   DC 1.165 AC 1
VB1  4   0   1.67
VB2  5   0   5
IB   5   3   100U
CP   2   0   0.2P
CL   3   0   2P
M1   2   1   0   0    CMOSN  W=20U  L=0.5U
M2   3   4   2   2    CMOSN  W=20U  L=0.5U
.MODEL CMOSN NMOS VT0=1 KP=180U LAMBDA=0.04
.OPTIONS NOMOD
.AC DEC 5 100 100G
.PLOT AC VM(3)
.WIDTH OUT=80
.OPTIONS SPICE
.END

 ******  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
+0:1        = 1.165E+00 0:2        = 5.076E-01 0:3        = 1.838E+00
+0:4        = 1.670E+00 0:5        = 5.000E+00

**** MOSFETS

SUBCKT
ELEMENT  0:M1        0:M2
MODEL    0:CMOSN     0:CMOSN
 ID       1.000E-04   1.000E-04
 IBS        0.          0.
 IBD     -5.076E-15  -1.331E-14
 VGS      1.165E+00   1.162E+00
 VDS      5.076E-01   1.331E+00
 VBS        0.          0.
 VTH      1.000E+00   1.000E+00
 VDSAT    1.650E-01   1.624E-01
 BETA     7.346E-03   7.583E-03
 GAM EFF    0.          0.
 GM       1.212E-03   1.232E-03
 GDS      3.920E-06   3.798E-06
 GMB        0.          0.
 CDTOT      0.          0.
 CGTOT      0.          0.
 CSTOT      0.          0.
 CBTOT      0.          0.
 CGS        0.          0.
 CGD        0.          0.

 ******  AC ANALYSIS                          TNOM=  27.000 TEMP=  27.000
```

FREQ	VM(3)
1.000E+02	1.00E+05
1.584E+02	9.92E+04
2.511E+02	9.72E+04
3.981E+02	9.28E+04
6.309E+02	8.39E+04
1.000E+03	6.94E+04
1.584E+03	5.19E+04
2.511E+03	3.57E+04
3.981E+03	2.34E+04
6.309E+03	1.50E+04
1.000E+04	9.56E+03
1.584E+04	6.05E+03
2.511E+04	3.82E+03
3.981E+04	2.41E+03
6.309E+04	1.52E+03
1.000E+05	9.61E+02
1.584E+05	6.06E+02
2.511E+05	3.82E+02
3.981E+05	2.41E+02
6.309E+05	1.52E+02
1.000E+06	9.61E+01
1.584E+06	6.06E+01
2.511E+06	3.82E+01
3.981E+06	2.41E+01
6.309E+06	1.52E+01
1.000E+07	9.61E+00
1.584E+07	6.06E+00
2.511E+07	3.82E+00
3.981E+07	2.41E+00
6.309E+07	1.52E+00
1.000E+08	9.56E-01
1.584E+08	5.99E-01
2.511E+08	3.71E-01
3.981E+08	2.24E-01
6.309E+08	1.28E-01
1.000E+09	6.75E-02
1.584E+09	3.20E-02
2.511E+09	1.40E-02
3.981E+09	5.81E-03
6.309E+09	2.35E-03
1.000E+10	9.44E-04
1.584E+10	3.77E-04
2.511E+10	1.50E-04
3.981E+10	5.98E-05
6.309E+10	2.38E-05
1.000E+11	9.48E-06



7.44





$R_S = 5k\Omega,\ r_b = 300\Omega,\ r_\pi = 10.4k\Omega,$

$R_L = 3k\Omega,\ R = (R_S + r_b) // r_\pi = 3.5k\Omega$

$g_m = \frac{I_C}{V_T} = \frac{0.5mA}{26mV} = 0.019 A/V$

$C_\pi = 5.8pF,\ C_\mu = 0.3pF$

The dominant pole (open circuit TC)

$C_\pi R = 5.8\times10^{-12}\times3.5\times10^{3} = 2\times10^{-8}s$

$C_\mu(R + R_L + g_m R R_L)$

$= 0.3\times10^{-12}(3.5\times10^3 + 3\times10^3 + 0.019\times3.5\times10^3\times3\times10^3)$

$= 6.2\times10^{-8}s$

$$P_1 = -\frac{1}{2\times10^{-8} + 6.2\times10^{-8}} = -1.2\times10^{7} rad/s$$

The nondominant pole (short circuit TC)

$C_\pi(R // \frac{1}{g_m} // R_L) = 5.8\times10^{-12}(3.5\times10^3 // \frac{1}{0.019} // 3\times10^3)$

$= 3\times10^{-10}s$

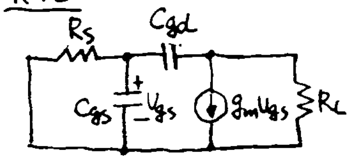
$C_\mu R_L = 0.3\times10^{-12}\times3\times10^3 = 9\times10^{-10}s$

$$P_2 = -\left(\frac{1}{3\times10^{-10}} + \frac{1}{9\times10^{-10}}\right) = -4.4\times10^{9} rad/s$$

```
COMMON EMITTER GAIN STAGE
VCC 1 0 5V
RL 1 2 3K
Q1 2 3 0 NPN
RS 4 3 5K
VI 4 0 0.7696 AC
.PLOT AC VDB(2)
.AC DEC 8 100K 10GIG
.MODEL NPN NPN IS=1E-16A BF=200
+ RB=300 CJC=0.3PF CJS=0 TF=302PS
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

 ******  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
+0:1       = 5.000E+00 0:2       = 3.497E+00 0:3       = 7.571E-01
+0:4       = 7.696E-01

**** BIPOLAR JUNCTION TRANSISTORS
ELEMENT  0:Q1
MODEL    0:NPN
 IB       2.504E-06
 IC       5.009E-04
 VBE      7.571E-01
 VCE      3.497E+00
 VBC     -2.740E+00
 VS      -3.497E+00
 POWER    1.754E-03
 BETAD    2.000E+02
 GM       1.937E-02
 RPI      1.032E+04
 RX       3.000E+02
 RO       2.741E+16
 CPI      5.849E-12
 CMU      1.806E-13
 CBX       0.
 CCS       0.
 BETAAC   2.000E+02
 FT       5.112E+08

 ******  AC ANALYSIS                                TNOM=  27.000 TEMP=  27.000
    FREQ        VDB(2)
(A        )   -1.000E+02    -5.000E+01       0.         5.000E+01    1.000E+02
                   +             +             +             +            +
 1.000E+05  3.16E+01-+------+------+------+------+------+-A----+------+------+-
 1.333E+05  3.16E+01 +      +      +      +      +      + A    +      +      +
 1.778E+05  3.16E+01 +      +      +      +      +      + A    +      +      +
 2.371E+05  3.16E+01 +      +      +      +      +      + A    +      +      +
 3.162E+05  3.16E+01 +      +      +      +      +      + A    +      +      +
 4.217E+05  3.15E+01 +      +      +      +      +      + A    +      +      +
 5.623E+05  3.15E+01 +      +      +      +      +      + A    +      +      +
 7.498E+05  3.13E+01 +      +      +      +      +      + A    +      +      +
 1.000E+06  3.11E+01 +      +      +      +      +      + A    +      +      +
 1.333E+06  3.07E+01 +      +      +      +      +      + A    +      +      +
 1.778E+06  3.01E+01-+------+------+------+------+------+A-----+------+------+-
 2.371E+06  2.92E+01 +      +      +      +      +      +A     +      +      +
 3.162E+06  2.80E+01 +      +      +      +      +      +A     +      +      +
 4.217E+06  2.64E+01 +      +      +      +      +      A      +      +      +
 5.623E+06  2.45E+01 +      +      +      +      +      A      +      +      +
 7.498E+06  2.23E+01 +      +      +      +      +     A+      +      +      +
 1.000E+07  2.01E+01 +      +      +      +      +     A+      +      +      +
 1.333E+07  1.77E+01 +      +      +      +      +    A +      +      +      +
 1.778E+07  1.53E+01 +      +      +      +      +   A  +      +      +      +
 2.371E+07  1.28E+01 +      +      +      +      +   A  +      +      +      +
 3.162E+07  1.03E+01-+------+------+------+------+--A---+------+------+------+-
 4.217E+07  7.89E+00 +      +      +      +      + A    +      +      +      +
 5.623E+07  5.39E+00 +      +      +      +      + A    +      +      +      +
 7.498E+07  2.88E+00 +      +      +      +      +A     +      +      +      +
 1.000E+08  3.56E-01 +      +      +      +      A      +      +      +      +
 1.333E+08 -2.19E+00 +      +      +      +     A+      +      +      +      +
 1.778E+08 -4.77E+00 +      +      +      +     A+      +      +      +      +
 2.371E+08 -7.41E+00 +      +      +      +    A +      +      +      +      +
 3.162E+08 -1.01E+01 +      +      +      +   A  +      +      +      +      +
 4.217E+08 -1.30E+01 +      +      +      +  A   +      +      +      +      +
 5.623E+08 -1.62E+01-+------+------+------+-A----+------+------+------+------+-
 7.498E+08 -1.96E+01 +      +      +      + A    +      +      +      +      +
 1.000E+09 -2.34E+01 +      +      +      A      +      +      +      +      +
 1.333E+09 -2.75E+01 +      +      +     A+      +      +      +      +      +
 1.778E+09 -3.19E+01 +      +      +    A +      +      +      +      +      +
 2.371E+09 -3.65E+01 +      +      +   A  +      +      +      +      +      +
 3.162E+09 -4.12E+01 +      +      + A    +      +      +      +      +      +
 4.217E+09 -4.60E+01 +      +      +A     +      +      +      +      +      +
 5.623E+09 -5.07E+01 +      +      A      +      +      +      +      +      +
 7.498E+09 -5.54E+01 +      +    A +      +      +      +      +      +      +
 1.000E+10 -5.99E+01-+------+---A--+------+------+------+------+------+------+-
                     +             +             +             +             +
```

7-65

7.45



The dominant pole (open circuit TC)

$C_{gs}R_S = 89\times10^{-15}\times10\times10^{3} = 8.9\times10^{-10}s$

$C_{gd}(R_S+R_L+g_mR_SR_L)$

$=14\times10^{-15}(10\times10^{3}+5\times10^{3}+1.9\times10^{-3}\times10\times10^{3}\times5\times10^{3})$

$=1.5\times10^{-9}s$

$$P_1 = -\frac{1}{8.9\times10^{-10}+1.5\times10^{-9}} = -4.2\times10^{8}\,rad/s$$

The nondominant pole (short circuit TC)

$C_{gs}(R_S\|\frac{1}{g_m}\|R_L)$

$=89\times10^{-15}(10\times10^{3}\|\frac{1}{1.9\times10^{-3}}\|5\times10^{3})$

$=4\times10^{-11}s$

$C_{gd}R_L = 14\times10^{-15}\times5\times10^{3} = 7\times10^{-11}s$

$$P_2 = -\left(\frac{1}{4\times10^{-11}}+\frac{1}{7\times10^{-11}}\right) = -3.9\times10^{10}\,rad/s$$

```
COMMON SOURCE AMPLIFIER
VDD 1 0 5
VI 2 0 DC 1.216 AC 1
RS 2 3 10K
RL 1 4 5K
M1 4 3 0 0 CMOSN  W=100U  L=2U
* COX'=0.7FF/UM**2=EOX/TOX => TOX=500 ANGSTROMS
.MODEL CMOSN NMOS LEVEL=1 LAMBDA=0 VTO=0.7 KP=60U LD=0.2U TOX=500E-10
.OPTIONS NOMOD
.AC DEC 10 10MEG 100G
.PLOT AC VM(4)
.WIDTH OUT=80
.OPTIONS SPICE
.END

 ******  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000

+0:1       = 5.000E+00 0:2       = 1.216E+00 0:3       = 1.216E+00
+0:4       = 2.503E+00

**** MOSFETS

ELEMENT  0:M1
MODEL    0:CMOSN
 ID        4.992E-04
 IBS         0.
 IBD      -2.504E-14
 VGS       1.216E+00
 VDS       2.503E+00
 VBS         0.
 VTH       7.000E-01
 VDSAT     5.160E-01
 BETA      3.750E-03
 GAM EFF     0.
 GM        1.935E-03
 GDS         0.
 GMB         0.
 CDTOT     1.418E-14
 CGTOT     1.050E-13
 CSTOT     8.748E-14
 CBTOT     3.349E-15
 CGS       8.748E-14
 CGD       1.418E-14

 ******  AC ANALYSIS                              TNOM=  27.000 TEMP=  27.000

    FREQ       VM(4)
(A       )   1.000E-03     1.000E-02     1.000E-01     1.000E+00     1.000E+01
                 +             +             +             +             +
 1.000E+07  9.56E+00-+------+------+------+------+------+------+------+------A-
 1.258E+07  9.49E+00 +      +      +      +      +      +      +      +      A
 1.584E+07  9.39E+00 +      +      +      +      +      +      +      +      A
 1.995E+07  9.24E+00 +      +      +      +      +      +      +      +      A
 2.511E+07  9.01E+00 +      +      +      +      +      +      +      +     A+
 3.162E+07  8.68E+00 +      +      +      +      +      +      +      +     A+
 3.981E+07  8.23E+00 +      +      +      +      +      +      +      +     A+
 5.011E+07  7.64E+00 +      +      +      +      +      +      +      +    A +
 6.309E+07  6.91E+00 +      +      +      +      +      +      +      +    A +
 7.943E+07  6.09E+00 +      +      +      +      +      +      +      +   A  +
 1.000E+08  5.24E+00-+------+------+------+------+------+------+------+--A---+-
 1.259E+08  4.41E+00 +      +      +      +      +      +      +      + A    +
 1.584E+08  3.64E+00 +      +      +      +      +      +      +      +A     +
 1.995E+08  2.97E+00 +      +      +      +      +      +      +      A      +
 2.511E+08  2.40E+00 +      +      +      +      +      +      +    A +      +
 3.162E+08  1.93E+00 +      +      +      +      +      +      +   A  +      +
 3.981E+08  1.54E+00 +      +      +      +      +      +      +  A   +      +
 5.011E+08  1.23E+00 +      +      +      +      +      +      +A     +      +
 6.309E+08  9.79E-01 +      +      +      +      +      +      A      +      +
 7.943E+08  7.77E-01 +      +      +      +      +      +     A +      +      +
 1.000E+09  6.15E-01-+------+------+------+------+------+---A--+------+------+-
 1.258E+09  4.86E-01 +      +      +      +      +      +  A   +      +      +
 1.584E+09  3.82E-01 +      +      +      +      +      +A     +      +      +
 1.995E+09  2.98E-01 +      +      +      +      +      A      +      +      +
 2.511E+09  2.31E-01 +      +      +      +      +    A +      +      +      +
 3.162E+09  1.77E-01 +      +      +      +      +  A   +      +      +      +
 3.981E+09  1.33E-01 +      +      +      +      + A    +      +      +      +
 5.011E+09  9.87E-02 +      +      +      +      A      +      +      +      +
 6.309E+09  7.16E-02 +      +      +      +    A +      +      +      +      +
 7.943E+09  5.09E-02 +      +      +      +  A   +      +      +      +      +
 1.000E+10  3.58E-02-+------+------+------+A-----+------+------+------+------+-
 1.258E+10  2.50E-02 +      +      +     A+      +      +      +      +      +
 1.584E+10  1.75E-02 +      +      +  A   +      +      +      +      +      +
 1.995E+10  1.24E-02 +      +      +A     +      +      +      +      +      +
 2.511E+10  8.96E-03 +      +     A+      +      +      +      +      +      +
 3.162E+10  6.60E-03 +      +   A  +      +      +      +      +      +      +
 3.981E+10  4.96E-03 +      +  A   +      +      +      +      +      +      +
 5.011E+10  3.78E-03 +      +A     +      +      +      +      +      +      +
 6.309E+10  2.92E-03 +      A      +      +      +      +      +      +      +
 7.943E+10  2.28E-03 +    A +      +      +      +      +      +      +      +
 1.000E+11  1.79E-03-+---A--+------+------+------+------+------+------+------+-
                     +             +             +             +             +
```

7.46

To calculate the dominant pole, calculate the open circuit time constants

$C_{in}R = 0.2\times10^{-12}\times20\times10^{3} = 4\times10^{-9}\,s$

$C(R+R_o+\frac{a_v}{R_o}RR_o) = C(R+R_o+a_vR)$

$= C[(1+a_v)R+R_o]$

$= 50\times10^{-12}[(1+1000)20\times10^{3}+5\times10^{3}]$

$= 1\times10^{-3}\,s$

$$P_1 = -\frac{1}{4\times10^{-9}+1\times10^{-3}} = -1\times10^{3}\,rad/s$$

To calculate the nondominant pole, calculate the short circuit time constants

$C_{in}(R \| \frac{R_o}{a_v} \| R_o) = 0.2\times10^{-12}(20\times10^{3} \| \frac{5\times10^{3}}{1000} \| 5\times10^{3})$

$= 1\times10^{-12}\,s$

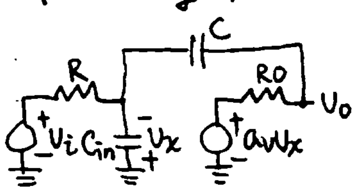
$CR_o = 50\times10^{-12}\times5\times10^{3} = 2.5\times10^{-7}\,s$

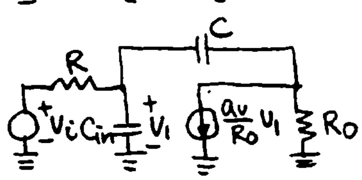
$$P_2 = -(\frac{1}{1\times10^{-12}}+\frac{1}{2.5\times10^{-7}}) = -1\times10^{12}\,rad/s$$

Note that there is a zero at

$$z = -\frac{a_v/R_o}{C} = -\frac{1000/5\times10^{3}}{50\times10^{-12}} = -4\times10^{9}\,rad/s$$

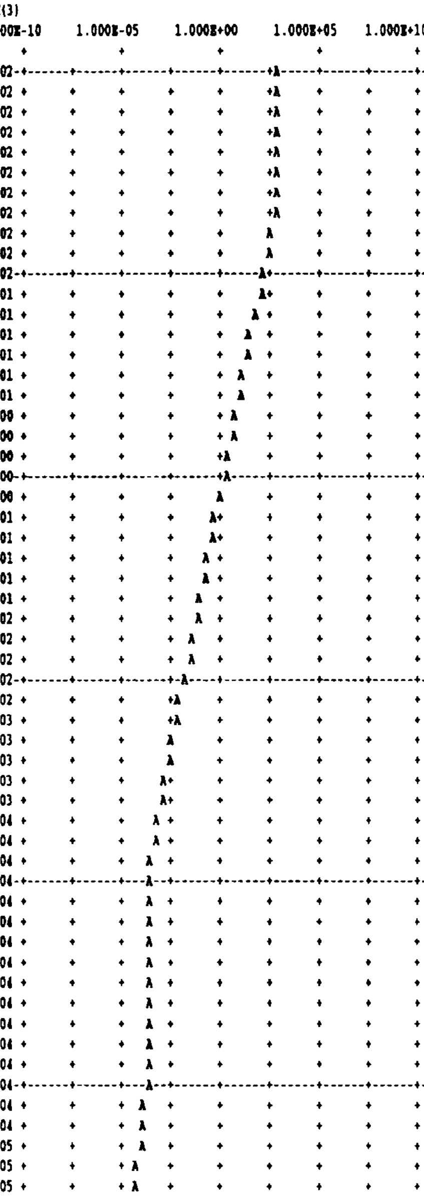
It is between the two poles and confirmed by SPICE.



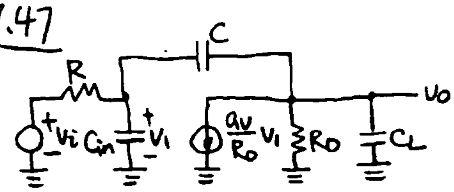



```
INTEGRATOR
VI   1    0    AC   1
R    1    2    20K
RO   3    4    5K
CIN  2    0    0.2P
C    2    3    50P
E    4    0    0    2    1000
.OPTIONS NOMOD
.AC DEC 5 10 1000G
.PLOT AC VM(3)
.WIDTH OUT=80
.OPTIONS SPICE
.END

****** OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000

+0:1     =   0.       0:2      =   0.      0:3      =   0.
+0:4     =   0.

****** AC ANALYSIS                      TNOM=  27.000 TEMP=  27.000
```

FREQ (A)	VM(3)
1.000E+01	9.98E+02
1.584E+01	9.95E+02
2.511E+01	9.87E+02
3.981E+01	9.70E+02
6.309E+01	9.29E+02
1.000E+02	8.46E+02
1.584E+02	7.08E+02
2.511E+02	5.34E+02
3.981E+02	3.70E+02
6.309E+02	2.44E+02
1.000E+03	1.57E+02
1.584E+03	9.97E+01
2.511E+03	6.31E+01
3.981E+03	3.99E+01
6.309E+03	2.51E+01
1.000E+04	1.58E+01
1.584E+04	1.00E+01
2.511E+04	6.32E+00
3.981E+04	3.99E+00
6.309E+04	2.51E+00
1.000E+05	1.59E+00
1.584E+05	1.00E+00
2.511E+05	6.33E-01
3.981E+05	3.99E-01
6.309E+05	2.52E-01
1.000E+06	1.59E-01
1.584E+06	1.00E-01
2.511E+06	6.33E-02
3.981E+06	3.99E-02
6.309E+06	2.52E-02
1.000E+07	1.59E-02
1.584E+07	1.00E-02
2.511E+07	6.33E-03
3.981E+07	4.00E-03
6.309E+07	2.53E-03
1.000E+08	1.61E-03
1.584E+08	1.03E-03
2.511E+08	6.80E-04
3.981E+08	4.71E-04
6.309E+08	3.55E-04
1.000E+09	2.96E-04
1.584E+09	2.69E-04
2.511E+09	2.58E-04
3.981E+09	2.53E-04
6.309E+09	2.51E-04
1.000E+10	2.50E-04
1.584E+10	2.49E-04
2.511E+10	2.47E-04
3.981E+10	2.42E-04
6.309E+10	2.32E-04
1.000E+11	2.11E-04
1.584E+11	1.77E-04
2.511E+11	1.34E-04
3.981E+11	9.28E-05
6.309E+11	6.11E-05
1.000E+12	3.93E-05



7.47



The zero value time constants

$C_{in}R = 0.2\times10^{-12}\times 20\times10^{3} = 4\times10^{-9}s$

$C(R+R_o+\frac{a_v}{R_o}RR_o) = C(R+R_o+a_vR)$

$= C[(1+a_v)R+R_o]$

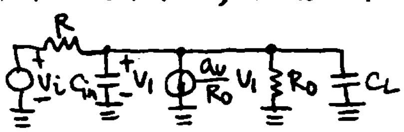
$= 50\times10^{-12}[(1+1000)20\times10^{3}+5\times10^{3}]$

$= 1\times10^{-3}s$

$C_LR_o = 0.5\times10^{-12}\times5\times10^{3} = 2.5\times10^{-9}s$

$$P_1 = -\frac{1}{4\times10^{-9}+1\times10^{-3}+2.5\times10^{-9}} = -1\times10^{3}\text{ rad/s}$$

$1\times10^{-3}s \gg 4\times10^{-9}s, 2.5\times10^{-9}s$. C is shorted.



$(C_{in}+C)(R\|\frac{R_o}{a_v}\|R_o)$

$\approx (C_{in}+C)\frac{R_o}{a_v}$

$= (0.2+0.5)\times10^{-12}\frac{5\times10^{3}}{1000}$

$= 3.5\times10^{-12}s$

$$P_2 = -\frac{1}{3.5\times10^{-12}} = -2.9\times10^{11}\text{ rad/s.}$$

Note that there is a zero at

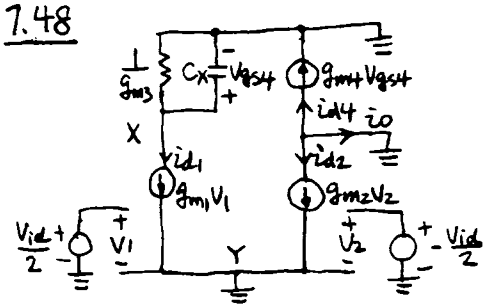
$$z = -\frac{a_v/R_o}{C} = -\frac{1000/5\times10^{3}}{50\times10^{-12}} = -4\times10^{9}\text{ rad/s}$$

It is between the two poles and confirmed by SPICE.

```
INTEGRATOR
VI  1  0  AC  1
R   1  2  20K
RO  3  4  5K
CIN 2  0  0.2P
C   2  3  50P
CL  3  0  0.5P
E   4  0  0  2   1000
.OPTIONS NOMOD
.AC DEC 5 10 100G
.PLOT AC VM(3)
.WIDTH OUT=80
.OPTIONS SPICE
.END

******  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000

+0:1      =  0.       0:2      =  0.       0:3      =  0.
+0:4      =  0.

******  AC ANALYSIS                      TNOM=  27.000 TEMP=  27.000

   FREQ       VM(3)
(A        )   1.000E-04    1.000E-02    1.000E+00    1.000E+02    1.000E+04
```

FREQ	VM(3)
1.000E+01	9.98E+02
1.584E+01	9.95E+02
2.511E+01	9.87E+02
3.981E+01	9.70E+02
6.309E+01	9.29E+02
1.000E+02	8.46E+02
1.584E+02	7.08E+02
2.511E+02	5.34E+02
3.981E+02	3.70E+02
6.309E+02	2.44E+02
1.000E+03	1.57E+02
1.584E+03	9.97E+01
2.511E+03	6.31E+01
3.981E+03	3.99E+01
6.309E+03	2.51E+01
1.000E+04	1.58E+01
1.584E+04	1.00E+01
2.511E+04	6.32E+00
3.981E+04	3.99E+00
6.309E+04	2.51E+00
1.000E+05	1.59E+00
1.584E+05	1.00E+00
2.511E+05	6.33E-01
3.981E+05	3.99E-01
6.309E+05	2.52E-01
1.000E+06	1.59E-01
1.584E+06	1.00E-01
2.511E+06	6.33E-02
3.981E+06	3.99E-02
6.309E+06	2.52E-02
1.000E+07	1.59E-02
1.584E+07	1.00E-02
2.511E+07	6.33E-03
3.981E+07	4.00E-03
6.309E+07	2.53E-03
1.000E+08	1.61E-03
1.584E+08	1.03E-03
2.511E+08	6.80E-04
3.981E+08	4.71E-04
6.309E+08	3.55E-04
1.000E+09	2.96E-04
1.584E+09	2.69E-04
2.511E+09	2.57E-04
3.981E+09	2.52E-04
6.309E+09	2.49E-04
1.000E+10	2.44E-04
1.584E+10	2.36E-04
2.511E+10	2.19E-04
3.981E+10	1.88E-04
6.309E+10	1.46E-04
1.000E+11	1.03E-04

7.48



Ignore all r_o's and capacitances except C_x

$$i_{d1} = \frac{1}{2} g_{m1} V_{id}$$

$$V_{gs4} = -i_{d1}\left(\frac{1}{g_{m3}} \| \frac{1}{sC_x}\right) = -i_{d1}\frac{1}{g_{m3}+sC_x}$$

$$i_{d4} = g_{m4} V_{gs4}$$

$$i_{d2} = -\frac{1}{2} g_{m2} V_{id}$$

$$g_{m1} = g_{m2},\ g_{m3} = g_{m4}$$

$$\therefore i_o = -i_{d2} - i_{d4}$$

$$= \frac{1}{2} g_{m1} V_{id} - g_{m3} V_{gs4}$$

$$= \frac{1}{2} g_{m1} V_{id} + g_{m3}\frac{i_{d1}}{g_{m3}+sC_x}$$

$$= \frac{1}{2} g_{m1} V_{id} + g_{m3}\frac{1}{2} g_{m1} V_{id}\frac{1}{g_{m3}+sC_x}$$

$$= \frac{1}{2} g_{m1} V_{id}\left(1+\frac{g_{m3}}{g_{m3}+sC_x}\right)$$

$$= g_{m1} V_{id}\frac{1+sC_x/2g_{m3}}{1+sC_x/g_{m3}}$$

$$p = -\frac{g_{m3}}{C_x}$$

$$z = -2\frac{g_{m3}}{C_x}$$

7.49

$$g_{m3} = \frac{2|I_{D3}|}{|V_{ov3}|} = \frac{2\times 100\mu A}{0.2V} = 1mA/V$$

$$p = -\frac{g_{m3}}{C_x} = -\frac{1mA/V}{0.1pF} = -10^{10}\,rad/s$$

$$z = -2\frac{g_{m3}}{C_x} = -2\times 10^{10}\,rad/s$$

CHAPTER 8

8.1

(a) $A = \frac{a}{1+af} = \frac{10^5}{1+100} = 990.1$

$\frac{\delta A}{A} = \frac{\delta a}{a} \frac{1}{1+T} = \frac{10}{101} = 0.1\ \%$

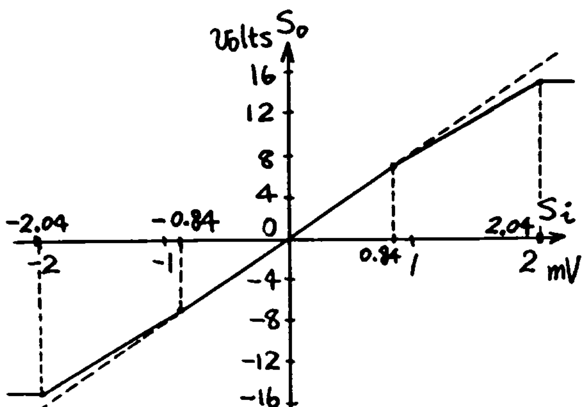
(b) $A = \frac{10^5}{1+10^4} = 9.999$

$\frac{\delta A}{A} = \frac{10}{10{,}001} = 0.001\ \%$

8.2

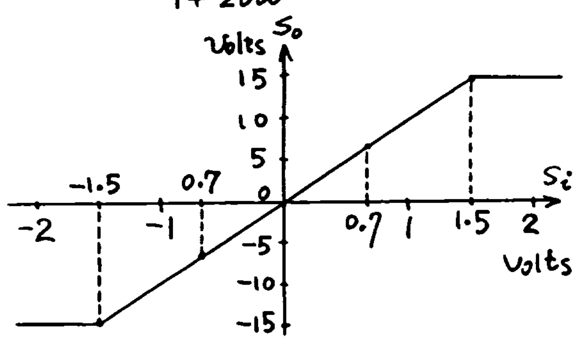
(a) $A_1 = \frac{a_1}{1+a_1 f} = \frac{50{,}000}{1+5} = 8333$

$A_2 = \frac{20{,}000}{1+2} = 6667$



(b) $A_1 = \frac{50{,}000}{1+5000} = 9.998$

$A_2 = \frac{20{,}000}{1+2000} = 9.995$



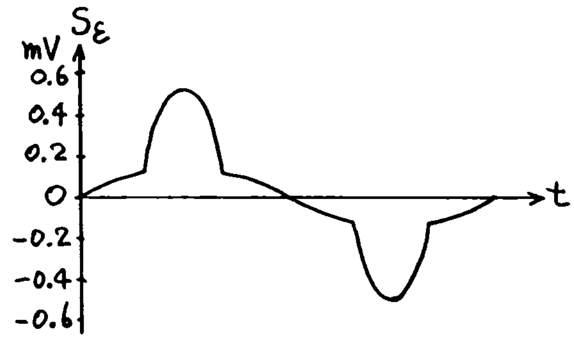
8.3

(a) $\Delta S_\varepsilon = \frac{\Delta S_i}{1+af}$

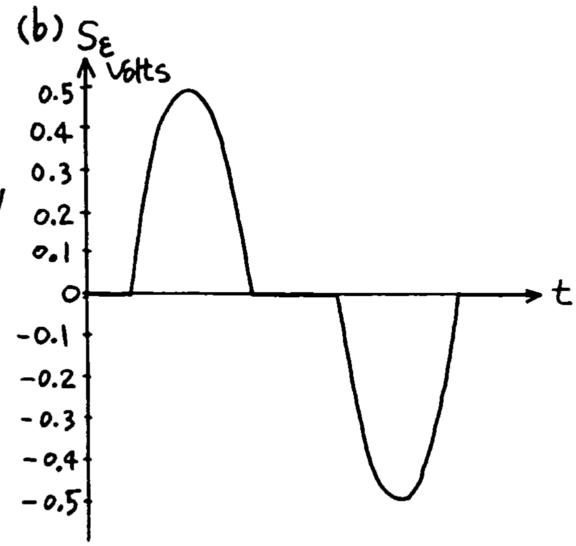
For $|S_i| < 0.7\text{V}$ $\quad 1+af = 5001$

For $0.7\text{V} < |S_i| < 1.5\text{V}$ $\quad 1+af = 2001$

For $|S_i| > 1.5\text{V}$ $\quad 1+af = 1$



(b)



8.4

$i_i = i_\varepsilon + i_{fb}$

$i_o = a i_\varepsilon = a(i_i - i_{fb})$

$\quad = a i_i - af\, i_o$

$\therefore \frac{i_o}{i_i} = \frac{a}{1+af}$ ------------ (8.40)

$$v_i = i_\varepsilon Z_i = \frac{i_o}{a} Z_i = \frac{Z_i}{a}\,\frac{a}{1+af}\, i_i$$

$$\therefore Z_{ii} = \frac{v_i}{i_i} = \frac{z_i}{1+T} \quad \text{-------(8.41)}$$

Apply a voltage v_o at the output and open-circuit input

$$i_o = \frac{v_o}{z_o} + a i_\varepsilon = \frac{v_o}{z_o} - af\, i_o$$

$$\therefore i_o(1+T) = \frac{v_o}{z_o}$$

$$\therefore Z_{io} = \frac{v_o}{i_o} \quad \frac{z_o}{1+T}$$

8.5

$$v_i = v_\varepsilon + v_{fb}$$

$$i_o = a v_\varepsilon = a(v_i - v_{fb})$$

$$= a v_i - af\, i_o$$

$$\therefore \frac{i_o}{v_i} = \frac{a}{1+af} \quad \text{------------(8.43)}$$

$$i_\varepsilon = \frac{v_\varepsilon}{z_i} = \frac{i_o}{a}\,\frac{1}{z_i} = \frac{v_i}{1+af}\,\frac{1}{z_i}$$

$$\therefore Z_{ii} = \frac{v_i}{i_\varepsilon} = z_i(1+T)$$

Apply a voltage v_o at the output and short-circuit the input

$$i_o = \frac{v_o}{z_o} + a v_\varepsilon = \frac{v_o}{z_o} - af\, i_o$$

$$\therefore i_o(1+T) = \frac{v_o}{z_o}$$

$$\therefore Z_{io} = \frac{v_o}{i_o} = z_o(1+T)$$

8.6(a)

From (8.66)

$$Z_{ia} = \frac{R_F Z_i}{R_F + Z_i} = \frac{100 \times 500}{600} = 83.3\ \text{k}\Omega$$

From (8.68)

$$Z_{oa} = Z_o \| R_F \| R_L$$

$$= 200 \| 100\text{k} \| 15\text{K}$$

$$\simeq 200\,\Omega$$

From (8.70)

$$T = \left(\frac{10^5 \times 15 \times 10^3}{10^5 \times 15 \times 10^3 + 200 \times 10^5 + 200 \times 15 \times 10^3}\right) \times 75{,}000 \times \frac{500}{600}$$

$$= 61{,}560$$

Thus with feedback

$$Z_i = \frac{83.3\text{K}}{61{,}560} = 1.4\,\Omega$$

$$Z_o = \frac{200}{61{,}560} = 0.0032\,\Omega$$

$$A = \frac{1}{f}\,\frac{1}{1+\frac{1}{T}} = \frac{100\text{k}\Omega}{1+\frac{1}{61{,}560}}$$

$$= 99.998\ \text{K}\Omega$$

8.6(b)

$$\mathcal{R} = \frac{R_L \| (R_F + Z_i)}{Z_0 + R_L \| (R_F + Z_i)} \frac{Z_i}{Z_i + R_F} a_v$$

$$= \frac{15k \| (100k + 500k)}{200 + 15k \| (100k + 500k)} \frac{500k}{500k + 100k} 75000$$

$$= 6.16 \times 10^4$$

$$A_\infty = -R_F = -100\,k\Omega$$

$$d = \frac{v_o}{i_i}\Big|_{a_v=0} = \frac{Z_i}{Z_i + [R_F + Z_0 \| R_L]} (Z_0 \| R_L)$$

$$= \frac{500k}{500k + 100k + 200 \| 15k} (200 \| 15k)$$

$$= 160\,\Omega$$

$$A = A_\infty \frac{\mathcal{R}}{1+\mathcal{R}} + \frac{d}{1+\mathcal{R}}$$

$$= -100k \frac{6.16\times10^4}{1+6.16\times10^4} + \frac{160}{1+6.16\times10^4}$$

$$= -99.9983\,k\Omega$$

$$R_{in}(a_v=0) = Z_i \| (R_F + Z_0 \| R_L)$$

$$= 500k \| (100k + 200 \| 15k) = 83\,k\Omega$$

$$\mathcal{R}(\text{short input}) = 0$$

$$\mathcal{R}(\text{open input}) = \mathcal{R} = 6.16\times10^4$$

$$R_{in} = R_{in}(a_v=0) \frac{1+\mathcal{R}(\text{short})}{1+\mathcal{R}(\text{open})} = 83k \frac{1+0}{1+6.16\times10^4}$$

$$= 1.3\,\Omega$$

$$R_{out}(a_v=0) = R_L \| Z_0 \| (R_F + Z_i)$$

$$= 15k \| 200 \| (100k + 500k) = 197\,\Omega$$

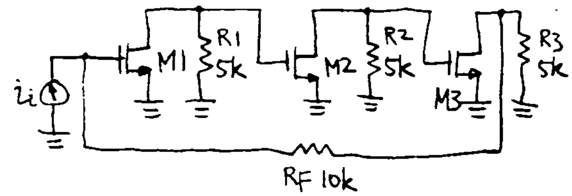
$$\mathcal{R}(\text{short output}) = 0$$

$$\mathcal{R}(\text{open output}) = \mathcal{R} = 6.16\times10^4$$

$$R_{out} = R_{out}(a_v=0) \frac{1+\mathcal{R}(\text{short})}{1+\mathcal{R}(\text{open})}$$

$$= 197 \frac{1+0}{1+6.16\times10^4} = 3.2\times10^{-3}\,\Omega = 3.2\,m\Omega$$

8.7

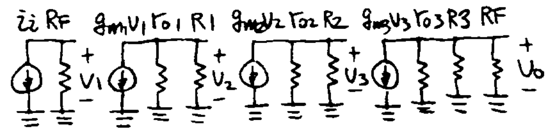


$$g_m = \sqrt{2k' \frac{W}{L} I_D} = \sqrt{2\times60\times10^{-6}\times100\times10^{-3}}$$

$$= 3.5\times10^{-3}\,A/V$$

$$r_{o1} = \frac{1}{\lambda I_D} = \frac{50}{10^{-3}} = 50\,k\Omega$$

(a)



$$a = \frac{v_o}{i_i}\Big|_{f=0} = R_F(-g_{m1})(r_{o1} \| R_1)(-g_{m2})(r_{o2} \| R_2)$$

$$(-g_{m3})(r_{o3} \| R_3 \| R_F)$$

$$= -g_{m1}^3 (r_{o1} \| R_1)^2 R_F (r_{o3} \| R_3 \| R_F)$$

$$= -(3.5\times10^{-3})^3 (50k \| 5k)^2\, 10k\, (50k \| 5k \| 10k)$$

$$= -2.76\times10^7\,\Omega$$

$$f = -\frac{i_{fb}}{v_o} = -\frac{1}{R_F} = -\frac{1}{10k\Omega}$$

$$af = 2.76\times10^3$$

$$\frac{v_o}{i_i} = \frac{a}{1+af} = \frac{-2.76\times10^7}{1+2.76\times10^3} = -10k\Omega$$

$$R_i = \frac{R_F}{1+af} = \frac{10k}{1+2.76\times10^3} = 16.4\,\Omega$$

$$R_o = \frac{r_{o3} \| R_3 \| R_F}{1+af} = \frac{50k \| 5k \| 10k}{1+2.76\times10^3} = 1.13\,\Omega$$

(b)

$$a = -2.76\times10^7 \frac{R_F \| R_S}{R_F} = -2.76\times10^7 \frac{10k \| 1k}{10k}$$

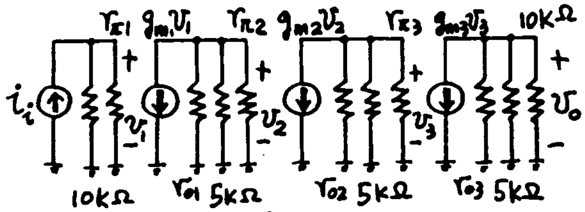
$$= -2.51\times10^6\,\Omega$$

$$af = 251$$

$$R_o = \frac{r_{o3} \| R_3 \| R_F}{1+af} = \frac{50k \| 5k \| 10k}{1+251} = 12.4\,\Omega$$

8.8

(a) Basic amplifier



$r_{\pi1} = r_{\pi2} = r_{\pi3} = \frac{\beta}{g_m} = 5.2\,K\Omega$

$g_m = \frac{1}{26}\mho,\ r_o = 50K\Omega$

$R_1 = 10K \| r_{\pi1} = \frac{5.2\times10}{15.2} = 3.42\,K\Omega$

$R_2 = r_{o1} \| 5K \| r_{\pi2} = 2.42\,K\Omega$

$R_3 = r_{o2} \| 5K \| r_{\pi3} = 2.42\,K\Omega$

$R_4 = r_{o3} \| 5K \| 10K = 3.13\,K\Omega$

$\therefore \frac{v_o}{i_i} = -R_1 g_{m1} R_2 g_{m2} R_3 g_{m3} R_4$

$= -3.42 \frac{2420}{26}\frac{2420}{26}\frac{3130}{26}\,K\Omega$

$= -3.57\times10^9\,\Omega \quad = a$

$f = -\frac{i_{fb}}{v_o} = -\frac{1}{10K\Omega}$

$\therefore$ overall $\frac{v_o}{i_i} = \frac{a}{1+af} = \frac{-3.57\times10^9}{1+3.57\times10^5}$

$= -10K\Omega$

loop gain $= af = 3.57\times10^5$

$R_i = \frac{R_1}{1+af} = \frac{3420}{1+3.57\times10^5} = 0.0096\,\Omega$

$R_o = \frac{R_4}{1+af} = \frac{3130}{1+3.57\times10^5} = 0.0088\,\Omega$

(b)

New value of $R_1 = 3.42^K \| 1^K = 774\,\Omega$

$\therefore a = -3.57\times10^9 \frac{774}{3420} = -808\,M\Omega$

$\therefore af = 808\times10^6\times10^{-4} = 8.08\times10^4$

$R_o = \frac{R_4}{1+af} = \frac{3130}{1+8.08\times10^4} = 0.0387\,\Omega$

8.9

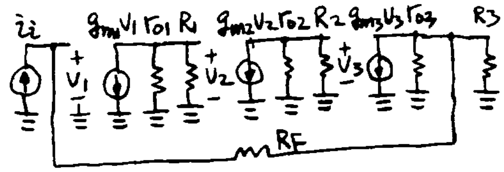
g_{m1}, r_{o1} are the same as in Problem 8.7

(a)

$$\mathcal{R}=(r_{o3}\|R_3)(-g_{m1})(r_{o1}\|R_1)(-g_{m2})(r_{o2}\|R_2)g_{m3}$$
$$=[g_{m1}(r_{o1}\|R_1)]^3=[3.5\times10^{-3}(50k\|5k)]^3$$
$$=4.03\times10^3$$

$$A_\infty=-R_F=-10k\Omega$$

$$d=\left.\frac{v_o}{i_i}\right|_{g_{m3}=0}=r_{o3}\|R_3=50k\|5k=4.54k\Omega$$



$$A=A_\infty\frac{\mathcal{R}}{1+\mathcal{R}}+\frac{d}{1+\mathcal{R}}$$
$$=-10k\frac{4.03\times10^3}{1+4.03\times10^3}+\frac{4.54k}{1+4.03\times10^3}=-10k\Omega$$

$$R_{in}(g_{m3}=0)=R_F+(r_{o3}\|R_3)$$
$$=10k+(50k\|5k)=14.5k$$

$$\mathcal{R}(short)=0$$

$$\mathcal{R}(open)=\mathcal{R}=4.03\times10^3$$

$$R_{in}=R_{in}(g_{m3}=0)\frac{1+\mathcal{R}(short)}{1+\mathcal{R}(open)}$$
$$=14.5k\frac{1+0}{1+4.03\times10^3}=3.60\Omega$$

$$R_{out}(g_{m3}=0)=r_{o3}\|R_3=50k\|5k=4.54k$$

$$\mathcal{R}(short)=0$$

$$\mathcal{R}(open)=\mathcal{R}=4.03\times10^3$$

$$R_{out}=R_{out}(g_{m3}=0)\frac{1+\mathcal{R}(short)}{1+\mathcal{R}(open)}$$
$$=4.54k\frac{1+0}{1+4.03\times10^3}=1.13\Omega$$

(b)

Replace $r_{o3}\|R_3=4.54k\Omega$ with

$$[r_{o3}\|R_3\|(R_F+R_S)]\frac{R_S}{R_F+R_S}$$
$$=[50k\|5k\|(10k+1k)]\frac{1k}{10k+1k}$$
$$=292\Omega$$

$$\mathcal{R}(open)=4.03\times10^3\frac{292}{4.54k}=259$$

$$\mathcal{R}(short)=0$$

$$R_{out}(g_{m3}=0)=r_{o3}\|R_3\|(R_F+R_S)$$
$$=50k\|5k\|(10k+1k)=3.22k$$

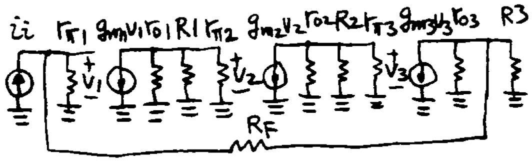
$$R_{out}=3.22k\frac{1+0}{1+259}=12.4\Omega$$

8.10

$$g_{m1} = \frac{I_C}{V_T} = \frac{1mA}{26mV} = 3.85\times10^{-2} A/V$$

$$r_{o1} = \frac{V_A}{I_C} = \frac{50}{10^{-3}} = 50k\Omega$$

$$r_{\pi 1} = \frac{\beta}{g_{m1}} = \frac{100}{3.85\times10^{-2}} = 5.2k\Omega$$



(a)

$$\mathcal{R} = [r_{o3}\|R_3\|(R_F + r_{\pi1})]\frac{r_{\pi1}}{R_F + r_{\pi1}}(-g_{m1})$$

$$(r_{o1}\|R_1\|r_{\pi2})(-g_{m2})(r_{o2}\|R_2\|r_{\pi3})g_{m3}$$

$$= g_{m1}^3[(r_{o1}\|R_1\|r_{\pi2})]^2[r_{o3}\|R_3\|(R_F + r_{\pi1})]$$

$$\frac{r_{\pi1}}{R_F + r_{\pi1}}$$

$$= (3.85\times10^{-2})^3[50k\|5k\|5.2k]^2$$

$$[50k\|5k\|(10k+5.2k)]\frac{5.2k}{10k+5.2k}$$

$$= 4.00\times10^5$$

$$A_\infty = -R_F = -10k\Omega$$

$$d = \frac{v_o}{i_i}\bigg|_{g_{m3}=0} = \frac{r_{\pi1}}{r_{\pi1} + [R_F + (r_{o3}\|R_3)]}(r_{o3}\|R_3)$$

$$= \frac{5.2k}{5.2k + [10k + (50k\|5k)]}(50k\|5k)$$

$$= 1.20k\Omega$$

$$A = A_\infty\frac{\mathcal{R}}{1+\mathcal{R}} + \frac{d}{1+\mathcal{R}}$$

$$= -10k\frac{4.00\times10^5}{1+4.00\times10^5} + \frac{1.20k}{1+4.00\times10^5}$$

$$= -10k\Omega$$

$$R_{in}(g_{m3}=0) = r_{\pi1}\|[R_F + (r_{o3}\|R_3)]$$

$$= 5.2k\|[10k + (50k\|5k)] = 3.83k\Omega$$

$$\mathcal{R}(short) = 0$$

$$\mathcal{R}(open) = \mathcal{R} = 4.00\times10^5$$

$$R_{in} = R_{in}(g_{m3}=0)\frac{1+\mathcal{R}(short)}{1+\mathcal{R}(open)}$$

$$= 3.83k\frac{1+0}{1+4.00\times10^5}$$

$$= 9.60m\Omega$$

$$R_{out}(g_{m3}=0) = (R_F + r_{\pi1})\|r_{o3}\|R_3$$

$$= (10k+5.2k)\|50k\|5k$$

$$= 3.50k\Omega$$

$$\mathcal{R}(short) = 0$$

$$\mathcal{R}(open) = \mathcal{R} = 4.00\times10^5$$

$$R_{out} = R_{out}(g_{m3}=0)\frac{1+\mathcal{R}(short)}{1+\mathcal{R}(open)}$$

$$= 3.50k\frac{1+0}{1+4.00\times10^5}$$

$$= 8.75m\Omega$$

(b)

$$R_{out}(g_{m3}=0) = [R_F + (R_S\|r_{\pi1})]\|r_{o3}\|R_3$$

$$= [10k + (1k\|5.2k)]\|50k\|5k$$

$$= 3.20k\Omega$$

$$\mathcal{R}(short) = 0$$

Replace $r_{\pi1} = 5.2k\Omega$ with

$$R_S\|r_{\pi1} = 1k\|5.2k = 839\Omega$$

$$\mathcal{R}(open) = (3.85\times10^{-2})^3[50k\|5k\|5.2k]^2$$

$$[50k\|5k\|(10k+839)]\frac{839}{10k+839}$$

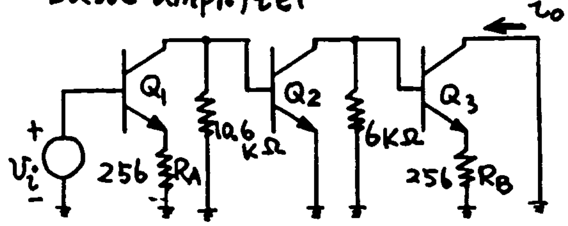
$$= 8.28\times10^4$$

$$R_{out} = 3.20k\frac{1+0}{1+8.28\times10^4}$$

$$= 38.7m\Omega$$

8.11

Basic amplifier



$R_{E1} \| (R_F + R_{E2}) = 290 \| 2.19k = 256\Omega$

$r_{\pi 1} = \frac{\beta}{g_{m1}} = 52 \times 120 = 6.24\ k\Omega$

$r_{o1} = 80 k\Omega$

$r_{\pi 2} = \frac{26 \times 120}{0.77} = 4.05\ k\Omega$

$r_{o2} = \frac{40}{0.77} = 52\ k\Omega$

$r_{\pi 3} = \frac{26 \times 120}{0.73} = 4.27 k\Omega$

$r_{o3} = \frac{40}{0.73} = 54.8\ k\Omega$

In forward gain calculation, neglect r_{o1} and r_{o3}.

For the basic amplifier,

$$\frac{i_o}{v_i} = \frac{g_{m1}}{1 + g_{m1} R_A} R_1 g_{m2} R_2 \frac{g_{m3}}{1 + g_{m3} R_B}$$

$R_1 = 10.6K \| r_{\pi 2} = 2.93\ k\Omega$

$R_2 = r_{o2} \| 6K \| R_{i3}$

$R_{i3} = r_{\pi 3}(1 + g_{m3} R_B)$

$= 4.27\left(1 + \frac{0.73}{26} \times 256\right)$

$= 35\ k\Omega$

$\therefore R_2 = 52k \| 6K \| 35K = 4.66\ k\Omega$

$$\therefore \frac{i_o}{v_i} = \frac{1}{52} \frac{1}{1 + \frac{256}{52}} 2930 \frac{0.77}{26} 4660 \times \frac{0.73}{26} \frac{1}{8.19}$$

$\therefore a = 4.5\ A/V$

From (8.95)

$$f = \frac{1}{\alpha_3} \frac{R_{E1} R_{E2}}{R_{E1} + R_{E2} + R_F}$$

$$= \frac{1}{0.99} \frac{290 \times 290}{290 + 290 + 1900}$$

$= 34.25\ \Omega$

$\therefore$ loop gain $= af = 4.5 \times 34.25 = 154$

Overall gain with feedback

$$= \frac{a}{1 + af} = \frac{4.5}{1 + 154} = \frac{4.5}{155}\ A/V$$

$\therefore \frac{i_o}{v_s} = .29\ mA/V$

For the basic amplifier

Input resistance

$r_{ia} = r_{\pi 1}(1 + g_{m1} R_A)$

$= 6.24\left(1 + \frac{256}{52}\right) = 36.96\ k\Omega$

Output resistance

$$r_{oa} = r_{o3}\left(1 + g_{m3} R_B \frac{r_{\pi 3}}{r_{\pi 3} + R_{s3}}\right)$$

$R_{s3} = r_{o2} \| 6K = 5.38\ k\Omega$

$$\therefore r_{oa} = 54.8\left(1 + \frac{0.73}{26} 256 \frac{4.27}{4.27 + 5.38}\right)$$

$= 229\ k\Omega$

For the feedback amplifier

$R_i = r_{ia}(1 + af) = 36.96 \times 155 = 5.73\ M\Omega$

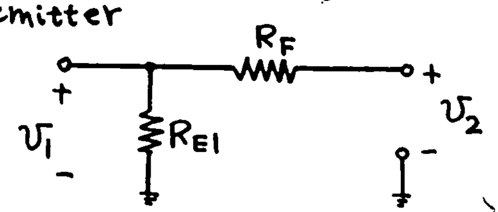
$R_o = r_{oa}(1 + af) = 229 \times 155 = 35.5\ M\Omega$

8.12

For the basic amplifier

$$\frac{v_o}{v_i} = \frac{i_o}{v_i} R_B = 4.5 \times 256 = 1152$$

where v_o is the voltage at Q_3 emitter



$$f = h_{12f} = \frac{v_1}{v_2} = \frac{R_{E1}}{R_{E1} + R_F}$$

$$= \frac{290}{290 + 1900} = 0.132$$

$\therefore$ loop gain $= af = 1152 \times 0.132 = 152$
as in 8.8

$\therefore$ with feedback, overall gain is

$$\frac{v_o}{v_i} = \frac{a}{1+af} = \frac{1152}{1+152} = 7.53$$

Input resistance is

$$R_i = r_{ia}(1+af) = 36.96 \times 153$$
$$= 5.65\ M\Omega \quad \text{as in } 8.8$$

Output resistance

$$R_o = \frac{r_{oa}}{1+af}$$

$$r_{oa} = 256 \| \left(\frac{1}{g_{m3}} + \frac{R_{S3}}{\beta_3}\right)$$
$$= 256 \| \left(36 + \frac{5380}{120}\right)$$
$$= 256 \| 81 = 61.5\ \Omega$$

$\therefore$ with feedback

$$R_o = \frac{61.5}{153} = 0.4\ \Omega$$

8.13

Bias

$$I_{c1} + I_{c2} = \frac{5.3}{5} = 1.06\ mA$$

$$I_{c1} = \frac{V_{BE3}}{1.25} = \frac{0.7}{1.25} = 0.56\ mA$$

$\therefore I_{c2} = 0.5\ mA$

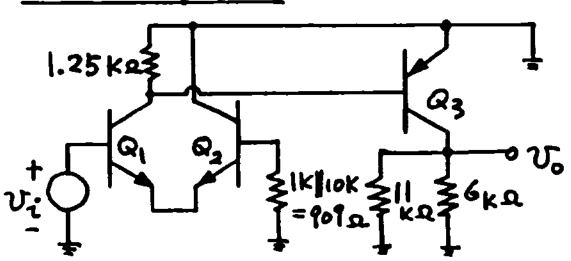
$I_{c3} = \frac{6V}{6\ k\Omega} = 1\ mA$ for $v_o|_{dc} = 0$

Assume $I_{c1} = I_{c2} = 0.53\ mA$

Then $r_{\pi 1} = r_{\pi 2} = \frac{200 \times 26}{0.53} = 9.81\ k\Omega$

$r_{\pi 3} = 2.6\ k\Omega$

Basic amplifier



$$\frac{v_o}{v_i} = \frac{g_{m1}}{1 + g_{m1} R_{E1}} R_1 g_{m3} R_2$$

$$R_{E1} = \frac{1}{g_{m2}} + \frac{909}{\beta_2} = \frac{26}{0.53} + \frac{909}{200}$$
$$= 54\ \Omega$$

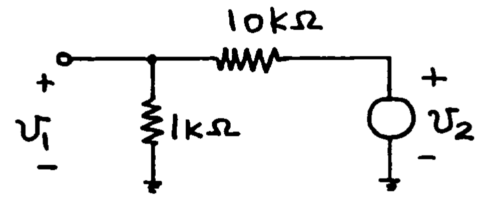
$R_1 = 1.25k \| r_{\pi 3} = 844\ \Omega$

$R_2 = 6k \| 11k = 3.88\ k\Omega$

$$\therefore \frac{v_o}{v_i} = \frac{0.53}{26} \frac{1}{1 + \frac{0.53}{26} 54} 844 \frac{3880}{26}$$

$\therefore a = 1222$

$$f = h_{12f} = \frac{v_1}{v_2} = \frac{1}{11}$$



$$\therefore \text{loop gain} = \frac{1222}{11} = 111$$

$\therefore$ with feedback gain

$$\frac{v_o}{v_i} = \frac{1222}{1+111} = 10.9$$

For the basic amplifier

$r_{oa} = 11k \| 6K = 3.88\ k\Omega$

$r_{ia} = r_{\pi 1}(1 + g_{m1} R_{E1})$

$$= 9.81\left(1 + \frac{0.53}{26} 54\right) = 20.6\ k\Omega$$

With feedback

$$R_o = \frac{3880}{112} = 34.6\ \Omega$$

$$R_i = 20.6 \times 112 = 2.3\ M\Omega$$

8-9

```
FEEDBACK AMP
VCC 1 0 6V
VEE 2 0 -6V
RL 1 3 1.25K
Q1 3 5 4 NPN
Q2 1 6 4 NPN
REE 4 2 5K
Q3 7 3 1 PNP
RBIAS 7 2 6K
RF 7 6 10K
RE 6 0 1K
.MODEL NPN NPN BF=200 IS=1E-15
.MODEL PNP PNP BF=100 IS=1E-15
VI 5 0 SIN 0 0.25 10K 0 0
.TRAN 4US 200US
.PLOT TRAN V(7)
.FOUR 10K V(7)
.DC VI -1 1 0.05
.PLOT DC V(7)
.TF V(7) VI
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END
```

```
 ******  DC TRANSFER CURVES                    TNOM=  27.000 TEMP=  27.000

    VOLT       V(7)
(A        )   -5.000E+00     0.            5.000E+00     1.000E+01     1.500E+01
                     +             +             +             +             +
-1.000E+00 -3.88E+00-+---A---+------+------+------+------+------+------+------+-
-9.500E-01 -3.88E+00 +  A   +      +      +      +      +      +      +      +
-9.000E-01 -3.88E+00 +  A   +      +      +      +      +      +      +      +
-8.500E-01 -3.88E+00 +  A   +      +      +      +      +      +      +      +
-8.000E-01 -3.88E+00 +  A   +      +      +      +      +      +      +      +
-7.500E-01 -3.88E+00 +  A   +      +      +      +      +      +      +      +
-7.000E-01 -3.88E+00 +  A   +      +      +      +      +      +      +      +
-6.500E-01 -3.88E+00 +  A   +      +      +      +      +      +      +      +
-6.000E-01 -3.88E+00 +  A   +      +      +      +      +      +      +      +
-5.500E-01 -3.88E+00 +  A   +      +      +      +      +      +      +      +
-5.000E-01 -3.88E+00-+--A---+------+------+------+------+------+------+------+-
-4.500E-01 -3.88E+00 +  A   +      +      +      +      +      +      +      +
-4.000E-01 -3.88E+00 +  A   +      +      +      +      +      +      +      +
-3.500E-01 -3.81E+00 +  A   +      +      +      +      +      +      +      +
-3.000E-01 -3.31E+00 +    A +      +      +      +      +      +      +      +
-2.500E-01 -2.77E+00 +     A+      +      +      +      +      +      +      +
-2.000E-01 -2.23E+00 +      +A     +      +      +      +      +      +      +
-1.500E-01 -1.68E+00 +      + A    +      +      +      +      +      +      +
-1.000E-01 -1.13E+00 +      +   A  +      +      +      +      +      +      +
-5.000E-02 -5.86E-01 +      +    A +      +      +      +      +      +      +
 0.        -3.50E-02-+------+------A------+------+------+------+------+------+-
 5.000E-02  5.17E-01 +      +      +A     +      +      +      +      +      +
 1.000E-01  1.06E+00 +      +      +  A   +      +      +      +      +      +
 1.500E-01  1.62E+00 +      +      +    A +      +      +      +      +      +
 2.000E-01  2.17E+00 +      +      +     A+      +      +      +      +      +
 2.500E-01  2.72E+00 +      +      +      +A     +      +      +      +      +
 3.000E-01  3.27E+00 +      +      +      + A    +      +      +      +      +
 3.500E-01  3.83E+00 +      +      +      +   A  +      +      +      +      +
 4.000E-01  4.38E+00 +      +      +      +    A +      +      +      +      +
 4.500E-01  4.93E+00 +      +      +      +      A      +      +      +      +
 5.000E-01  5.49E+00-+------+------+------+------+A-----+------+------+------+-
 5.500E-01  5.91E+00 +      +      +      +      + A    +      +      +      +
 6.000E-01  5.94E+00 +      +      +      +      + A    +      +      +      +
 6.500E-01  5.95E+00 +      +      +      +      + A    +      +      +      +
 7.000E-01  5.95E+00 +      +      +      +      + A    +      +      +      +
 7.500E-01  5.95E+00 +      +      +      +      + A    +      +      +      +
 8.000E-01  5.95E+00 +      +      +      +      + A    +      +      +      +
 8.500E-01  5.95E+00 +      +      +      +      + A    +      +      +      +
 9.000E-01  5.95E+00 +      +      +      +      + A    +      +      +      +
 9.500E-01  5.95E+00 +      +      +      +      + A    +      +      +      +
 1.000E+00  5.95E+00-+------+------+------+------+-A----+------+------+------+-
                     +             +             +             +             +
```

```
 ******  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000

+0:1       = 6.000E+00 0:2       =-6.000E+00 0:3       = 5.285E+00
+0:4       =-7.006E-01 0:5       =   0.      0:6       =-5.331E-03
+0:7       =-3.498E-02
```

**** BIPOLAR JUNCTION TRANSISTORS

ELEMENT	0:Q1	0:Q2	0:Q3
MODEL	0:NPN	0:NPN	0:PNP
IB	2.907E-06	2.366E-06	-9.912E-06
IC	5.815E-04	4.731E-04	-9.912E-04
VBE	7.006E-01	6.953E-01	-7.144E-01
VCE	5.986E+00	6.700E+00	-6.035E+00
VBC	-5.285E+00	-6.005E+00	5.320E+00
VS	-5.285E+00	-6.000E+00	-5.285E+00
POWER	3.483E-03	3.172E-03	5.989E-03
BETAD	2.000E+02	2.000E+02	1.000E+02
GM	2.248E-02	1.829E-02	3.832E-02
RPI	8.896E+03	1.093E+04	2.609E+03
RX	0.	0.	0.
RO	5.285E+15	6.005E+15	5.320E+15
CPI	0.	0.	0.
CMU	0.	0.	0.
CBX	0.	0.	0.
CCS	0.	0.	0.
BETAAC	2.000E+02	2.000E+02	9.999E+01
FT	3.578E+12	2.911E+12	6.099E+12

```
****     SMALL-SIGNAL TRANSFER CHARACTERISTICS

     V(7)/VI                                      =  1.102E+01
     INPUT RESISTANCE AT           VI             =  2.280E+06
     OUTPUT RESISTANCE AT V(7)                    =  3.507E+01
```

```
 ******  TRANSIENT ANALYSIS                  TNOM=  27.000 TEMP=  27.000

    TIME       V(7)
(A        )   -4.000E+00    -2.000E+00     0.            2.000E+00     4.000E+00
                     +             +             +             +             +
 0.        -3.50E-02-+------+------+------+------A------+------+------+------+-
 4.000E-06  6.51E-01 +      +      +      +      +    A +      +      +      +
 8.000E-06  1.29E+00 +      +      +      +      +      + A    +      +      +
 1.200E-05  1.85E+00 +      +      +      +      +      +     A+      +      +
 1.600E-05  2.29E+00 +      +      +      +      +      +      + A    +      +
 2.000E-05  2.57E+00 +      +      +      +      +      +      +   A  +      +
 2.400E-05  2.71E+00 +      +      +      +      +      +      +    A +      +
 2.800E-05  2.67E+00 +      +      +      +      +      +      +    A +      +
 3.200E-05  2.46E+00 +      +      +      +      +      +      +  A   +      +
 3.600E-05  2.09E+00 +      +      +      +      +      +      +A     +      +
 4.000E-05  1.57E+00-+------+------+------+------+------+---A--+------+------+-
 4.400E-05  9.73E-01 +      +      +      +      +      A      +      +      +
 4.800E-05  3.08E-01 +      +      +      +      + A    +      +      +      +
 5.200E-05 -3.80E-01 +      +      +      +   A  +      +      +      +      +
 5.600E-05 -1.04E+00 +      +      +      A      +      +      +      +      +
 6.000E-05 -1.64E+00 +      +      + A    +      +      +      +      +      +
 6.400E-05 -2.14E+00 +      +     A+      +      +      +      +      +      +
 6.800E-05 -2.52E+00 +      +  A   +      +      +      +      +      +      +
 7.200E-05 -2.73E+00 +      + A    +      +      +      +      +      +      +
 7.600E-05 -2.77E+00 +      + A    +      +      +      +      +      +      +
 8.000E-05 -2.62E+00-+------+--A---+------+------+------+------+------+------+-
 8.400E-05 -2.34E+00 +      +    A +      +      +      +      +      +      +
 8.800E-05 -1.91E+00 +      +      +A     +      +      +      +      +      +
 9.200E-05 -1.36E+00 +      +      +   A  +      +      +      +      +      +
 9.600E-05 -7.20E-01 +      +      +      +A     +      +      +      +      +
 1.000E-04 -3.50E-02 +      +      +      +      A      +      +      +      +
```

******

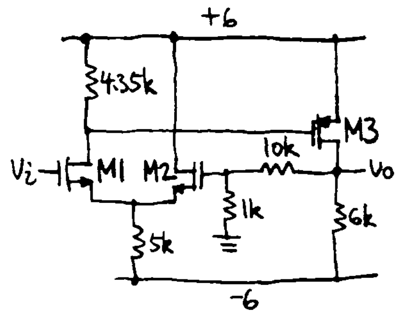
FOURIER COMPONENTS OF TRANSIENT RESPONSE V(7)

DC COMPONENT = -3.122D-02

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	9.999E+03	2.744E+00	1.000E+00	-7.176E-03	0.
2	2.000E+04	4.050E-03	1.476E-03	-8.646E+01	-8.645E+01
3	3.000E+04	6.302E-04	2.297E-04	1.017E+02	1.017E+02
4	4.000E+04	3.677E-04	1.340E-04	8.741E+01	8.741E+01
5	5.000E+04	9.451E-04	3.444E-04	1.441E+02	1.441E+02
6	6.000E+04	5.495E-05	2.003E-05	-9.498E+01	-9.497E+01
7	7.000E+04	5.195E-04	1.893E-04	-1.563E+02	-1.563E+02
8	8.000E+04	1.778E-05	6.478E-06	1.607E+01	1.607E+01
9	9.000E+04	2.990E-03	1.090E-03	-1.997E+01	-1.996E+01

TOTAL HARMONIC DISTORTION =   1.895E-01 PERCENT

8.14



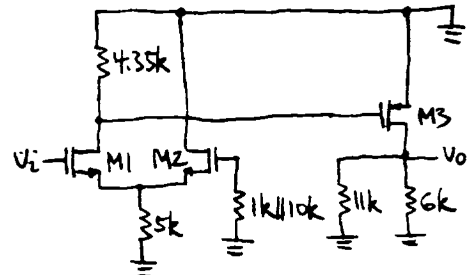
$$I_{D1} = \frac{k_n'}{2}\frac{W}{L}(0 - V_{S12} - V_{tn})^2$$
$$= \frac{60\times10^{-6}}{2}100(-V_{S12}-1)^2 = 3\times10^{-3}(V_{S12}+1)^2$$
$$I_{D2} = \frac{k_n'}{2}\frac{W}{L}(V_{G2} - V_{S12} - V_{tn})^2$$
$$= 3\times10^{-3}(V_{G2}-V_{S12}-1)^2$$
$$V_{S12} = -6 + 5k(I_{D1}+I_{D2})$$
$$|V_{GS3}| = 4.35k\, I_{D1}$$
$$I_{D3} = \frac{k_p'}{2}\frac{W}{L}(|V_{GS3}| - |V_{tp}|)^2$$
$$= \frac{20\times10^{-6}}{2}100(|V_{GS3}|-1)^2 = 10^{-3}(|V_{GS3}|-1)^2$$
$$V_o = -6 + 6k\, I_{D3}$$
$$V_{G2} = \frac{1k}{10k+1k}V_o = \frac{1}{11}V_o$$

Assuming $V_o = V_{G2} = 0V$, iteratively solve the equations

$V_{S12} = -1.39V$, $V_o = V_G = 0V$,

$I_{D1} = I_{D2} = 0.46mA$, $I_{D3} = 1mA$

$$g_{m1} = g_{m2} = \sqrt{2k_n'\frac{W}{L}I_D}$$
$$= \sqrt{2\times60\times10^{-6}\times100\times0.46\times10^{-3}} = 2.3\times10^{-3}A/V$$
$$g_{m3} = \sqrt{2k_p'\frac{W}{L}I_D} = \sqrt{2\times20\times10^{-6}\times100\times10^{-3}}$$
$$= 2\times10^{-3}A/V$$



The 1k||10k resistance at the gate of M2 is effectively a short circuit since $I_{g2} = 0$

$$R_{S1} = \frac{1}{g_{m2}}||5k = \frac{1}{2.3\times10^{-3}}||5k = 435||5k$$
$$= 400$$
$$\frac{V_o}{V_i} = \frac{g_{m1}}{1+g_{m1}R_{S1}}R_1 g_{m3} R_2$$
$$= \frac{2.3\times10^{-3}}{1+2.3\times10^{-3}\times400}4.35k\times2\times10^{-3}\times(11k||6k)$$
$$= 40$$
$$f = \frac{1k}{10k+1k} = \frac{1}{11}$$

loop gain $af = 40\frac{1}{11} = 3.6$

$$A = \frac{a}{1+af} = \frac{40}{1+3.6} = 8.7$$

$r_{ia} \to \infty$

$r_{oa} = 11k||6k = 3.9k\Omega$

$R_i = (1+af)r_{ia} \to \infty$

$$R_o = \frac{r_{oa}}{1+af} = \frac{3.9k}{1+3.6} = 850\Omega$$

```
FEEDBACK AMPLIFIER
VDD 1 0 6
VSS 2 0 -6
VI 5 0 SIN (0 0.25 10K) AC 1
M1 3 5 4 4 CMOSN W=100U L=1U
M2 1 6 4 4 CMOSN W=100U L=1U
M3 7 3 1 1 CMOSP W=100U L=1U
RL 1 3 4.35K
RSS 4 2 5K
RE 6 0 1K
RF 6 7 10K
RBIAS 7 2 6K
.MODEL CMOSN NMOS VTO=1  KP=60U LAMDA=0
.MODEL CMOSP PMOS VTO=-1 KP=20U LAMDA=0
.OPTIONS NOMOD
.TF V(7) VI
.DC VI -1 1 0.1
.PLOT DC V(7)
.TRAN 5U 200U
.FOUR 10K V(7)
.WIDTH OUT=80
.OPTIONS SPICE
.END
```

```
******  DC TRANSFER CURVES                 TNOM=  27.000 TEMP=  27.000

    VOLT       V(7)
(A        )   -5.000E+00     0.          5.000E+00     1.000E+01     1.500E+01
                    +             +             +             +             +
-1.000E+00 -3.88E+00-+--A---+------+------+------+------+------+------+------+-
-9.000E-01 -3.88E+00 +  A   +      +      +      +      +      +      +      +
-8.000E-01 -3.88E+00 +  A   +      +      +      +      +      +      +      +
-7.000E-01 -3.88E+00 +  A   +      +      +      +      +      +      +      +
-6.000E-01 -3.88E+00 +  A   +      +      +      +      +      +      +      +
-5.000E-01 -3.83E+00 +  A   +      +      +      +      +      +      +      +
-4.000E-01 -3.32E+00 +    A +      +      +      +      +      +      +      +
-3.000E-01 -2.59E+00 +      A      +      +      +      +      +      +      +
-2.000E-01 -1.77E+00 +      + A    +      +      +      +      +      +      +
-1.000E-01 -9.03E-01 +      +   A  +      +      +      +      +      +      +
  0.        7.85E-03-+------+------A------+------+------+------+------+------+-
 1.000E-01  9.47E-01 +      +      +  A   +      +      +      +      +      +
 2.000E-01  1.90E+00 +      +      +    A +      +      +      +      +      +
 3.000E-01  2.88E+00 +      +      +      +A     +      +      +      +      +
 4.000E-01  3.87E+00 +      +      +      +   A  +      +      +      +      +
 5.000E-01  4.81E+00 +      +      +      +     A+      +      +      +      +
 6.000E-01  5.22E+00 +      +      +      +      +A     +      +      +      +
 7.000E-01  5.41E+00 +      +      +      +      +A     +      +      +      +
 8.000E-01  5.52E+00 +      +      +      +      +A     +      +      +      +
 9.000E-01  5.59E+00 +      +      +      +      + A    +      +      +      +
 1.000E+00  5.63E+00-+------+------+------+------+-A----+------+------+------+-
```

```
******  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000

+0:1        = 6.000E+00 0:2       =-6.000E+00 0:3       = 3.999E+00
+0:4        =-1.391E+00 0:5       =    0.     0:6       = 7.140E-04
+0:7        = 7.854E-03
```

```
****     SMALL-SIGNAL TRANSFER CHARACTERISTICS

     V(7)/VI                                   =  9.262E+00
     INPUT RESISTANCE AT          VI           =  9.999E+19
     OUTPUT RESISTANCE AT V(7)                 =  8.691E+02
```

******

FOURIER COMPONENTS OF TRANSIENT RESPONSE V(7)

DC COMPONENT =   5.318D-02

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	9.999E+03	2.291E+00	1.000E+00	-7.659E-03	0.
2	2.000E+04	4.535E-02	1.979E-02	-8.974E+01	-8.974E+01
3	3.000E+04	4.182E-03	1.825E-03	7.000E+00	7.008E+00
4	4.000E+04	7.555E-04	3.297E-04	9.087E+01	9.087E+01
5	5.000E+04	8.457E-04	3.690E-04	1.459E+02	1.459E+02
6	6.000E+04	1.723E-04	7.520E-05	-1.101E+02	-1.101E+02
7	7.000E+04	4.216E-04	1.840E-04	-1.537E+02	-1.537E+02
8	8.000E+04	2.989E-05	1.304E-05	9.134E+01	9.134E+01
9	9.000E+04	2.487E-03	1.085E-03	-1.988E+01	-1.988E+01

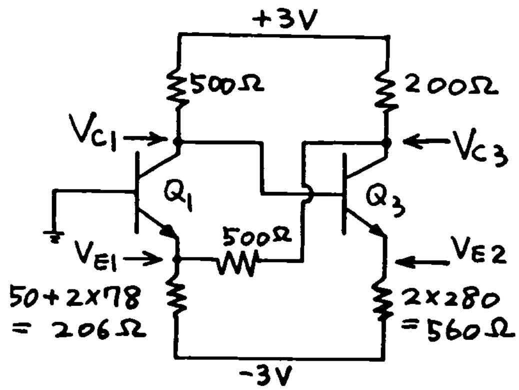
TOTAL HARMONIC DISTORTION =   1.991E+00   PERCENT

8.15

(a)

Bias

Common-mode, half-circuit



$V_{E1} = -0.7V$

ΣI at emitter of Q_1

$\therefore I_{C1} + \frac{V_{C3}+0.7}{500} = \frac{2.3}{206}$ ------(1)

$V_{C1} = 3 - 500 I_{C1}$

$\therefore V_{E3} = V_{C1} - 0.7 = 2.3 - 500 I_{C1}$

$\therefore I_{C3} = \frac{3 + V_{E2}}{560} = \frac{5.3 - 500 I_{C1}}{560}$

$V_{C3} = 3 - 200\left(I_{C3} + \frac{V_{C3}+0.7}{500}\right)$

$\therefore 1.4 V_{C3} = 2.72 - 200\,\frac{5.3 - 500 I_{C1}}{560}$

$= 2.72 - 1.89 + 178 I_{C1}$

$\therefore V_{C3} = 0.59 + 127 I_{C1}$

In (1)

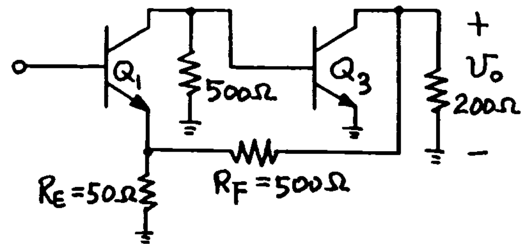
$I_{C1} + \frac{1.29}{500} + \frac{127}{500} I_{C1} = \frac{2.3}{206}$

$\therefore I_{C1} = 6.85\,mA$

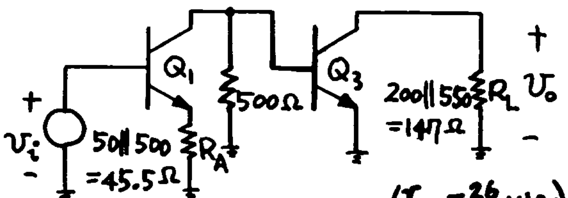
$I_{C3} = \frac{5.3 - 500 I_{C1}}{560} = 3.3\,mA$

(b)

Differetial-mode, half-circuit



Basic amplifier



Basic amplifier gain $\left(r_{\pi3} = \frac{26}{3.3}\times 100 = 788\right)$

$\frac{v_o}{v_i} \simeq \frac{g_{m1}}{1+g_{m1}R_A} R_1 \frac{r_{\pi3}}{r_{\pi3}+r_b} g_{m3} R_L$

$R_1 = 500 \| (r_{\pi3} + r_b)$

$= 500 \| (788 + 50) = 313\Omega$

$\therefore \frac{v_o}{v_i} = \frac{6.85}{26} \frac{1}{1 + \frac{6.85}{26}45.5} 313 \frac{788}{838} \frac{3.3}{26} 147$

$\therefore a = 111$

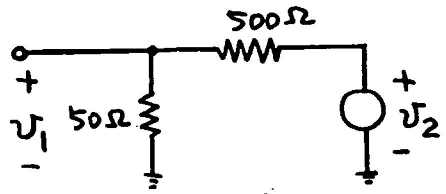
8-13

$r_{ia} = r_{\pi 1}(1+g_{m1}R_A)$

$= \frac{2600}{6.85}\left(1+\frac{6.85}{26}45.5\right)$

$= 4.9k\Omega$

$r_{oa} = R_L = 147\Omega$



$f = h_{12f} = \frac{v_1}{v_2} = \frac{1}{11}$

∴ loop gain $= af = \frac{111}{11} = 10.1$

∴ with feedback loop closed,

gain $= \frac{v_o}{v_i} = \frac{a}{1+af} = \frac{111}{11.1} = 10.0$

$R_i = r_{ia}(1+af) = 4.9 \times 11.1 = 54k\Omega$

$R_o = \frac{r_{oa}}{1+T} = \frac{147}{11.1} = 13.2\Omega$

For the full differential circuit

$R_{id} = 2R_i = 108k\Omega$

$R_{od} = 2R_o = 26.4\Omega$

```
SERIES SHUNT FEEDBACK AMP
VCC 1 0 3V
VEE 2 0 -3V
RCL 1 9 500
RC2 1 10 500
Q1 9 3 5 NPN
Q2 10 4 6 NPN
RE1 5 7 50
RE2 6 7 50
RF1 11 5 500
RF2 12 6 500
Q3 11 9 8 NPN
Q4 12 10 8 NPN
RC3 1 11 200
RC4 1 12 200
REE1 7 2 78
REE2 8 2 280
.MODEL NPN NPN BF=100 IS=1E-14 RB=50
VI1 3 0 0V
EVIL 0 4 3 0 1
.DC VI1 -0.1 0.1 0.005
.PLOT DC V(11,12)
.TF V(11,12) VI1
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END
```

```
****** DC TRANSFER CURVES                      TNOM=  27.000 TEMP=  27.000

    VOLT      V(11,12)
(A      )    -2.000E+00    -1.000E-00    0.          1.000E-00    2.000E+00
                     +             +             +             +             +
-1.000E-01 -1.16E+00-+------+----A-+------+------+------+------+------+------+-
-9.500E-02 -1.14E+00 +      +    A +      +      +      +      +      +      +
-9.000E-02 -1.13E+00 +      +    A +      +      +      +      +      +      +
-8.500E-02 -1.11E+00 +      +    A +      +      +      +      +      +      +
-8.000E-02 -1.10E+00 +      +     A+      +      +      +      +      +      +
-7.500E-02 -1.08E+00 +      +     A+      +      +      +      +      +      +
-7.000E-02 -1.07E+00 +      +     A+      +      +      +      +      +      +
-6.500E-02 -1.05E+00 +      +     A+      +      +      +      +      +      +
-6.000E-02 -1.04E+00 +      +     A+      +      +      +      +      +      +
-5.500E-02 -1.01E+00 +      +      A      +      +      +      +      +      +
-5.000E-02 -9.58E-01-+------+------+A-----+------+------+------+------+------+-
-4.500E-02 -8.77E-01 +      +      + A    +      +      +      +      +      +
-4.000E-02 -7.87E-01 +      +      +  A   +      +      +      +      +      +
-3.500E-02 -6.93E-01 +      +      +   A  +      +      +      +      +      +
-3.000E-02 -5.96E-01 +      +      +     A+      +      +      +      +      +
-2.500E-02 -4.98E-01 +      +      +      A      +      +      +      +      +
-2.000E-02 -3.99E-01 +      +      +      +A     +      +      +      +      +
-1.500E-02 -3.00E-01 +      +      +      +  A   +      +      +      +      +
-1.000E-02 -2.00E-01 +      +      +      +   A  +      +      +      +      +
-5.000E-03 -1.00E-01 +      +      +      +     A+      +      +      +      +
  0.         0.     -+------+------+------+-- ---A------+------+------+------+-
 5.000E-03  1.00E-01 +      +      +      +      +A     +      +      +      +
 1.000E-02  2.00E-01 +      +      +      +      +  A   +      +      +      +
 1.500E-02  3.00E-01 +      +      +      +      +   A  +      +      +      +
 2.000E-02  3.99E-01 +      +      +      +      +     A+      +      +      +
 2.500E-02  4.98E-01 +      +      +      +      +      A      +      +      +
 3.000E-02  5.96E-01 +      +      +      +      +      +A     +      +      +
 3.500E-02  6.93E-01 +      +      +      +      +      +  A   +      +      +
 4.000E-02  7.87E-01 +      +      +      +      +      +   A  +      +      +
 4.500E-02  8.77E-01 +      +      +      +      +      +    A +      +      +
 5.000E-02  9.58E-01-+------+------+------+------+------+-----A+------+------+-
 5.500E-02  1.01E+00 +      +      +      +      +      +      A      +      +
 6.000E-02  1.04E+00 +      +      +      +      +      +      +A     +      +
 6.500E-02  1.05E+00 +      +      +      +      +      +      +A     +      +
 7.000E-02  1.07E+00 +      +      +      +      +      +      +A     +      +
 7.500E-02  1.08E+00 +      +      +      +      +      +      +A     +      +
 8.000E-02  1.10E+00 +      +      +      +      +      +      +A     +      +
 8.500E-02  1.11E+00 +      +      +      +      +      +      + A    +      +
 9.000E-02  1.13E+00 +      +      +      +      +      +      + A    +      +
 9.500E-02  1.14E+00 +      +      +      +      +      +      + A    +      +
 1.000E-01  1.16E+00-+------+------+------+------+------+------+-A----+------+-
                     +             +             +             +             +
```

```
****** OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000

+0:1       = 3.000E+00 0:2       =-3.000E+00 0:3       =  0.
+0:4       =  0.       0:5       =-7.078E-01 0:6       =-7.078E-01
+0:7       =-1.264E+00 0:8       =-1.073E+00 0:9       =-3.851E-01
+0:10      =-3.851E-01 0:11      = 1.454E+00 0:12      = 1.454E+00
```

**** BIPOLAR JUNCTION TRANSISTORS

ELEMENT	0:Q1	0:Q2	0:Q3	0:Q4
MODEL	0:NPN	0:NPN	0:NPN	0:NPN
IB	6.739E-05	6.739E-05	3.406E-05	3.406E-05
IC	6.736E-03	6.736E-03	3.406E-03	3.406E-03
VBE	7.078E-01	7.078E-01	6.885E-01	6.885E-01
VCE	3.227E-01	3.227E-01	2.527E+00	2.527E+00
VBC	3.851E-01	3.851E-01	-1.839E+00	-1.839E+00
VS	3.851E-01	3.851E-01	-1.454E+00	-1.454E+00
POWER	2.222E-03	2.222E-03	8.633E-03	8.633E-03
BETAD	9.996E+01	9.996E+01	1.000E+02	1.000E+02
GM	2.604E-01	2.604E-01	1.317E-01	1.317E-01
RPI	3.839E+02	3.839E+02	7.593E+02	7.593E+02

RX	5.000E+01	5.000E+01	5.000E+01	5.000E+01
RO	1.008E+06	1.008E+06	1.840E+14	1.840E+14
CPI	0.	0.	0.	0.
CMU	0.	0.	0.	0.
CBX	0.	0.	0.	0.
CCS	0.	0.	0.	0.
BETAAC	9.999E+01	9.999E+01	9.999E+01	9.999E+01
FT	4.145E+13	4.145E+13	2.095E+13	2.095E+13

```
****     SMALL-SIGNAL TRANSFER CHARACTERISTICS

    V(11,12)/VI1                               =  2.002E+01
    INPUT RESISTANCE AT           VI1          =  5.154E+04
    OUTPUT RESISTANCE AT V(11,12)              =  2.630E+01

VI1 IS ONLY HALF OF TOTAL VI. VO/VI=20/2=10.
VI1 IS ONLY HALF OF TOTAL VI. RIN=2*5.154E+04=1.0308E+5.

*****
SERIES SHUNT FEEDBACK AMP
VCC 1 0 3V
VEE 2 0 -3V
RC1 1 9 500 TC=1E-3
RC2 1 10 500 TC=1E-3
Q1 9 3 5 NPN
Q2 10 4 6 NPN
RE1 5 7 50 TC=1E-3
RE2 6 7 50 TC=1E-3
RF1 11 5 500 TC=1E-3
RF2 12 6 500 TC=1E-3
Q3 11 9 8 NPN
Q4 12 10 8 NPN
RC3 1 11 200 TC=1E-3
RC4 1 12 200 TC=1E-3
REE1 7 2 78 TC=1E-3
REE2 8 2 280 TC=1E-3
.MODEL NPN NPN BF=100 IS=1E-14 RB=50
VI1 3 0 0V
EVIL 0 4 3 0 1
.TF V(11,12) VI1
.TEMP -55 -35 -15 5 25 45 65 85 105 125
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

TEMP=-55 DEGREE C
 ******  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP= -55.000

+0:1       = 3.000E+00 0:2      =-3.000E+00 0:3       =   0.
+0:4       =   0.      0:5      =-8.361E-01 0:6       =-8.361E-01
+0:7       =-1.361E+00 0:8      =-8.659E-01 0:9       =-3.985E-02
+0:10      =-3.985E-02 0:11     = 1.364E+00 0:12      = 1.364E+00
```

**** BIPOLAR JUNCTION TRANSISTORS

ELEMENT	0:Q1	0:Q2	0:Q3	0:Q4
MODEL	0:NPN	0:NPN	0:NPN	0:NPN
IB	6.582E-05	6.582E-05	4.110E-05	4.110E-05
IC	6.582E-03	6.582E-03	4.110E-03	4.110E-03
VBE	8.361E-01	8.361E-01	8.260E-01	8.260E-01
VCE	7.962E-01	7.962E-01	2.230E+00	2.230E+00
VBC	3.985E-02	3.985E-02	-1.404E+00	-1.404E+00
VS	3.985E-02	3.985E-02	-1.364E+00	-1.364E+00
POWER	5.296E-03	5.296E-03	9.203E-03	9.203E-03
BETAD	9.999E+01	9.999E+01	1.000E+02	1.000E+02
GM	3.501E-01	3.501E-01	2.187E-01	2.187E-01
RPI	2.856E+02	2.856E+02	4.573E+02	4.573E+02
RX	5.000E+01	5.000E+01	5.000E+01	5.000E+01
RO	7.097E+18	7.097E+18	3.714E+21	3.714E+21
CPI	0.	0.	0.	0.
CMU	0.	0.	0.	0.
CBX	0.	0.	0.	0.
CCS	0.	0.	0.	0.
BETAAC	1.000E+02	9.999E+01	1.000E+02	1.000E+02
FT	5.572E+13	5.572E+13	3.480E+13	3.480E+13

```
****     SMALL-SIGNAL TRANSFER CHARACTERISTICS

    V(11,12)/VI1                               =  2.040E+01
    INPUT RESISTANCE AT           VI1          =  6.280E+04
    OUTPUT RESISTANCE AT V(11,12)              =  1.951E+01

TEMP=-35 DEGREE C
****     SMALL-SIGNAL TRANSFER CHARACTERISTICS
    V(11,12)/VI1                               =  2.032E+01

TEMP=-15 DEGREE C
****     SMALL-SIGNAL TRANSFER CHARACTERISTICS
    V(11,12)/VI1                               =  2.023E+01

TEMP=5 DEGREE C
****     SMALL-SIGNAL TRANSFER CHARACTERISTICS
    V(11,12)/VI1                               =  2.013E+01

TEMP=25 DEGREE C
****     SMALL-SIGNAL TRANSFER CHARACTERISTICS
    V(11,12)/VI1                               =  2.003E+01

TRANSISTORS Q1 AND Q2 BEGIN TO GET INTO SATURATION

TEMP=45 DEGREE C
**** BIPOLAR JUNCTION TRANSISTORS
```

ELEMENT	0:Q1	0:Q2	0:Q3	0:Q4
MODEL	0:NPN	0:NPN	0:NPN	0:NPN
IB	7.018E-05	7.018E-05	3.267E-05	3.267E-05
IC	6.768E-03	6.768E-03	3.267E-03	3.267E-03
VBE	6.790E-01	6.790E-01	6.571E-01	6.571E-01
VCE	2.173E-01	2.173E-01	2.592E+00	2.592E+00
VBC	4.617E-01	4.617E-01	-1.935E+00	-1.935E+00
VS	4.617E-01	4.617E-01	-1.473E+00	-1.473E+00
POWER	1.518E-03	1.518E-03	8.492E-03	8.492E-03
BETAD	9.643E+01	9.643E+01	1.000E+02	1.000E+02
GM	2.470E-01	2.470E-01	1.192E-01	1.192E-01
RPI	4.047E+02	4.047E+02	8.391E+02	8.391E+02
RX	5.000E+01	5.000E+01	5.000E+01	5.000E+01
RO	1.118E+04	1.118E+04	1.434E+13	1.434E+13
CPI	0.	0.	0.	0.
CMU	0.	0.	0.	0.
CBX	0.	0.	0.	0.
CCS	0.	0.	0.	0.
BETAAC	9.996E+01	9.996E+01	9.999E+01	9.999E+01
FT	3.929E+13	3.929E+13	1.896E+13	1.896E+13

```
****     SMALL-SIGNAL TRANSFER CHARACTERISTICS
    V(11,12)/VI1                               =  1.963E+01

TEMP=65 DEGREE C
**** BIPOLAR JUNCTION TRANSISTORS
```

ELEMENT	0:Q1	0:Q2	0:Q3	0:Q4
MODEL	0:NPN	0:NPN	0:NPN	0:NPN
IB	1.342E-04	1.342E-04	3.174E-05	3.174E-05
IC	6.740E-03	6.740E-03	3.174E-03	3.174E-03
VBE	6.500E-01	6.500E-01	6.223E-01	6.223E-01
VCE	1.356E-01	1.356E-01	2.623E+00	2.623E+00
VBC	5.144E-01	5.144E-01	-2.000E+00	-2.000E+00
VS	5.144E-01	5.144E-01	-1.486E+00	-1.486E+00
POWER	1.001E-03	1.001E-03	8.345E-03	8.345E-03
BETAD	5.023E+01	5.023E+01	1.000E+02	1.000E+02
GM	2.335E-01	2.335E-01	1.089E-01	1.089E-01
RPI	4.241E+02	4.241E+02	9.181E+02	9.181E+02
RX	5.000E+01	5.000E+01	5.000E+01	5.000E+01
RO	4.451E+02	4.451E+02	1.126E+12	1.126E+12
CPI	0.	0.	0.	0.
CMU	0.	0.	0.	0.
CBX	0.	0.	0.	0.
CCS	0.	0.	0.	0.
BETAAC	9.904E+01	9.904E+01	9.999E+01	9.999E+01
FT	3.681E+13	3.681E+13	1.733E+13	1.733E+13

```
****     SMALL-SIGNAL TRANSFER CHARACTERISTICS
    V(11,12)/VI1                               =  1.369E+01

TEMP=85 DEGREE C
**** BIPOLAR JUNCTION TRANSISTORS
```

ELEMENT	0:Q1	0:Q2	0:Q3	0:Q4
MODEL	0:NPN	0:NPN	0:NPN	0:NPN
IB	2.861E-04	2.861E-04	3.165E-05	3.165E-05
IC	6.618E-03	6.618E-03	3.165E-03	3.165E-03
VBE	6.254E-01	6.254E-01	5.880E-01	5.880E-01
VCE	1.076E-01	1.076E-01	2.591E+00	2.591E+00
VBC	5.178E-01	5.178E-01	-2.003E+00	-2.003E+00
VS	5.178E-01	5.178E-01	-1.485E+00	-1.485E+00
POWER	8.912E-04	8.912E-04	8.222E-03	8.222E-03
BETAD	2.313E+01	2.313E+01	1.000E+02	1.000E+02
GM	2.214E-01	2.214E-01	1.026E-01	1.026E-01
RPI	4.377E+02	4.377E+02	9.749E+02	9.749E+02
RX	5.000E+01	5.000E+01	5.000E+01	5.000E+01
RO	1.431E+02	1.431E+02	1.131E+11	1.131E+11
CPI	0.	0.	0.	0.
CMU	0.	0.	0.	0.
CBX	0.	0.	0.	0.
CCS	0.	0.	0.	0.
BETAAC	9.694E+01	9.694E+01	9.999E+01	9.999E+01
FT	3.413E+13	3.413E+13	1.632E+13	1.632E+13

```
****     SMALL-SIGNAL TRANSFER CHARACTERISTICS
    V(11,12)/VI1                               =  6.436E+00

TEMP=105 DEGREE C
****     SMALL-SIGNAL TRANSFER CHARACTERISTICS
    V(11,12)/VI1                               =  2.461E+00

TEMP=125 DEGREE C
****     SMALL-SIGNAL TRANSFER CHARACTERISTICS
    V(11,12)/VI1                               =  1.740E-01

BEFORE Q1 AND Q2 BECOME SATURATED (-55 TO 25 DEG C),
THE CIRCUIT GAIN REMEINS NEARLY CONSTANT.
DGAIN/DT=-0.1/20 DEG C=-0.005/DEG C
(1/GAIN)(DGAIN/DT)=(1/20)(-0.1/20)=-250 PPM/DEG C
```

8.16

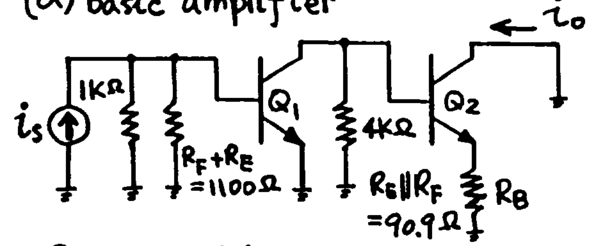
(a) T is almost independent of R_E. This can be seen if the loop is broken and a signal inserted. R_F feeds current to the emitter of Q_1 and most of this is shunted into Q_1.
If $\underline{a}$ and $\underline{f}$ are calculated, $\underline{a}$ decreases as R_E increases and $\underline{f}$ increases by about the same percentage.

(b) Loop gain is almost inversely proportional to R_F. As R_F increases, $\underline{f}$ decreases proportionately, whereas $\underline{a}$ changes slowly due to the 200Ω load resistor.

(c) Loop gain is almost directly proportional to R_L since $\underline{a}$ depends on this quantity.

8.17

(a) Basic amplifier



Basic amplifier gain

$$\frac{i_o}{i_s} = -(1k \| 1.1k \| r_{\pi 1}) g_{m1} R_1 \frac{g_{m2}}{1+g_{m2}R_B}$$

$$R_1 = 4k \| r_{\pi 2}(1+g_{m2}R_B) \| r_{o1}$$

$$= 4k \| 5.2\left(1+\frac{90.9}{26}\right) k \| 100k$$

$$= 3.30\ k\Omega$$

$$\therefore \frac{i_o}{i_s} = -476 \times \frac{3300}{26} \times \frac{1}{26} \times \frac{1}{4.5}$$

$$\therefore a = -516$$

$$r_{ia} = 1k \| 1.1k \| r_{\pi 1} = 476\ \Omega$$

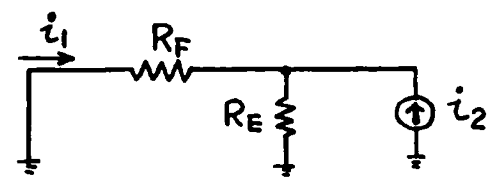
$$r_{oa} = r_{o2}\left(1+g_{m2}R_B \frac{r_{\pi 2}}{r_{\pi 2}+R_{S2}}\right)$$

$$R_{S2} = r_{o1} \| 4k = 3.85\ k\Omega$$

$$\therefore r_{oa} = 100\left(1+\frac{90.9}{26}\ \frac{5.2}{5.2+3.85}\right) k$$

$$= 300\ k\Omega$$

Feedback network



$f = g_{12f} = \frac{i_1}{i_2} = -\frac{R_E}{R_E+R_F} = -\frac{100}{1100}$

$= -\frac{1}{11}$

$\therefore$ loop gain $= \frac{516}{11} = 46.9 = af$

$\therefore$ with feedback applied

overall gain $= \frac{i_o}{i_i} = \frac{a}{1+af}$

$= \frac{-516}{47.9} = -10.8$

Input resistance

$R_i = \frac{r_{ia}}{1+T} = \frac{476}{47.9} = 9.94\,\Omega$

Output resistance

$R_o = r_{oa}(1+T) = 300 \times 47.9 = 14.4\,M\Omega$

(b) $\underline{f}$ is unchanged

$\underline{a}$ increases by about 10 %

$\therefore$ change in overall gain is

$\simeq \frac{10}{47.9} = 0.2\,\%$

R_i changes by −10 % because

$R_i = \frac{r_{ia}}{1+af}$

8.18

(a) Basic amplifier gain

$\frac{i_o}{i_s} = -\left[(R_F+R_E)\|r_{\pi 1}\right] g_{m1} R_1 \frac{g_{m2}}{1+g_{m2}R_B}$

$R_F + R_E = 5.2\,K\Omega$

$R_B = R_E \| R_F = 192\,\Omega$

$R_1 = R_{L1} \| r_{\pi 2}(1+g_{m2}R_B) \| r_{o1}$

$= 10K \| 5.2(1+\frac{192}{26})k \| 100k$

$= 7.52\,k\Omega$

$\therefore \frac{i_o}{i_i} = -\left[5.2k \| 5.2k\right] \frac{7520}{26} \frac{1}{26} \frac{1}{8.38}$

$\therefore a = -3451$

$r_{ia} = 5.2k \| 5.2k = 2.6\,k\Omega$

$r_{oa} = r_{o2}\left(1 + g_{m2} R_B \frac{r_{\pi 2}}{r_{\pi 2}+R_{s2}}\right)$

$R_{s2} = r_{o1} \| 10k = 9.09\,k\Omega$

$\therefore r_{oa} = 100\left(1 + \frac{192}{26} \frac{5.2}{5.2+9.09}\right)$

$= 369\,k\Omega$

Feedback network

$f = g_{12f} = \frac{i_1}{i_2} = -\frac{R_E}{R_E+R_F}$

$= -\frac{200}{5200} = -0.0385$

$\therefore$ loop gain $= 3451 \times 0.0385$

$= 133$

$\therefore$ With feedback applied

overall gain $= \frac{i_o}{i_i} = \frac{a}{1+af}$

$= \frac{-3451}{134} = -25.8$

Input resistance

$R_i = \frac{2600}{134} = 19.4\,\Omega$

Output resistance

$R_o = 369 \times 134 = 49.4\,M\Omega$

(b) If I_{C1} increases 20 %

g_{m1} increases 20 %

$r_{\pi 1}$ decreases 20 %

$\therefore$ $\underline{a}$ increases about 10 %, since $(R_F+R_E) = r_{\pi 1}$

$\underline{f}$ is unchanged

$\therefore$ Change in overall gain is

$\frac{10}{1+T} = \frac{10}{134} = 0.075\,\%$

$R_o = r_{oa}(1+af)$

$\therefore$ R_o increases about 10%

8.19

Transconductance

$$G_m = \frac{1}{R_E}\,\frac{1}{1+\frac{1}{R_E}\left(\frac{1}{g_m}+\frac{r_b+R_E}{\beta_o}\right)}$$

$$= \frac{1}{200}\,\frac{1}{1+\frac{1}{200}\left(26+\frac{400}{150}\right)}$$

$$= 4.37\ mA/V$$

Input resistance

$$R_i = r_b + r_\pi + (1+\beta_o)R_E$$

$$= 200 + 150\times 26 + 151\times 200$$

$$= 34.3\ k\Omega$$

Output resistance

$$R_o = r_o\left(1+\frac{g_m R_E}{1+\frac{r_b+R_E}{r_\pi}}\right)$$

$$= 80\left(1+\frac{\frac{200}{26}}{1+\frac{400}{150\times 26}}\right)$$

$$= 638\ k\Omega$$

Loop gain

$$T = \frac{g_m R_E}{1+\frac{r_b+R_E}{r_\pi}}$$

$$= 7$$

8.20

(a) Assume high β

$$I_{Q8} = \frac{12-0.6}{11.4} = 1\ mA$$

$$\therefore I_{Q7} \simeq \frac{1400}{300}\times 1 = 4.7\ mA$$

$$\therefore I_{Q1} = I_{Q2} = \frac{1}{2}\times 4.7 = 2.3\ mA$$

$$I_{Q9} = 4.7\ mA$$

$$\therefore I_{Q3} = I_{Q4} = 2.3\ mA$$

$$I_{Q10} = I_{Q11} = \frac{1400}{400}\times 1 = 3.5\ mA$$

$$V_{C3} = V_{C4} = 6 - 1.1\times 2.3 = 3.5V$$

$\therefore$ DC output voltage

$$= 3.5 - 0.6 = 2.9\ V$$

Sum currents at collector of Q_1

$$I_{Q1} = \frac{6-V_{C1}}{2.4} + \frac{2.9-V_{C1}}{7}$$

$$\therefore 2.3 = 2.5 - 0.42V_{C1} + 0.41 - 0.14V_{C1}$$

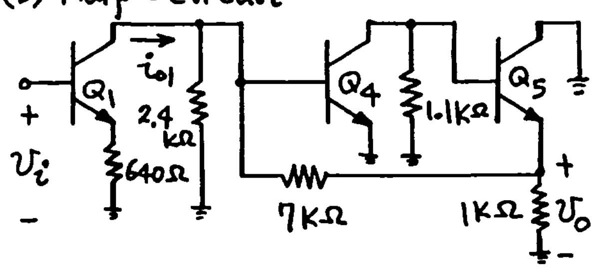
$$\therefore V_{C1} = 1V$$

$\therefore$ Current in $7k\Omega$ resistor

$$= \frac{2.9-1}{7} = 0.27\ mA$$

$$\therefore I_{Q5} = I_{Q6} = I_{Q10} + 0.27 = 3.8mA$$

(b) Half-circuit



$$R_i = r_{\pi 1} + (1+\beta)R_{E1}$$

$$= \frac{100\times 26}{2.3} + 101\times 640 = 66k\Omega$$

— for the half circuit

$\therefore R_i = 132k\Omega$ — for the complete circuit

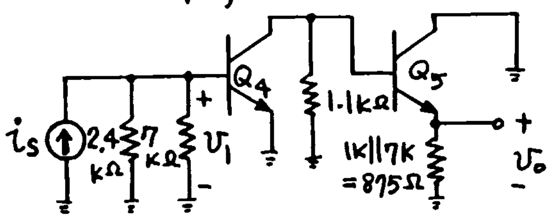
For the first stage

$$\frac{i_{o1}}{v_i} = -\frac{1}{640}\,\frac{1}{1+\frac{1}{600}\left(\frac{26}{2.3}+\frac{640}{100}\right)}$$

$$= -1.52\ mA/V$$

Consider the shunt-shunt feedback stage.

Basic amplifier is



$v_1 = i_s(2.4k \| 7k \| r_{\pi 4})$

$= i_s \times 0.69k$

$R_{i5} = r_{\pi 5} + (1+\beta) \times 875$

$= 684 + 88.4k = 89\ k\Omega$

$\therefore \frac{v_o}{i_s} = -0.69K \times g_{m4}[1.1k \| 89k]$

$= -0.69k \times \frac{2.3}{26} \times 1087$

$\therefore a = -66.3\ k\Omega$

$f = -\frac{1}{7k}$

$\therefore$ For the output stage with feedback applied

$\frac{v_o}{i_{o1}} = \frac{a}{1+af} = \frac{-281k}{1+9.47} = -6.33\ k\Omega$

$\therefore$ for the overall circuit

$\frac{v_o}{v_i} = 1.52 \times 10^{-3} \times 6.33 \times 10^3 = 9.6$

Loop gain of output stage

$T = af = 9.47$

Output impedance of half circuit

$= 875 \| \left[\frac{1}{g_{m5}} + \frac{1100}{\beta}\right]$

$= 875 \| [7 + 11] = 18\ \Omega$

$\therefore$ For the complete circuit $r_{oa} = 36\ \Omega$, and with feedback applied. $R_o = \frac{36}{1+T} = 3.6\ \Omega$

```
733 AMP
VCC 1 0 6V
VEE 2 0 -6V
RCL 1 5 2.4K
RC2 1 6 2.4K
Q1 5 3 7 NPN
Q2 6 4 8 NPN
RE1 7 16 640
RE2 8 16 640
Q3 9 6 15 NPN
Q4 10 5 15 NPN
RC3 1 9 1.1K
RC4 1 10 1.1K
Q5 1 10 11 NPN
Q6 1 9 12 NPN
RF1 11 5 7K
RF2 12 6 7K
RL 11 12 2K
Q7 16 17 18 NPN
Q8 17 17 19 NPN
Q9 15 17 20 NPN
Q10 11 17 13 NPN
Q11 12 17 14 NPN
RQ7 18 2 300
RQ8 19 2 1.4K
RQ9 20 2 300
RQ10 13 2 400
RQ11 14 2 400
RBIAS 1 17 10K
.MODEL NPN NPN BF=100 IS=1E-13
VI1 3 0 0V
VI2 4 0 0V
.TF V(11,12) VI1
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END
```

```
 ******  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
+0:1       = 6.000E+00 0:2       =-6.000E+00 0:3       =   0.
+0:4       =   0.      0:5       = 1.767E+00 0:6       = 1.767E+00
+0:7       =-6.128E-01 0:8       =-6.128E-01 0:9       = 3.822E+00
+0:10      = 3.822E+00 0:11      = 3.197E+00 0:12      = 3.197E+00
+0:13      =-4.800E+00 0:14      =-4.800E+00 0:15      = 1.155E+00
+0:16      =-1.872E+00 0:17      =-4.176E+00 0:18      =-4.807E+00
+0:19      =-4.768E+00 0:20      =-4.807E+00

**** BIPOLAR JUNCTION TRANSISTORS
ELEMENT  0:Q1       0:Q2       0:Q3       0:Q4       0:Q5       0:Q6
MODEL    0:NPN      0:NPN      0:NPN      0:NPN      0:NPN      0:NPN
 IB       1.948E-05  1.948E-05  1.948E-05  1.948E-05  3.142E-05  3.142E-05
 IC       1.948E-03  1.948E-03  1.948E-03  1.948E-03  3.142E-03  3.142E-03
 VBE      6.128E-01  6.128E-01  6.128E-01  6.128E-01  6.252E-01  6.252E-01
 VCE      2.380E+00  2.380E+00  2.667E+00  2.667E+00  2.802E+00  2.802E+00
 VBC     -1.767E+00 -1.767E+00 -2.054E+00 -2.054E+00 -2.177E+00 -2.177E+00
 VS      -1.767E+00 -1.767E+00 -3.822E+00 -3.822E+00 -6.000E+00 -6.000E+00
 POWER    4.650E-03  4.650E-03  5.209E-03  5.209E-03  8.826E-03  8.826E-03
 BETAD    1.000E+02  1.000E+02  1.000E+02  1.000E+02  1.000E+02  1.000E+02
 GM       7.532E-02  7.532E-02  7.532E-02  7.532E-02  1.215E-01  1.215E-01
 RPI      1.327E+03  1.327E+03  1.327E+03  1.327E+03  8.231E+02  8.231E+02
 RX        0.         0.         0.         0.         0.         0.
 RO       1.767E+13  1.767E+13  2.054E+13  2.054E+13  2.177E+13  2.177E+13
 BETAAC   9.999E+01  9.999E+01  9.999E+01  9.999E+01  9.999E+01  9.999E+01
 FT       1.198E+13  1.198E+13  1.198E+13  1.198E+13  1.933E+13  1.933E+13
ELEMENT  0:Q7       0:Q8       0:Q9       0:Q10      0:Q11
MODEL    0:NPN      0:NPN      0:NPN      0:NPN      0:NPN
 IB       3.935E-05  8.709E-06  3.935E-05  2.969E-05  2.969E-05
 IC       3.935E-03  8.709E-04  3.935E-03  2.969E-03  2.969E-03
 VBE      6.310E-01  5.920E-01  6.310E-01  6.237E-01  6.237E-01
 VCE      2.935E+00  5.920E-01  5.962E+00  7.997E+00  7.997E+00
 VBC     -2.304E+00   0.       -5.331E+00 -7.373E+00 -7.373E+00
 VS       1.872E+00  4.176E+00 -1.155E+00 -3.197E+00 -3.197E+00
 POWER    1.158E-02  5.207E-04  2.349E-02  2.377E-02  2.377E-02
 BETAD    1.000E+02  1.000E+02  1.000E+02  1.000E+02  1.000E+02
 GM       1.522E-01  3.367E-02  1.522E-01  1.148E-01  1.148E-01
 RPI      6.572E+02  2.970E+03  6.572E+02  8.710E+02  8.710E+02
 RX        0.         0.         0.         0.         0.
 RO       2.304E+13  2.586E+11  5.331E+13  7.373E+13  7.373E+13
 BETAAC   9.999E+01  9.999E+01  9.999E+01  9.999E+01  9.999E+01
 FT       2.421E+13  5.358E+12  2.421E+13  1.827E+13  1.827E+13
```

HAND ANALYSIS STARTS WITH BIAS STRING: Q8 AND RESISTORS OF 10K AND 1.4K AND FIND IC8=1MA. BUT IT FAILS TO ACCOUNT FOR BASE CURRENTS OF Q7, Q9, Q10, Q11.

USING SPICE, WE SEE THAT THIS 1MA IS DIVIDED AMONG THESE TRANSISTORS: 1MA=IC8+IB7+IB9+IB10+IB11

SO THE SPICE DC BIAS CURRENTS OF TRANSISTORS ARE DIFFERENT FROM THE VALUES OBTAINED BY HAND.

```
****      SMALL-SIGNAL TRANSFER CHARACTERISTICS

      V(11,12)/VI1                            =  9.531E+00
      INPUT RESISTANCE AT          VI1        =  1.319E+05
      OUTPUT RESISTANCE AT V(11,12)           =  3.793E+00
```

8.21

Output resistance before loop is closed, $r_{oa} = 93\Omega$

Regulator amplifier gain

$a = 3054$

$$V_o = V_R \frac{R_1 + R_2}{R_2}$$

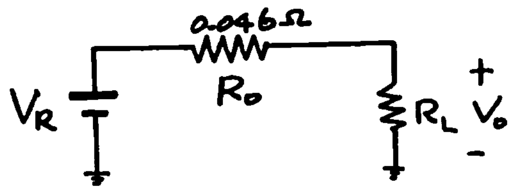
$$\therefore \frac{R_1 + R_2}{R_2} = \frac{V_o}{V_R} = \frac{10}{6.8} = 1.5$$

$$\therefore T = a \frac{R_2}{R_1 + R_2} = \frac{3054}{1.5} = 2036$$

$$\text{Output resistance} = \frac{r_{oa}}{1+T}$$

$$= \frac{93}{2037}$$

$\therefore R_o = 0.046\Omega$



$$V_o = \frac{R_L}{R_L + R_o} V_R$$

$R_L = 1k\Omega$

$$10 = \frac{1000}{1000.046} V_R$$

$\therefore V_R = 10.00046$ V

$R_L = 500\Omega$

$$V_o = \frac{500}{500.046} \times 10.00046$$

$= 9.9995$ V

```
723 VOLTAGE REGULATOR
* VR VOLTAGE REFERENCE GENERATOR
VCC 1 0 15V
D1 2 1 DIODE
IBIAS 2 0 1MA
R1 1 3 500
Q2 4 4 3 P
R2 4 2 15.5K
Q3 6 4 5 P
R3 1 5 25K
Q6 6 7 0 N
C1 6 7 5PF
Q4 1 6 11 N
Q5 1 11 10 N
R6 10 9 100
D2 8 9 DIODE
R7 7 8 30K
R8 8 0 5K
* VOLTAGE AMPLIFIER
RC 9 18 667
R4 1 12 1K
Q7 13 4 12 P
Q10 13 14 15 N
R9 15 0 300
R10 14 0 20K
Q9 1 13 14 N
Q11 1 18 17 N
Q8 19 4 20 P
R5 1 20 1K
Q12 19 21 17 N
C2 19 21 100PF
Q13 17 14 16 N
R11 16 0 150
Q14 1 19 22 N
R12 22 23 15K
Q15 1 22 23 N
* (RA+RB)/RB = VO/VR = 10/6.8 = 1.5 = 3/2
* CHOOSE RA = 1K, RB = 2K
RA 23 21 1K
RB 21 0 2K
RLOAD 23 0 1K
.MODEL N NPN BF=100 VAF=100 IS=1E-15
.MODEL P PNP BF=100 VAF=100 IS=1E-15
.MODEL DIODE D BV=6.2 IS=1E-15
.TF V(23) VCC
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END
```

```
 ******  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000

+0:1        = 1.500E+01 0:2       = 8.810E+00 0:3       = 1.483E+01
+0:4        = 1.414E+01 0:5       = 1.473E+01 0:6       = 7.949E+00
+0:7        = 5.946E-01 0:8       = 5.975E-01 0:9       = 6.742E+00
+0:10       = 6.754E+00 0:11      = 7.412E+00 0:12      = 1.481E+01
+0:13       = 1.356E+00 0:14      = 7.276E-01 0:15      = 5.653E-02
+0:16       = 4.543E-02 0:17      = 6.085E+00 0:18      = 6.741E+00
+0:19       = 1.158E+01 0:20      = 1.481E+01 0:21      = 6.754E+00
+0:22       = 1.091E+01 0:23      = 1.013E+01

**** DIODES

ELEMENT  0:D1       0:D2
MODEL    0:DIODE    0:DIODE
 ID      -6.560E-04 -1.196E-04
 VD      -6.189E+00 -6.145E+00
 REQ      3.942E+01  2.162E+02
 CAP       0.         0.

**** BIPOLAR JUNCTION TRANSISTORS

ELEMENT  0:Q2       0:Q3       0:Q6       0:Q4       0:Q5       0:Q7
MODEL    0:P        0:P        0:N        0:N        0:N        0:P
 IB      -3.371E-06 -9.770E-08  9.655E-08  1.028E-08  1.111E-06 -1.657E-06
 IC      -3.371E-04 -1.038E-05  1.036E-05  1.101E-06  1.195E-04 -1.869E-04
 VBE     -6.865E-01 -5.949E-01  5.946E-01  5.367E-01  6.578E-01 -6.682E-01
 VCE     -6.865E-01 -6.789E+00  7.949E+00  7.587E+00  8.245E+00 -1.345E+01
 VBC       0.        6.194E+00 -7.354E+00 -7.050E+00 -7.587E+00  1.278E+01
 VS      -1.414E+01 -1.414E+01 -7.949E+00 -1.500E+01 -1.500E+01 -1.414E+01
 POWER    2.337E-04  7.049E-05  8.245E-05  8.358E-06  9.864E-04  2.516E-03
 BETAD    1.000E+02  1.061E+02  1.073E+02  1.070E+02  1.075E+02  1.127E+02
 GM       1.303E-02  4.010E-04  4.006E-04  4.255E-05  4.621E-03  7.226E-03
 RPI      7.672E+03  2.647E+05  2.678E+05  2.515E+06  2.327E+04  1.560E+04
 RX        0.         0.         0.         0.         0.         0.
 RO       2.966E+05  1.023E+07  1.035E+07  9.724E+07  8.999E+05  6.033E+05
 CPI       0.         0.         0.         0.         0.         0.
 CMU       0.         0.         0.         0.         0.         0.
 CBX       0.         0.         0.         0.         0.         0.
 CCS       0.         0.         0.         0.         0.         0.
 BETAAC   9.997E+01  1.061E+02  1.073E+02  1.070E+02  1.075E+02  1.127E+02
 FT       2.073E+12  6.382E+10  6.376E+10  6.772E+09  7.354E+11  1.150E+12

ELEMENT  0:Q10      0:Q9       0:Q11      0:Q8       0:Q12      0:Q13
MODEL    0:N        0:N        0:N        0:P        0:N        0:N
 IB       1.854E-06  3.583E-07  1.056E-06 -1.800E-06  1.745E-06  2.848E-06
 IC       1.866E-04  4.072E-05  1.143E-04 -1.847E-04  1.829E-04  3.000E-04
 VBE      6.711E-01  6.286E-01  6.565E-01 -6.703E-01  6.695E-01  6.822E-01
 VCE      1.299E+00  1.427E+01  8.914E+00 -3.229E+00  5.498E+00  6.040E+00
 VBC     -6.286E-01 -1.364E+01 -8.258E+00  2.559E+00 -4.829E+00 -5.357E+00
 VS      -1.356E+00 -1.500E+01 -1.500E+01 -1.414E+01 -1.158E+01 -6.085E+00
 POWER    2.437E-04  5.814E-04  1.020E-03  5.976E-04  1.007E-03  1.814E-03
 BETAD    1.006E+02  1.136E+02  1.082E+02  1.025E+02  1.048E+02  1.053E+02
 GM       7.212E-03  1.574E-03  4.418E-03  7.138E-03  7.071E-03  1.160E-02
 RPI      1.394E+04  7.217E+04  2.449E+04  1.436E+04  1.482E+04  9.082E+03
 RX        0.         0.         0.         0.         0.         0.
 RO       5.393E+05  2.790E+06  9.471E+05  5.554E+05  5.730E+05  3.511E+05
 CPI       0.         0.         0.         0.         0.         0.
 CMU       0.         0.         0.         0.         0.         0.
 CBX       0.         0.         0.         0.         0.         0.
 CCS       0.         0.         0.         0.         0.         0.
 BETAAC   1.006E+02  1.136E+02  1.082E+02  1.025E+02  1.048E+02  1.053E+02
 FT       1.147E+12  2.505E+11  7.031E+11  1.136E+12  1.125E+12  1.845E+12

ELEMENT  0:Q14      0:Q15
MODEL    0:N        0:N
 IB       1.725E-06  1.281E-04
 IC       1.784E-04  1.333E-02
 VBE      6.692E-01  7.806E-01
 VCE      4.085E+00  4.865E+00
 VBC     -3.416E+00 -4.085E+00
 VS      -1.500E+01 -1.500E+01
 POWER    7.300E-04  6.498E-02
 BETAD    1.034E+02  1.040E+02
 GM       6.896E-03  5.154E-01
 RPI      1.499E+04  2.019E+02
 RX        0.         0.
 RO       5.796E+05  7.806E+03
 CPI       0.         0.
 CMU       0.         0.
 CBX       0.         0.
 CCS       0.         0.
 BETAAC   1.033E+02  1.040E+02
 FT       1.097E+12  8.202E+13

****     SMALL-SIGNAL TRANSFER CHARACTERISTICS

      V(23)/VCC                                 =  4.207E-04
      INPUT RESISTANCE AT          VCC          =  8.035E+05
      OUTPUT RESISTANCE AT V(23)                =  5.444E-02

LOAD REGULATION:
     (DVO/VO)/DIO=(DVO/DIO)/VO=RO/VO=5.444E-2/10=5.4E-3
LINE REGULATION:
     (DVO/VO)/DVCC=(DVO/DVCC)/VO=4.207E-4/10=4.3E-5
```

$V_{CC} = I_{D2}\,10k + V_{BE2} + V_{GS2}$

$5 = I_{D2}\,10k + 0.8 + V_{GS2}$

$= \frac{40\mu}{2} 30 (V_{GS2} - 0.8)^2 10k + 0.8 + V_{GS2}$

$= 6(V_{GS2} - 0.8)^2 + 0.8 + V_{GS2}$

$0 = 6V_{GS2}^2 - 8.6V_{GS2} - 0.36$

$V_{GS2} = \frac{8.6 \pm \sqrt{8.6^2 - 4(6)(-0.36)}}{12}$

$= \frac{8.6 \pm 9.088}{12}$

$V_{GS2} = 1.47V$

$I_{D2} = \frac{40\mu}{2} 30(1.47 - 0.8)^2 = 273\mu A$

$V_{BQ2} = 5 - I_{D2}\,10k = 2.27V$

$V_{EQ2} = V_{BQ2} - 0.8 = 1.47V$

$I_{R_{L1}} = \frac{5 - 1.47}{1k} = 3.53mA$

$I_{D1} = 3.53mA + \frac{5 - (V_{GS1} + 0.8)}{10k}$

$10k\,I_{D1} = 35.3 + 5 - V_{GS1} - 0.8$

$= 39.5 - V_{GS1}$

$10k\,\frac{40\mu}{2} 300 (V_{GS1} - 0.8)^2 = 39.5 - V_{GS1}$

$60(V_{GS1} - 0.8)^2 = 39.5 - V_{GS1}$

$60V_{GS1} - 95V_{GS1} - 1.1 = 0$

$V_{GS1} = \frac{95 \pm \sqrt{95^2 - 4(60)(-1.1)}}{120}$

$= \frac{95 \pm 96.4}{120}$

$V_{GS1} = 1.59V$

$I_{D1} = 3.53m + \frac{5 - (1.59 + 0.8)}{10k}$

$= 3.53m + I_{CQ1}$

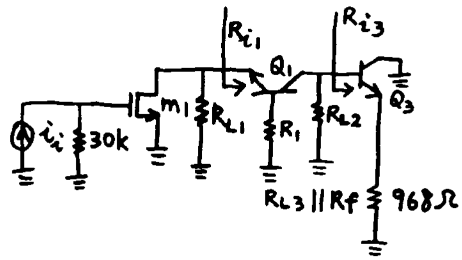
$= 3.53m + 0.26m$

$= 3.79mA$

$I_{CQ1} = 0.26mA$

$I_{C3} = \frac{1.59V}{1k} = 1.59mA$

forward path



$R_{i1} = \frac{1}{g_{mQ1}} + \frac{R_1}{\beta}$

$= \frac{26mV}{0.26mA} + \frac{1174}{100}$

$= 112$

$R_1 = 10k \| \left(\frac{1}{g_{mQ2}} + \frac{1}{g_{m\,m2}}\right)$

$= 10k \| \left(\frac{26mV}{273\mu A} + \frac{1}{\sqrt{2(40\mu)(30)(273\mu)}}\right)$

$= 10k \| (95.2 + 1.24k)$

$= 1174$

$R_{i3} = r_{\pi3}(1 + g_{m3} R_{E3})$

$= \frac{100}{g_{m3}}(1 + g_{m3}\,968)$

$= 98.4k$

$\frac{V_o}{i_i} = -30k\,g_{mM1} \frac{R_{L1}}{R_{L1} + R_{i1}} (R_{L2} \| R_{i3}) A_{v3}$

$= -30k(9.54m)\left(\frac{1000}{1112}\right)(9.08k)(0.983)$

$= -2.3M\Omega = a$

$g_{mM1} = \sqrt{2(40\mu)(300)(3.79m)}$

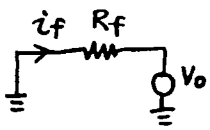
$= 9.54\,mA/V$

$A_{v3} = \frac{g_{m3}\,968}{1 + g_{m3}\,968} = 0.983$

$R_{L2} \| R_{i3} = 10k \| 98.4k$

$= 9.08k$

feedback



$V_o f = i_f$

$f = \frac{-1}{R_f} = \frac{-1}{30k}$

$T = af = 76.7$

$R_{in} = \frac{30k}{1+76.7} = 386\Omega$

$R_{out} = \frac{r_{out}}{1+76.7}$

$= \frac{104}{77.7} = 1.34\Omega$

$r_{out} = 968 \| \left(\frac{1}{g_{m3}} + \frac{R_{L2}}{\beta}\right)$

$= 104$

$A = \frac{a}{1+T} = \frac{-2.3M}{1+76.7} = -29.6k\Omega = \frac{V_o}{i_i}$

```
BICMOS AMP
VCC 1 0 5V
RL1 1 4 1K
M1 4 2 0 0 NMOS W=300U L=1U
II 2 0 0A
RF 2 7 30K
RE 7 0 1K
RL2 1 3 10K
RBIAS 1 5 10K
Q1 3 5 4 NPN
Q2 5 5 6 NPN
Q3 1 3 7 NPN
M2 6 6 0 0 NMOS W=30U L=1U
.DC II -0.1M 0.1M 0.01M
.PLOT DC V(7)
.TF V(7) II
.MODEL NMOS NMOS KP=40U LAMBDA=0 VTO=0.8
.MODEL NPN NPN IS=1E-16 BF=100 RB=0
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END
******
 ******  DC TRANSFER CURVES                       TNOM=  27.000 TEMP=  27.000
   AMPS      V(7)
(A       )      0.         1.000E-00   2.000E+00   3.000E+00   4.000E+00
                   +          +           +           +           +
-1.000E-04  1.00E-01-+A-----+-----+-----+-----+-----+-----+-----+-----+-
-9.000E-05  9.00E-02 +A     +     +     +     +     +     +     +     +
-8.000E-05  8.00E-02 +A     +     +     +     +     +     +     +     +
-7.000E-05  7.00E-02 +A     +     +     +     +     +     +     +     +
-6.000E-05  6.01E-02 +A     +     +     +     +     +     +     +     +
-5.000E-05  1.97E-01 +  A   +     +     +     +     +     +     +     +
-4.000E-05  4.57E-01 +     A+     +     +     +     +     +     +     +
-3.000E-05  7.14E-01 +      +  A  +     +     +     +     +     +     +
-2.000E-05  1.00E+00 +      +     A     +     +     +     +     +     +
-1.000E-05  1.29E+00 +      +     +  A  +     +     +     +     +     +
  0.        1.59E+00-+------+-----+-----+A----+-----+-----+-----+-----+-
 1.000E-05  1.88E+00 +      +     +     +   A +     +     +     +     +
 2.000E-05  2.18E+00 +      +     +     +     +  A  +     +     +     +
 3.000E-05  2.48E+00 +      +     +     +     +     A     +     +     +
 4.000E-05  2.77E+00 +      +     +     +     +     +  A  +     +     +
 5.000E-05  3.07E+00 +      +     +     +     +     +     +A    +     +
 6.000E-05  3.36E+00 +      +     +     +     +     +     +   A +     +
 7.000E-05  3.66E+00 +      +     +     +     +     +     +     + A   +
 8.000E-05  3.80E+00 +      +     +     +     +     +     +     +   A +
 9.000E-05  3.80E+00 +      +     +     +     +     +     +     +   A +
 1.000E-04  3.80E+00-+------+-----+---  -+-----+-----+-----+-----+---A--+-
                   +          +           +           +           +
 ******  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
+0:1       = 5.000E+00 0:2       = 1.592E+00 0:3       = 2.378E+00
+0:4       = 1.480E+00 0:5       = 2.218E+00 0:6       = 1.477E+00
+0:7       = 1.592E+00
**** BIPOLAR JUNCTION TRANSISTORS
ELEMENT  0:Q1       0:Q2       0:Q3
MODEL    0:NPN      0:NPN      0:NPN
 IB       2.464E-06  2.730E-06  1.577E-05
 IC       2.464E-04  2.730E-04  1.577E-03
 VBE      7.380E-01  7.406E-01  7.860E-01
 VCE      8.980E-01  7.406E-01  3.407E+00
 VBC     -1.600E-01   0.        -2.621E+00
 VS      -2.378E+00 -2.218E+00 -5.000E+00
 POWER    2.231E-04  2.042E-04  5.385E-03
 BETAD    1.000E+02  1.000E+02  1.000E+02
 GM       9.526E-03  1.055E-02  6.096E-02
 RPI      1.049E+04  9.475E+03  1.640E+03
 RX        0.         0.         0.
 RO       1.257E+17  2.586E+14  2.621E+16
 BETAAC   9.999E+01  9.999E+01  9.999E+01
 FT       1.516E+12  1.679E+12  9.702E+12
**** MOSFETS
ELEMENT  0:M1       0:M2
MODEL    0:NMOS     0:NMOS
 ID       3.768E-03  2.757E-04
 IBS       0.         0.
 IBD     -1.480E-14 -1.478E-14
 VGS      1.592E+00  1.477E+00
 VDS      1.480E+00  1.477E+00
 VBS       0.         0.
 VTH      8.000E-01  8.000E-01
 VDSAT    7.925E-01  6.779E-01
 BETA     1.200E-02  1.200E-03
 GAM EFF   0.         0.
 GM       9.510E-03  8.134E-04
****      SMALL-SIGNAL TRANSFER CHARACTERISTICS
     V(7)/II                                        =   2.960E+04
     INPUT RESISTANCE AT            II              =   3.925E+02
     OUTPUT RESISTANCE AT V(7)                      =   1.347E+00
```

8.23

$$\frac{V_{DD} - V_{GS_2}}{10k} = I_{D_2} = \frac{30\mu}{2} 20 (V_{GS_2} - 0.8)^2$$

$$5 - a = 3(a - 0.8)^2$$

$$= 3a^2 - 4.8a + 1.92$$

$$0 = 3a^2 - 3.8a - 3.08$$

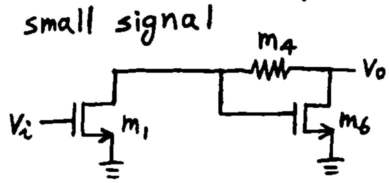
$$a = \frac{+3.8 \pm \sqrt{3.8^2 - 4(3)(-3.08)}}{6}$$

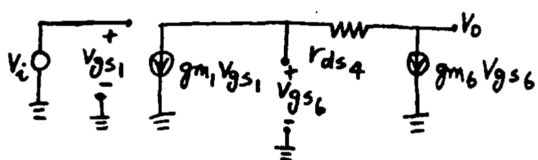
$V_{GS_2} = 1.83\,V$

$$I_{D_2} = \frac{30\mu}{2} 20 (1.83 - 0.8)^2$$

$$= 317\,\mu A = I_{D_1} = I_{D_5} = I_{D_6}$$

small signal





$$V_o = V_{gs_6} - g_{m_6} V_{gs_6} r_{ds_4}$$

$$g_{m_1} = g_{m_6}$$

$$-g_{m_1} V_{gs_1} = g_{m_6} V_{gs_6}$$

$$-V_{gs_1} = V_{gs_6} = -V_i$$

$$V_o = -V_i + g_{m_6} V_i r_{ds_4}$$

$$\frac{V_o}{V_i} = -1 + g_{m_6} r_{ds_4}$$

$$g_{m_6} = \sqrt{2(317\mu)(60\mu)(20)}$$

$$= 872\,\mu A/V$$

$$g_{ds_4} = \mu_n C_{ox} \frac{W}{L} (V_{GS_4} - V_{t_4})$$

$$= 150\mu (V_c - 1.53 - 1.14)$$

$$= 150\mu (V_c - 2.67)$$

$$V_{t_4} = V_{t_0} + \gamma\left(\sqrt{V_{SB_4} + 2\phi_f} - \sqrt{2\phi_f}\right)$$

$$= 0.8 + 0.5\left(\sqrt{1.53 + 0.6} - \sqrt{0.6}\right)$$

$$= 1.14\,V$$

$$V_{SB_4} = V_{GS_6} = V_{t_6} + \sqrt{\frac{2 I_{D6}}{\mu C_{ox} \frac{W}{L}_6}}$$

$$= 0.8 + \sqrt{\frac{2(317\mu)}{60\mu (20)}}$$

$$= 1.53\,V$$

$V_c = 3V$

$$g_{ds_4} = 150\mu (3 - 2.67)$$

$$= 49.5\mu$$

$$r_{ds_4} = 20.2\,k$$

$$\frac{V_o}{V_i} = -1 + (872\mu)(20.2k)$$

$$= 16.6$$

$V_c = 4V$

$$g_{ds_4} = 150\mu (4 - 2.67)$$

$$= 200\mu$$

$$r_{ds_4} = 5.01\,k$$

$$\frac{V_o}{V_i} = -1 + (872\mu)(5.01k)$$

$$= 3.37$$

$$R_o = \frac{1}{g_{m6}} = \frac{1}{872\mu} = 1.15\,k\Omega$$

```
VARIABLE GAIN CMOS AMP
VDD 1 0 5V
M1 3 4 0 0 NMOS W=20U L=1U
M2 2 2 1 1 PMOS W=20U L=1U
R1 2 0 10K
M3 3 2 1 1 PMOS W=20U L=1U
M5 5 2 1 1 PMOS W=20U L=1U
M6 5 3 0 0 NMOS W=20U L=1U
M4 5 6 3 0 NMOS W=5U L=2U
VC 6 0 3V
VI 4 0 1.527V
.DC VI 1.47 1.6 0.005
.PLOT DC V(5)
.TF V(5) VI
.NODESET V(2)=3.17V V(3)=1.53V V(5)=1.53V
.MODEL NMOS NMOS KP=60U VTO=0.8 GAMMA=0.5
.MODEL PMOS PMOS KP=30U VTO=-0.8 GAMMA=0.5
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END
```

```
****** DC TRANSFER CURVES                    TNOM=  27.000 TEMP=  27.000

   VOLT        V(5)
(A       )    1.000E-00    2.000E+00    3.000E+00    4.000E+00    5.000E+00
                   +            +            +            +            +
1.470E+00  1.06E+00-+A-----+-----+-----+-----+-----+-----+-----+-----+-
1.475E+00  1.09E+00 +A     +     +     +     +     +     +     +     +
1.480E+00  1.11E+00 + A    +     +     +     +     +     +     +     +
1.485E+00  1.14E+00 + A    +     +     +     +     +     +     +     +
1.490E+00  1.18E+00 +  A   +     +     +     +     +     +     +     +
1.495E+00  1.21E+00 +  A   +     +     +     +     +     +     +     +
1.500E+00  1.24E+00 +  A   +     +     +     +     +     +     +     +
1.505E+00  1.28E+00 +   A  +     +     +     +     +     +     +     +
1.510E+00  1.32E+00 +    A +     +     +     +     +     +     +     +
1.515E+00  1.37E+00 +    A +     +     +     +     +     +     +     +
1.520E+00  1.43E+00-+-----A+-----+-----+-----+-----+-----+-----+-----+-
1.525E+00  1.49E+00 +      A     +     +     +     +     +     +     +
1.530E+00  1.58E+00 +      +A    +     +     +     +     +     +     +
1.535E+00  1.70E+00 +      +  A  +     +     +     +     +     +     +
1.540E+00  4.29E+00 +      +     +     +     +     +     +  A  +     +
1.545E+00  4.46E+00 +      +     +     +     +     +     +   A+     +
1.550E+00  4.56E+00 +      +     +     +     +     +     +     +A    +
1.555E+00  4.63E+00 +      +     +     +     +     +     +     + A   +
1.560E+00  4.68E+00 +      +     +     +     +     +     +     +  A  +
1.565E+00  4.72E+00 +      +     +     +     +     +     +     +  A  +
1.570E+00  4.75E+00-+------+-----+-----+-----+-----+-----+-----+---A--+-
1.575E+00  4.77E+00 +      +     +     +     +     +     +     +   A +
1.580E+00  4.79E+00 +      +     +     +     +     +     +     +   A +
1.585E+00  4.81E+00 +      +     +     +     +     +     +     +   A +
1.590E+00  4.82E+00 +      +     +     +     +     +     +     +    A+
1.595E+00  4.83E+00 +      +     +     +     +     +     +     +    A+
1.600E+00  4.83E+00 +      +     +     +     +     +     +     +    A+
                   +            +            +            +            +
```

****** OPERATING POINT INFORMATION   TNOM= 27.000 TEMP= 27.000

```
+0:1     = 5.000E+00 0:2     = 3.171E+00 0:3     = 1.527E+00
+0:4     = 1.527E+00 0:5     = 1.525E+00 0:6     = 3.000E+00
```

**** MOSFETS

ELEMENT	0:M1	0:M2	0:M3	0:M5	0:M6	0:M4
MODEL	0:NMOS	0:PMOS	0:PMOS	0:PMOS	0:NMOS	0:NMOS
ID	3.171E-04	-3.172E-04	-3.172E-04	-3.172E-04	3.172E-04	-5.961E-08
IBS	0.	0.	0.	0.	0.	-1.527E-14
IBD	-1.527E-14	1.828E-14	3.473E-14	3.474E-14	-1.526E-14	-1.526E-14
VGS	1.527E+00	-1.828E+00	-1.828E+00	-1.828E+00	1.527E+00	1.472E+00
VDS	1.527E+00	-1.828E+00	-3.472E+00	-3.474E+00	1.525E+00	-1.198E-03
VBS	0.	0.	0.	0.	0.	-1.527E+00
VTH	8.000E-01	-8.000E-01	-8.000E-01	-8.000E-01	8.000E-01	1.141E+00
VDSAT	7.270E-01	-1.028E+00	-1.028E+00	-1.028E+00	7.271E-01	1.198E-03
BETA	1.200E-03	6.000E-04	6.000E-04	6.000E-04	1.200E-03	1.500E-04
GAM EFF	5.000E-01	5.000E-01	5.000E-01	5.000E-01	5.000E-01	5.000E-01
GM	8.724E-04	6.169E-04	6.169E-04	6.169E-04	8.726E-04	1.797E-07
GDS	0.	0.	0.	0.	0.	4.967E-05
GMB	2.816E-04	1.991E-04	1.991E-04	1.991E-04	2.816E-04	3.081E-08
CDTOT	0.	0.	0.	0.	0.	0.
CGTOT	0.	0.	0.	0.	0.	0.
CSTOT	0.	0.	0.	0.	0.	0.
CBTOT	0.	0.	0.	0.	0.	0.
CGS	0.	0.	0.	0.	0.	0.
CGD	0.	0.	0.	0.	0.	0.

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

```
V(5)/VI                              = 1.649E+01
INPUT RESISTANCE AT         VI       = 9.999E+19
OUTPUT RESISTANCE AT V(5)            = 1.141E+03
```

```
*****
VARIABLE GAIN CMOS AMP
VDD 1 0 5V
M1 3 4 0 0 NMOS W=20U L=1U
M2 2 2 1 1 PMOS W=20U L=1U
R1 2 0 10K
M3 3 2 1 1 PMOS W=20U L=1U
M5 5 2 1 1 PMOS W=20U L=1U
M6 5 3 0 0 NMOS W=20U L=1U
M4 5 6 3 0 NMOS W=5U L=2U
VC 6 0 4V
VI 4 0 1.527V
.DC VI 1.0 1.8 0.05
.PLOT DC V(5)
.TF V(5) VI
.NODESET V(2)=3.17V V(3)=1.53V V(5)=1.53V
.MODEL NMOS NMOS KP=60U VTO=0.8 GAMMA=0.5
.MODEL PMOS PMOS KP=30U VTO=-0.8 GAMMA=0.5
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END
```

```
****** DC TRANSFER CURVES                    TNOM=  27.000 TEMP=  27.000

   VOLT        V(5)
(A       )     0.          2.000E+00    4.000E+00    6.000E+00    8.000E+00
                   +            +            +            +            +
1.000E+00  7.25E-01-+----A-+-----+-----+-----+-----+-----+-----+-----+-
1.050E+00  7.50E-01 +    A +     +     +     +     +     +     +     +
1.100E+00  7.81E-01 +    A +     +     +     +     +     +     +     +
1.150E+00  8.20E-01 +     A+     +     +     +     +     +     +     +
1.200E+00  8.69E-01 +     A+     +     +     +     +     +     +     +
1.250E+00  9.30E-01 +      A     +     +     +     +     +     +     +
1.300E+00  1.00E+00 +      A     +     +     +     +     +     +     +
1.350E+00  1.08E+00 +      +A    +     +     +     +     +     +     +
1.400E+00  1.18E+00 +      +A    +     +     +     +     +     +     +
1.450E+00  1.30E+00 +      + A   +     +     +     +     +     +     +
1.500E+00  1.44E+00-+------+--A--+-----+-----+-----+-----+-----+-----+-
1.550E+00  1.60E+00 +      +   A +     +     +     +     +     +     +
1.600E+00  1.80E+00 +      +     A+    +     +     +     +     +     +
1.650E+00  2.03E+00 +      +     A     +     +     +     +     +     +
1.700E+00  2.33E+00 +      +     + A   +     +     +     +     +     +
1.750E+00  4.05E+00 +      +     +     +     A     +     +     +     +
1.800E+00  4.13E+00 +      +     +     +     +A    +     +     +     +
                   +            +            +            +            +
```

****** OPERATING POINT INFORMATION   TNOM= 27.000 TEMP= 27.000

```
+0:1     = 5.000E+00 0:2     = 3.171E+00 0:3     = 1.527E+00
+0:4     = 1.527E+00 0:5     = 1.526E+00 0:6     = 4.000E+00
```

**** MOSFETS

ELEMENT	0:M1	0:M2	0:M3	0:M5	0:M6	0:M4
MODEL	0:NMOS	0:PMOS	0:PMOS	0:PMOS	0:NMOS	0:NMOS
ID	3.171E-04	-3.172E-04	-3.172E-04	-3.172E-04	3.172E-04	-5.961E-08
IBS	0.	0.	0.	0.	0.	-1.527E-14
IBD	-1.527E-14	1.828E-14	3.473E-14	3.473E-14	-1.527E-14	-1.527E-14
VGS	1.527E+00	-1.828E+00	-1.828E+00	-1.828E+00	1.527E+00	2.472E+00
VDS	1.527E+00	-1.828E+00	-3.472E+00	-3.473E+00	1.526E+00	-2.985E-04
VBS	0.	0.	0.	0.	0.	-1.527E+00
VTH	8.000E-01	-8.000E-01	-8.000E-01	-8.000E-01	8.000E-01	1.141E+00
VDSAT	7.270E-01	-1.028E+00	-1.028E+00	-1.028E+00	7.271E-01	2.985E-04
BETA	1.200E-03	6.000E-04	6.000E-04	6.000E-04	1.200E-03	1.500E-04
GAM EFF	5.000E-01	5.000E-01	5.000E-01	5.000E-01	5.000E-01	5.000E-01
GM	8.724E-04	6.169E-04	6.169E-04	6.169E-04	8.726E-04	4.478E-08
GDS	0.	0.	0.	0.	0.	1.996E-04
GMB	2.816E-04	1.991E-04	1.991E-04	1.991E-04	2.816E-04	7.677E-09
CDTOT	0.	0.	0.	0.	0.	0.
CGTOT	0.	0.	0.	0.	0.	0.
CSTOT	0.	0.	0.	0.	0.	0.
CBTOT	0.	0.	0.	0.	0.	0.
CGS	0.	0.	0.	0.	0.	0.
CGD	0.	0.	0.	0.	0.	0.

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

```
V(5)/VI                              = 3.369E+00
INPUT RESISTANCE AT         VI       = 9.999E+19
OUTPUT RESISTANCE AT V(5)            = 1.145E+03
```

8.24

$I_{D_1} = I_{D_2} = \frac{1}{2} I_{D_6} = 100\mu A = I_{D_3}$

$I_{D_8} = 200\mu A$

$$a = \frac{1}{2} g_{m_1} (2r_{o_2} \| r_{o_3}) \; \frac{g_{m8}(21k)}{1 + g_{m8}(21k)}$$

$$= \frac{1}{2}(693\mu)(222k)(0.954)$$

$$= 73.4$$

$$g_{m_1} = \sqrt{2(100\mu)(60\mu)40}$$

$$= 693 \mu A/V$$

$$r_{o_2} = r_{o_3} = \frac{1}{\lambda I_D} = \frac{1}{0.03(100\mu)}$$

$$= 333k$$

$$g_{m8} = \sqrt{2(200\mu)(60\mu)40}$$

$$= 980 \mu A/V$$

$$f = \frac{1k}{1k + 20k} = \frac{1}{21}$$

$$T = af = 3.5$$

$$A = \frac{a}{1+T} = \frac{73.4}{4.5} = 16.3 = \frac{V_o}{V_i}$$

$$R_o = \frac{r_{out}}{1+T} = \frac{973}{4.5}$$

$$= 216\Omega$$

$$r_{out} = 21k \| \frac{1}{g_{m8}}$$

$$= 21k \| 1.02k$$

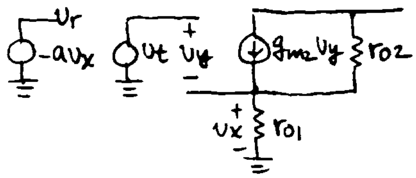
$$= 973\Omega$$

8-25

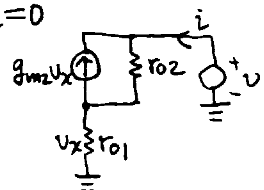
```
CMOS FEEDBACK AMP
VDD 1 0 5V
VSS 9 0 -5V
M4 2 2 1 1 PMOS W=20U L=1U
I1 2 3 100UA
M5 3 3 9 9 NMOS W=20U L=1U
M6 6 3 9 9 NMOS W=40U L=1U
M1 1 4 6 9 NMOS W=40U L=1U
M2 5 7 6 9 NMOS W=40U L=1U
M3 5 2 1 1 PMOS W=20U L=1U
M8 1 5 8 9 NMOS W=40U L=1U
M7 8 3 9 9 NMOS W=40U L=1U
RF 8 7 20K
RE 7 0 1K
VI 4 0 0V
.TF V(8) VI
.MODEL NMOS NMOS KP=60U VTO=0.8 LAMBDA=0.03
.MODEL PMOS PMOS KP=30U VTO=-0.8 LAMBDA=0.03
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

 ******  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000

+0:1        = 5.000E+00 0:2        = 3.634E+00 0:3        =-3.798E+00
+0:4        =   0.      0:5        = 1.413E+00 0:6        =-1.077E+00
+0:7        = 9.599E-03 0:8        = 2.016E-01 0:9        =-5.000E+00

**** MOSFETS

ELEMENT  0:M4       0:M5       0:M6       0:M1       0:M2       0:M3
MODEL    0:PMOS     0:NMOS     0:NMOS     0:NMOS     0:NMOS     0:PMOS
 ID      -1.000E-04  1.000E-04  2.158E-04  1.094E-04  1.064E-04 -1.064E-04
 IBS       0.         0.         0.       -3.922E-14 -3.922E-14   0.
 IBD      1.366E-14 -1.201E-14 -3.922E-14 -1.000E-13 -6.413E-14  3.587E-14
 VGS     -1.365E+00  1.201E+00  1.201E+00  1.077E+00  1.087E+00 -1.365E+00
 VDS     -1.365E+00  1.201E+00  3.922E+00  6.077E+00  2.491E+00 -3.586E+00
 VBS       0.         0.         0.       -3.922E+00 -3.922E+00   0.
 VTH     -8.000E-01  8.000E-01  8.000E-01  8.000E-01  8.000E-01 -8.000E-01
 VDSAT   -5.659E-01  4.011E-01  4.011E-01  2.776E-01  2.872E-01 -5.659E-01
 BETA     6.246E-04  1.243E-03  2.682E-03  2.838E-03  2.579E-03  6.646E-04
 GAM EFF   0.         0.         0.         0.         0.         0.
 GM       3.534E-04  4.986E-04  1.076E-03  7.878E-04  7.409E-04  3.761E-04
 GDS      2.882E-06  2.896E-06  5.791E-06  2.775E-06  2.970E-06  2.882E-06
 GMB       0.         0.         0.         0.         0.         0.
 CDTOT     0.         0.         0.         0.         0.         0.
 CGTOT     0.         0.         0.         0.         0.         0.
 CSTOT     0.         0.         0.         0.         0.         0.
 CBTOT     0.         0.         0.         0.         0.         0.
 CGS       0.         0.         0.         0.         0.         0.
 CGD       0.         0.         0.         0.         0.         0.

ELEMENT  0:M8       0:M7
MODEL    0:NMOS     0:NMOS
 ID       2.328E-04  2.232E-04
 IBS     -5.202E-14    0.
 IBD     -1.000E-13 -5.202E-14
 VGS      1.211E+00  1.201E+00
 VDS      4.798E+00  5.201E+00
 VBS     -5.201E+00    0.
 VTH      8.000E-01  8.000E-01
 VDSAT    4.118E-01  4.011E-01
 BETA     2.745E-03  2.775E-03
 GAM EFF   0.         0.
 GM       1.131E-03  1.113E-03
 GDS      6.104E-06  5.791E-06
 GMB       0.         0.
 CDTOT     0.         0.
 CGTOT     0.         0.
 CSTOT     0.         0.
 CBTOT     0.         0.
 CGS       0.         0.
 CGD       0.         0.

****      SMALL-SIGNAL TRANSFER CHARACTERISTICS

     V(8)/VI                                     =  1.662E+01
     INPUT RESISTANCE AT          VI             =  9.999E+19
     OUTPUT RESISTANCE AT V(8)                   =  1.707E+02
```

8.25

Consider a as the controlled source.



$a=0$



$$\frac{v_x}{r_{o1}} = g_{m2}v_x + \frac{v_x - v}{r_{o2}}$$

$$R_{out}(a=0) = \frac{v}{i} = \frac{v}{v_x/r_{o1}}$$

$$\approx g_{m2}r_{o1}r_{o2}$$

The output is shorted

$$v_x = g_{m2}(v_t - v_x)(r_{o1}\|r_{o2})$$

$$v_x = \frac{g_{m2}(r_{o1}\|r_{o2})}{1+g_{m2}(r_{o1}\|r_{o2})}v_t$$

$$R(\text{short}) = a\frac{g_{m2}(r_{o1}\|r_{o2})}{1+g_{m2}(r_{o1}\|r_{o2})}$$

$R(\text{open}) = 0$ ($v_x = 0$ when the output is open.)

$$R_{out} = R_{out}(a=0)\frac{1+R(\text{short})}{1+R(\text{open})}$$

$$\approx g_{m2}r_{o1}r_{o2}\frac{1+a\frac{g_{m2}(r_{o1}\|r_{o2})}{1+g_{m2}(r_{o1}\|r_{o2})}}{1+0}$$

$$\approx a g_{m2}r_{o1}r_{o2}$$

$$g_{m1} = g_{m2} = \frac{2I_D}{V_{ov}} = \frac{2\times 100\mu A}{0.3V} = 0.67\ mA/V$$

$$r_{o1} = r_{o2} = \frac{1}{\lambda_n I_D} = \frac{1}{0.03V^{-1}\times 100\mu A} = 330k\Omega$$

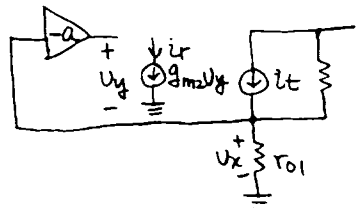
$$R_{out} \approx a g_{m2}r_{o1}r_{o2}$$

$$= 10^3\times 0.67m\times(330k)^2 = 73G\Omega$$

$$\frac{v_o}{v_i} \approx -g_{m1}R_{out} = -0.67m\times 73G = -4.9\times 10^7$$

8.26

(a) g_{m2} is the controlled source.



$$R_{out}(g_{m2}=0) = r_{o1} + r_{o2}$$

$$R(\text{short}) = (r_{o1}\|r_{o2})(a+1)g_{m2}$$

$$R(\text{open}) = 0$$

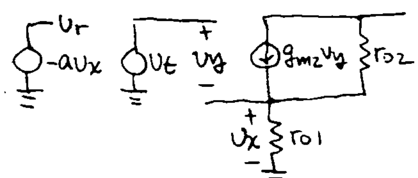
$$R_{out} = R_{out}(g_{m2}=0)\frac{1+R(\text{short})}{1+R(\text{open})}$$

$$= (r_{o1}+r_{o2})\frac{1+(r_{o1}\|r_{o2})(a+1)g_{m2}}{1+0}$$

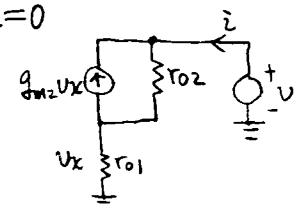
$$= r_{o1}+r_{o2}+(a+1)g_{m2}r_{o1}r_{o2}$$

$$\approx a g_{m2}r_{o1}r_{o2}$$

(b) a is the controlled source.



$a=0$



$$\frac{v_x}{r_{o1}} = g_{m2}v_x + \frac{v_x - v}{r_{o2}}$$

$$R_{out}(a=0) = \frac{v}{i} = \frac{v}{v_x/r_{o1}}$$

$$= g_{m2}r_{o1}r_{o2} + r_{o1} - r_{o2}$$

$$\approx g_{m2}r_{o1}r_{o2}$$

The output is short

$$v_x = g_{m2}(v_t - v_x)(r_{o1}\|r_{o2})$$

$$v_x = \frac{g_{m2}(r_{o1}\|r_{o2})}{1+g_{m2}(r_{o1}\|r_{o2})}v_t$$

$R(\text{short}) = a\frac{g_{m2}(r_{o1}||r_{o2})}{1+g_{m2}(r_{o1}||r_{o2})}$

$R(\text{open}) = 0$ ($v_x = 0$ when the output is open)

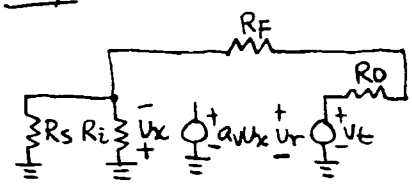
$R_{out} = R_{out}(a=0)\frac{1+R(\text{short})}{1+R(\text{open})}$

$\approx g_{m2} r_{o1} r_{o2} \frac{1+a\frac{g_{m2}(r_{o1}||r_{o2})}{1+g_{m2}(r_{o1}||r_{o2})}}{1+0}$

$\approx a g_{m2} r_{o1} r_{o2}$

(c) The results are the same, as they should be, even though the terms $R_{out}(k=0)$, $R(\text{open})$, and $R(\text{short})$ differ in (a) and (b).

8.27



$R = \frac{R_S||R_i}{R_o+R_F+R_S||R_i} a_v$

$= \frac{10k||1M}{10k+100k+10k||1M} 200 = 16.5$

$A_\infty = -\frac{R_F}{R_S} = -\frac{100k}{10k} = -10$

$d = \frac{v_o}{v_i}\Big|_{a_v=0} = \frac{R_i||(R_F+R_o)}{R_S+R_i||(R_F+R_o)} \frac{R_o}{R_F+R_o}$

$= \frac{1M||(100k+10k)}{10k+1M||(100k+10k)} \frac{10k}{100k+10k} = 0.082$

$A = A_\infty \frac{R}{1+R} + \frac{d}{1+R} = -10\frac{16.5}{1+16.5} + \frac{0.082}{1+16.5}$

$= -9.4$

$R_{in}(a_v=0) = R_S + R_i||(R_F+R_o)$

$= 10k + 1M||(100k+10k) = 1.1\times10^5\,\Omega$

$R(\text{short input}) = R = 16.5$

$R(\text{open input}) = \frac{R_i}{R_o+R_F+R_i} a_v$

$= \frac{1M}{10k+100k+1M} 200 = 180$

$R_{in} = R_{in}(a_v=0)\frac{1+R(\text{short})}{1+R(\text{open})} = 1.1\times10^5 \frac{1+16.5}{1+180}$

$= 1.1\times10^4\,\Omega = 11\,k\Omega$

$R_{out}(a_v=0) = R_o||[R_F+R_S||R_i]$

$= 10k||[100k+10k||1M] = 9.2\,k\Omega$

$R(\text{short output}) = 0$

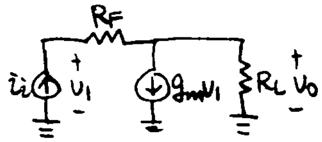
$R(\text{open output}) = R = 16.5$

$R_{out} = R_{out}(a_v=0)\frac{1+R(\text{short})}{1+R(\text{open})}$

$= 9.2k\frac{1+0}{1+16.5} = 0.52\,k\Omega = 520\,\Omega$

8.28

(a)



$g_m = \sqrt{2k' \frac{W}{L} I_D} = \sqrt{2 \times 180 \times 10^{-6} \times 100 \times 0.5 \times 10^{-3}}$

$= 4.2 \times 10^{-3}$ A/V

$a = R_F(-g_m)(R_L \| R_F) = -100k \times 4.2m(100k \| 15k)$

$= -5.5 \times 10^6 \Omega$

$f = -\frac{1}{R_F} = -\frac{1}{100k\Omega}$

shunt-shunt feedback

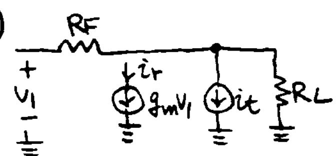
$af = 55$

$A = \frac{a}{1+af} = \frac{-5.5 \times 10^6}{1+55} = -9.8 \times 10^4 \Omega = -98k\Omega$

$R_i = \frac{R_F}{1+af} = \frac{100k}{1+55} = 1.8k\Omega$

$R_o = \frac{R_L \| R_F}{1+af} = \frac{15k \| 100k}{1+55} = 230\Omega$

(b)



$\mathcal{R} = g_m R_L = 4.2m \times 15k = 63$

$A_\infty = -R_F = -100k\Omega$

$d = \frac{v_o}{i_i}\Big|_{g_m=0} = R_L = 15k\Omega$

$A = A_\infty \frac{\mathcal{R}}{1+\mathcal{R}} + \frac{d}{1+\mathcal{R}} = -100k \frac{63}{1+63} + \frac{15k}{1+63}$

$= -98k\Omega$

$R_{in}(g_m=0) = R_F + R_L = 100k + 15k = 115k$

$\mathcal{R}$(short input) $= 0$

$\mathcal{R}$(open input) $= \mathcal{R} = 63$

$R_{in} = R_{in}(g_m=0) \frac{1+\mathcal{R}(\text{short})}{1+\mathcal{R}(\text{open})}$

$= 115k \frac{1+0}{1+63} = 1.8k\Omega$

$R_{out}(g_m=0) = R_L = 15k\Omega$

$\mathcal{R}(\text{short}) = 0$

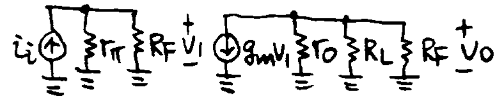
$\mathcal{R}(\text{open}) = \mathcal{R} = 63$

$R_{out} = R_{out}(g_m=0) \frac{1+\mathcal{R}(\text{short})}{1+\mathcal{R}(\text{open})}$

$= 15k \frac{1+0}{1+63} = 230\Omega$

8.29

(a)



$g_m = \frac{I_c}{V_T} = \frac{1mA}{26mV} = 38mA/V$

$r_\pi = \frac{\beta_o}{g_m} = \frac{20}{0.038} = 5.2k\Omega$

$r_o = \frac{V_A}{I_c} = \frac{100}{10^{-3}} = 100k\Omega$

$a = (r_\pi \| R_F)(-g_m)(r_o \| R_L \| R_F)$

$= -(5.2k\|2k)0.038(100k\|2k\|2k)$

$= -5.4\times10^4\Omega$

$f = -\frac{1}{R_F} = -\frac{1}{2k\Omega}$

$af = 27$

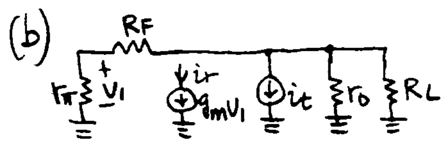
shunt-shunt feedback

$A = \frac{a}{1+af} = \frac{-5.4\times10^4}{1+27} = -1.9k\Omega$

$R_i = \frac{r_\pi \| R_F}{1+af} = \frac{5.2k\|2k}{1+27} = 52\Omega$

$R_o = \frac{r_o \| R_L \| R_F}{1+af} = \frac{100k\|2k\|2k}{1+27} = 35\Omega$

(b)



$\mathcal{R} = [r_o \| R_L \| (R_F + r_\pi)] \frac{r_\pi}{R_F + r_\pi} g_m$

$= [100k\|2k\|(2k+5.2k)] \frac{5.2k}{2k+5.2k} 3.8\times10^{-2}$

$= 42$

$A_\infty = -R_F = -2k\Omega$

$d = \frac{v_o}{i_i}\Big|_{g_m=0} = \{r_\pi \| [R_F + (r_o \| R_L)]\} \frac{r_o \| R_L}{R_F + (r_o \| R_L)}$

$= \{5.2k \| [2k + (100k\|2k)]\} \frac{100k\|2k}{2k+(100k\|2k)}$

$= 1.1k\Omega$

$A = A_\infty \frac{\mathcal{R}}{1+\mathcal{R}} + \frac{d}{1+\mathcal{R}} = -2k\frac{42}{1+42} + \frac{1.1k}{1+42}$

$= -1.9k\Omega$

$R_{in}(g_m=0) = r_\pi \| [R_F + (r_o \| R_L)]$

$= 5.2k \| [2k + (100k\|2k)] = 2.2k$

$\mathcal{R}(\text{short input}) = 0$

$\mathcal{R}(\text{open input}) = \mathcal{R} = 42$

$R_{in} = R_{in}(g_m=0)\frac{1+\mathcal{R}(\text{short})}{1+\mathcal{R}(\text{open})}$

$= 2.2k\frac{1+0}{1+42} = 51\Omega$

$R_{out}(g_m=0) = r_o \| R_L \| (R_F + r_\pi)$

$= 100k\|2k\|(2k+5.2k) = 1.5k\Omega$

$\mathcal{R}(\text{short output}) = 0$

$\mathcal{R}(\text{open output}) = \mathcal{R} = 42$

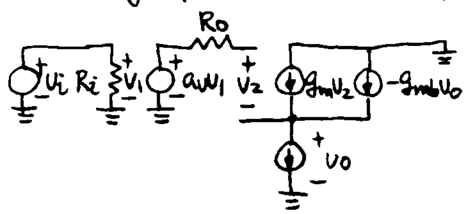
$R_{out} = R_{out}(g_m=0)\frac{1+\mathcal{R}(\text{short})}{1+\mathcal{R}(\text{open})}$

$= 1.5k\frac{1+0}{1+42} = 35\Omega$

8.30

(a)

The basic amplifier without the feedback signal inserted at the inverting input of the opamp



$$g_m = \sqrt{2k'\frac{W}{L}I_D} = \sqrt{2\times 180\times 10^{-6}\times 100\times 0.5\times 10^{-3}}$$
$$= 4.2\times 10^{-3}\,A/V$$

$$g_{mb} = \frac{\gamma}{2\sqrt{2\phi_f + V_{SB}}}g_m = \frac{\gamma}{2\sqrt{2\phi_f}}g_m$$
$$= \frac{0.3}{2\sqrt{2\times 0.3}}4.2\times 10^{-3} = 8.1\times 10^{-4}\,A/V$$

$$v_o = g_m(a_v v_i - v_o)\frac{1}{g_{mb}}$$

$$a = \frac{v_o}{v_i} = a_v\frac{g_m}{g_m + g_{mb}}$$

$$f = 1$$

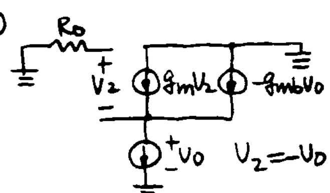
$$af = a_v\frac{g_m}{g_m + g_{mb}} = 1000\frac{4.2}{4.2 + 0.81} = 838$$

$$A = \frac{a}{1+af} = \frac{838}{1+838} = 0.999$$

$$r_{ia} = R_i$$

$$R_{in} = r_{ia}(1+af) = R_i(1+af)$$
$$= 1M(1+838) = 839\,M\Omega$$

$v_i = 0$

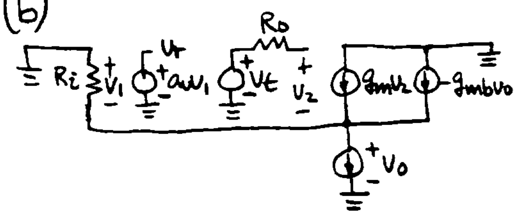


$v_2 = -v_o$

$$r_{oa} = \frac{1}{g_m}\|\frac{1}{g_{mb}} = \frac{1}{g_m + g_{mb}}$$

$$R_{out} = \frac{r_{oa}}{1+af} = \frac{1}{g_m + g_{mb}}\frac{1}{1+af}$$
$$= \frac{1}{4.2\times 10^{-3} + 8.1\times 10^{-4}}\frac{1}{1+838}$$
$$= 0.238\,\Omega$$

(b)



$$v_o = g_m(v_t - v_o)\left(\frac{1}{g_{mb}}\|R_i\right)$$

$$v_o = \frac{g_m}{\frac{1}{R_i} + g_m + g_{mb}}$$

$$\mathcal{R} = a_v\frac{g_m}{\frac{1}{R_i} + g_m + g_{mb}}$$
$$\approx a_v\frac{g_m}{g_m + g_{mb}}$$
$$= 838$$

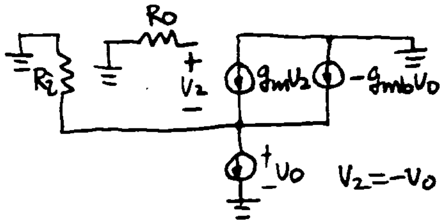
$$A_\infty = \frac{v_o}{v_i}\Big|_{a_v=\infty} = 1 \quad (v_1 = 0 \text{ and } v_o = v_i)$$

$$d = \frac{v_o}{v_i}\Big|_{a_v=0} = \frac{\frac{1}{g_m}\|\frac{1}{g_{mb}}}{R_i + \frac{1}{g_m}\|\frac{1}{g_{mb}}}$$
$$= \frac{\frac{1}{g_m + g_{mb}}}{R_i + \frac{1}{g_m + g_{mb}}}$$
$$\approx \frac{1}{(g_m + g_{mb})R_i}$$
$$= \frac{1}{(4.2\times 10^{-3} + 8.1\times 10^{-4})10^6}$$
$$= 2.00\times 10^{-4}$$

$$A = A_\infty\frac{\mathcal{R}}{1+\mathcal{R}} + \frac{d}{1+\mathcal{R}}$$
$$= 1\frac{838}{1+838} + \frac{2.00\times 10^{-4}}{1+838}$$
$$= 0.999$$

8.30 continued

$a_v = 0$



$V_2 = -V_o$

$R_{in}(a_v=0) = R_i + \frac{1}{g_m} \| \frac{1}{g_{mb}} \approx R_i = 1M\Omega$

$\mathcal{R}(\text{short}) = \mathcal{R} = 838$

$\mathcal{R}(\text{open}) = 0 \quad (v_1 = 0)$

$R_{in} = R_{in}(a_v=0) \frac{1+\mathcal{R}(\text{short})}{1+\mathcal{R}(\text{open})} \approx R_i \frac{1+\mathcal{R}}{1+0}$

$= R_i(1+\mathcal{R}) = 1M(1+838) = 839M\Omega$

$R_{out}(a_v=0) = R_i \| \frac{1}{g_m} \| \frac{1}{g_{mb}} \approx \frac{1}{g_m} \| \frac{1}{g_{mb}}$

$= \frac{1}{g_m + g_{mb}} = \frac{1}{4.2\times10^{-3} + 8.1\times10^{-4}} = 200\Omega$

$\mathcal{R}(\text{short}) = 0 \quad (V_o = 0)$

$\mathcal{R}(\text{open}) = \mathcal{R}$

$R_{out} = R_{out}(a_v=0) \frac{1+\mathcal{R}(\text{short})}{1+\mathcal{R}(\text{open})}$

$\approx \frac{1}{g_m + g_{mb}} \frac{1+0}{1+\mathcal{R}} = \frac{1}{g_m+g_{mb}} \frac{1}{1+\mathcal{R}}$

$= 200 \frac{1}{1+838} = 0.238\Omega$

8.31

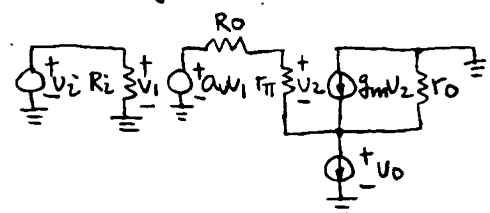
$g_m = \frac{I_C}{V_T} = \frac{0.5mA}{26mV} = 19mA/V$

$r_\pi = \frac{\beta}{g_m} = \frac{100}{19m} = 5.2k\Omega$

$r_o = \frac{V_A}{I_C} = \frac{50}{0.5m} = 100k\Omega$

(a).

The basic amplifier without the feedback signal inserted at the inverting input of the op amp



$v_o = g_m\left[(a_v v_i - v_o)\frac{r_\pi}{R_o + r_\pi}\right][r_o \| (R_o + r_\pi)]$

$a = \frac{v_o}{v_i} = a_v \frac{g_m \frac{r_\pi}{R_o+r_\pi}[r_o \| (R_o + r_\pi)]}{1 + g_m \frac{r_\pi}{R_o + r_\pi}[r_o \| (R_o + r_\pi)]}$

$= 1000 \frac{19m \frac{5.2k}{10k+5.2k}[100k \| (10k+5.2k)]}{1 + 19m \frac{5.2k}{10k+5.2k}[100k \| (10k+5.2k)]}$

$= 988$

$f = 1$

$af = 988$

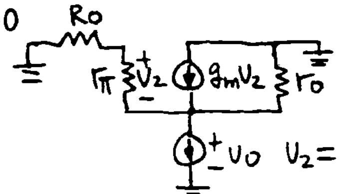
$A = \frac{a}{1+af} = \frac{988}{1+988} = 0.999$

$r_{ia} = R_i$

$R_{in} = r_{ia}(1+af) = R_i(1+af)$

$= 1M(1+988) = 989M\Omega$

$v_i = 0$



$V_2 = -V_o \frac{r_\pi}{R_o + r_\pi}$

$g_m v_2 = -g_m \frac{r_\pi}{R_o + r_\pi} v_o$ is equivalent to a resistance of

$$\frac{1}{g_m}\frac{R_o + r_\pi}{r_\pi} = \frac{1}{\beta}(R_o + r_\pi)$$

$$r_{oa} = (R_o + r_\pi) \| \frac{1}{\beta}(R_o + r_\pi) \| r_o$$

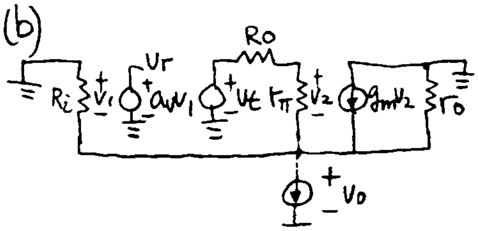
$$\approx (R_o + r_\pi)(1 \| \frac{1}{\beta})$$

$$= \frac{1}{\beta + 1}(R_o + r_\pi)$$

$$R_{out} = \frac{r_{oa}}{1 + af} \approx \frac{R_o + r_\pi}{\beta + 1}\frac{1}{1 + af}$$

$$= \frac{10k + 5.2k}{100 + 1}\frac{1}{1 + 988} = 0.152\Omega$$

(b)



$$v_o = g_m\left[(v_t - v_o)\frac{r_\pi}{R_o + r_\pi}\right]\left[r_o \| (R_o + r_\pi) \| R_i\right]$$

$$v_o = \frac{g_m \frac{r_\pi}{R_o + r_\pi}\left[r_o \| (R_o + r_\pi) \| R_i\right]}{1 + g_m \frac{r_\pi}{R_o + r_\pi}\left[r_o \| (R_o + r_\pi) \| R_i\right]}$$

$$\mathcal{R} = a_v \frac{g_m \frac{r_\pi}{R_o + r_\pi}\left[r_o \| (R_o + r_\pi) \| R_i\right]}{1 + g_m \frac{r_\pi}{R_o + r_\pi}\left[r_o \| (R_o + r_\pi) \| R_i\right]}$$

$$= 1000 \frac{19m \frac{5.2k}{10k + 5.2k}\left[100k \| (10k + 5.2k) \| 1M\right]}{1 + 19m \frac{5.2k}{10k + 5.2k}\left[100k \| (10k + 5.2k) \| 1M\right]}$$

$$= 988$$

$$A_\infty = \frac{v_o}{v_i}\Big|_{a_v = \infty} = 1 \quad (v_1 = 0 \text{ and } v_o = v_i)$$

$$d = \frac{v_o}{v_i}\Big|_{a_v = 0} = \frac{(R_o + r_\pi) \| \frac{1}{g_m}\frac{R_o + r_\pi}{r_\pi} \| r_o}{R_i + (R_o + r_\pi) \| \frac{1}{g_m}\frac{R_o + r_\pi}{r_\pi} \| r_o}$$

$$\approx \frac{(R_o + r_\pi) \| \frac{1}{\beta}(R_o + r_\pi)}{R_i} = \frac{R_o + r_\pi}{(\beta + 1)R_i}$$

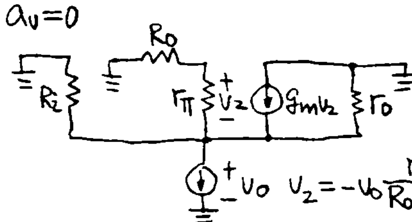
$$= \frac{10k + 5.2k}{(100 + 1)1M} = 1.50 \times 10^{-4}$$

8.31 continued

$$A = A_\infty \frac{\mathcal{R}}{1 + \mathcal{R}} + \frac{d}{1 + \mathcal{R}} = 1\frac{988}{1 + 988} + \frac{1.50 \times 10^{-4}}{1 + 988}$$

$$= 0.999$$

$a_v = 0$



$$v_2 = -v_o \frac{r_\pi}{R_o + r_\pi}$$

$$R_{in}(a_v = 0) = R_i + \left[(R_o + r_\pi) \| \frac{1}{g_m}\frac{R_o + r_\pi}{r_\pi} \| r_o\right]$$

$$\approx R_i + (R_o + r_\pi)(1 \| \frac{1}{\beta}) = R_i + \frac{R_o + r_\pi}{\beta + 1}$$

$$\approx R_i$$

$\mathcal{R}(\text{short}) = \mathcal{R} = 988$

$\mathcal{R}(\text{open}) = 0 \quad (v_1 = 0)$

$$R_{in} = R_{in}(a_v = 0)\frac{1 + \mathcal{R}(\text{short})}{1 + \mathcal{R}(\text{open})} \approx R_i(1 + \mathcal{R})$$

$$= 1M(1 + 988) = 989M\Omega$$

$$R_{out}(a_v = 0) = (R_o + r_\pi) \| \frac{1}{g_m}\frac{R_o + r_\pi}{r_\pi} \| r_o \| R_i$$

$$\approx (R_o + r_\pi)(1 \| \frac{1}{\beta}) = \frac{R_o + r_\pi}{\beta + 1}$$

$\mathcal{R}(\text{short}) = 0 \quad (v_o = 0)$

$\mathcal{R}(\text{open}) = \mathcal{R} = 988$

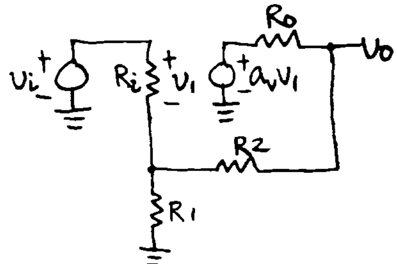
$$R_{out} = R_{out}(a_v = 0)\frac{1 + \mathcal{R}(\text{short})}{1 + \mathcal{R}(\text{open})}$$

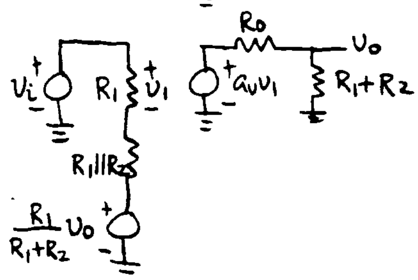
$$\approx \frac{R_o + r_\pi}{\beta + 1}\frac{1}{1 + \mathcal{R}} = \frac{10k + 5.2k}{100 + 1}\frac{1}{1 + 988}$$

$$= 0.152\Omega$$

8.32

(a)





$$a = \frac{R_i}{R_i + (R_1 \| R_2)} a_v \frac{R_1+R_2}{R_o+R_1+R_2}$$

$$= \frac{1M}{1M+(1k\|5k)} 10^4 \frac{1k+5k}{100+1k+5k} = 9.83\times 10^3$$

$$f = \frac{R_1}{R_1+R_2} = \frac{1k}{1k+5k} = 0.167$$

$$af = 1.64\times 10^3$$

$$A = \frac{a}{1+af} = \frac{9.83\times 10^3}{1+1.64\times 10^3} = 6$$

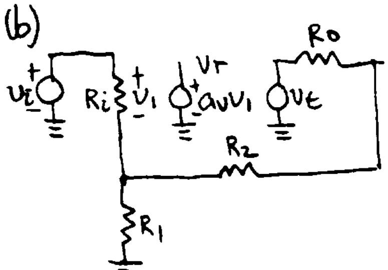
$$Z_{ia} = R_i + (R_1\|R_2) = 1M + (1k\|5k) = 1M\Omega$$

$$Z_i = Z_{ia}(1+af) = 1M(1+1.64\times 10^3) = 1.64G\Omega$$

$$Z_{oa} = R_o \| (R_1+R_2) = 100\|(1k+5k) = 98.4\Omega$$

$$Z_o = \frac{Z_{oa}}{1+af} = \frac{98.4}{1+1.64\times 10^3} = 0.06\Omega$$

(b)



$$\mathcal{R} = \frac{R_i\|R_1}{R_o+R_2+(R_i\|R_1)} a_v$$

$$= \frac{1M\|1k}{100+5k+(1M\|1k)} 10^4 = 1.64\times 10^3$$

$$A_\infty = \frac{R_1+R_2}{R_1} = \frac{1k+5k}{1k} = 6$$

$$d = \frac{v_o}{v_i}\Big|_{a_v=0} = \frac{R_1\|(R_2+R_o)}{R_i+[R_1\|(R_2+R_o)]} \frac{R_o}{R_2+R_o}$$

$$= \frac{1k\|(5k+100)}{1M+[1k\|(5k+100)]} \frac{100}{5k+100} = 1.64\times 10^{-5}$$

$$A = A_\infty \frac{\mathcal{R}}{1+\mathcal{R}} + \frac{d}{1+\mathcal{R}} = 6$$

$$R_{in}(a_v=0) = R_i + [R_1\|(R_2+R_o)]$$

$$= 1M + [1k\|(5k+100)] = 1M\Omega$$

$$\mathcal{R}(short) = \mathcal{R} = 1.64\times 10^3$$

$$\mathcal{R}(open) = 0$$

$$R_{in} = R_{in}(a_v=0)\frac{1+\mathcal{R}(short)}{1+\mathcal{R}(open)}$$

$$= 1M\frac{1+1.64\times 10^3}{1+0} = 1.64G\Omega$$

$$R_{out}(a_v=0) = R_o\|[R_2+(R_i\|R_1)]$$

$$= 100\|[5k+(1M\|1k)] = 98.4\Omega$$

$$\mathcal{R}(short) = 0$$

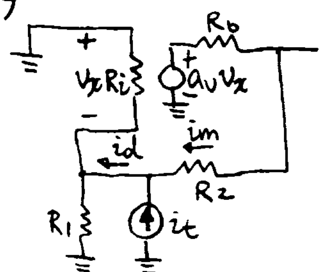
$$\mathcal{R}(open) = \mathcal{R} = 1.64\times 10^3$$

$$R_{out} = R_{out}(a_v=0)\frac{1+\mathcal{R}(short)}{1+\mathcal{R}(open)}$$

$$= 98.4\frac{1+0}{1+1.64\times 10^3} = 0.06\Omega$$

8.33

(a)



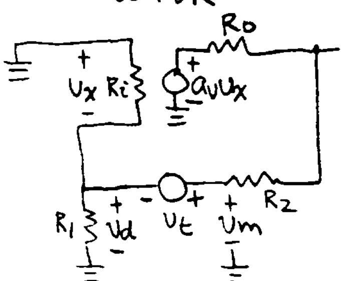
$$v = -i_d(R_i \| R_1)$$

$$i_m = \frac{a_v v_x - (-v_x)}{R_o + R_2} = \frac{(a_v+1)v_x}{R_o+R_2}$$

$$= -\frac{(a_v+1)(R_i \| R_1)}{R_o+R_2} i_d$$

$$\mathcal{R}_i' = -\frac{i_m}{i_d} = \frac{(a_v+1)(R_i \| R_1)}{R_o+R_2}$$

$$= \frac{(10^4+1)(1M \| 1k)}{100+5k} = 1960$$



$$\frac{v_d}{R_i \| R_1} = \frac{-a_v v_d - v_m}{R_o+R_2}$$

$$v_d\left(\frac{1}{R_i \| R_1} + \frac{a_v}{R_o+R_2}\right) = -\frac{1}{R_o+R_2} v_m$$

$$\mathcal{R}_v' = -\frac{v_m}{v_d} = \frac{\frac{1}{R_i \| R_1} + \frac{a_v}{R_o+R_2}}{\frac{1}{R_o+R_2}}$$

$$= \frac{\frac{1}{1M \| 1k} + \frac{10^4}{100+5k}}{\frac{1}{100+5k}} = 10^4$$

$$\frac{1}{1+\mathcal{R}} = \frac{1}{1+\mathcal{R}_v'} + \frac{1}{1+\mathcal{R}_i'};\ \mathcal{R} = 1640$$

(b)

$$\mathcal{R} = \frac{R_i \| R_1}{R_o + R_2 + (R_i \| R_1)} a_v$$

$$= \frac{1M \| 1k}{100+5k+(1M \| 1k)} 10^4 = 1.6 \times 10^3$$

8-34

(c)

```
RETURN RATIO
.SUBCKT AMP (1 2)
EAMP 4 0 0 1 1E4
RI 1 0 1MEG
RO 3 4 100
R1 1 0 1K
R2 2 3 5K
.ENDS AMP
.OPTIONS NOMOD
XRRV (11 12) AMP
VT 12 11 AC 1

XRRI (21 22) AMP
IT 0 31 AC 1
VDUMMY1 31 21 0
VDUMMY2 22 31 0

.AC DEC 1 1K 1G
.PRINT AC RRVR=PAR('-VM(12)/VM(11)*COS(3.14*(VP(12)-VP(11))/180)')\
RRVI=PAR('-VM(12)/VM(11)*SIN(3.14*(VP(12)-VP(11))/180)')\
RRIR=PAR('-IM(VDUMMY2)/IM(VDUMMY1)*COS(3.14*(IP(VDUMMY2)-IP(VDUMMY1))/180)')\
RRII=PAR('-IM(VDUMMY2)/IM(VDUMMY1)*SIN(3.14*(IP(VDUMMY2)-IP(VDUMMY1))/180)')\
.WIDTH OUT=80
.OPTIONS SPICE
.END

****** AC ANALYSIS                    TNOM= 27.000 TEMP= 27.000
```

FREQ	RRVR	RRVI	RRIR	RRII
9.9999E+02	1.000E+04	1.593E+01	1.959E+03	-3.119E+00
9.9999E+03	1.000E+04	1.593E+01	1.959E+03	-3.119E+00
1.0000E+05	1.000E+04	1.593E+01	1.959E+03	-3.119E+00
1.0000E+06	1.000E+04	1.593E+01	1.959E+03	-3.119E+00
1.0000E+07	1.000E+04	1.593E+01	1.959E+03	-3.119E+00
1.0000E+08	1.000E+04	1.593E+01	1.959E+03	-3.119E+00
1.0000E+09	1.000E+04	1.593E+01	1.959E+03	-3.119E+00

$$\frac{1}{1+\mathcal{R}} = \frac{1}{1+\mathcal{R}_v'} + \frac{1}{1+\mathcal{R}_i'}$$

$$= \frac{1}{1+10^4+j15.9} + \frac{1}{1+1959-j3.1}$$

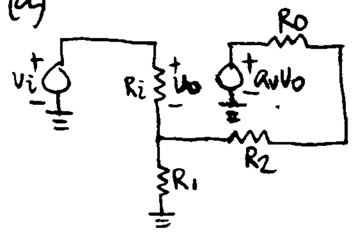
$$= 9.999\times10^{-5} - j1.59\times10^{-7} +$$
$$5.102\times10^{-4} + j8.07\times10^{-7}$$

$$= 6.102\times10^{-4} + j6.48\times10^{-7}$$

$$\mathcal{R} \approx 1638$$

8.34

(a)



$Z_i = h_{11a} + h_{11f} = 50k\Omega + 67k\Omega = 117k\Omega$

$h_{11a} = \frac{v_{1a}}{i_{1a}}\Big|_{v_{2a}=0} = R_i = 50\,k\Omega$

$h_{11f} = \frac{v_{1f}}{i_{1f}}\Big|_{v_{2f}=0} = R_1 \| R_2 = 67k\Omega$

$y_o = h_{22a} + h_{22f} = 10^{-6}\mho + 3.3\times10^{-6}\mho$
$= 4.3\times10^{-6}\mho$

$h_{22a} = \frac{i_{2a}}{v_{2a}}\Big|_{i_{1a}=0} = \frac{1}{R_o} = \frac{1}{1M\Omega} = 10^{-6}\mho$

$h_{22f} = \frac{i_{2f}}{v_{2f}}\Big|_{i_{1f}=0} = \frac{1}{R_1+R_2} = \frac{1}{300k\Omega}$
$= 3.3\times10^{-6}\mho$

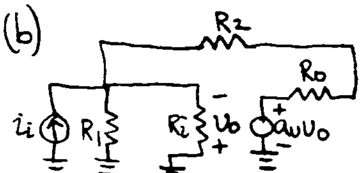
$h_{21a} = \frac{i_{2a}}{i_{1a}}\Big|_{v_{2a}=0} = -a_v\frac{R_i}{R_o} = -10^3\frac{50k}{1M} = -50$

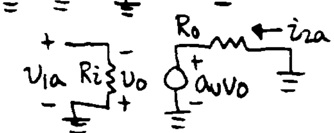
$f = h_{12f} = \frac{v_{1f}}{v_{2f}}\Big|_{i_{1f}=0} = \frac{R_1}{R_1+R_2} = \frac{2}{3}$

$a = -\frac{h_{21a}}{Z_i y_o} = -\frac{-50}{117k\times4.3\times10^{-6}} = 99$

$af = 66$

(b)





$y_i = y_{11a} + y_{11f} = 2\times10^{-5}\mho + 1.5\times10^{-5}\mho$
$= 3.5\times10^{-5}\mho$

$y_{11a} = \frac{i_{1a}}{v_{1a}}\Big|_{v_{2a}=0} = \frac{1}{R_i} = \frac{1}{50k} = 2\times10^{-5}\mho$

$y_{11f} = \frac{i_{1f}}{v_{1f}}\Big|_{v_{2f}=0} = \frac{1}{R_1} + \frac{1}{R_2} = \frac{1}{200k} + \frac{1}{100k}$
$= 1.5\times10^{-5}\mho$

$y_o = y_{22a} + y_{22f} = 1\times10^{-6}\mho + 1\times10^{-5}\mho$
$= 1.1\times10^{-5}\mho$

$y_{22a} = \frac{i_{2a}}{v_{2a}}\Big|_{v_{1a}=0} = \frac{1}{R_o} = \frac{1}{1M} = 10^{-6}\mho$

$y_{22f} = \frac{i_{2f}}{v_{2f}}\Big|_{v_{1f}=0} = \frac{1}{R_2} = \frac{1}{100k} = 10^{-5}\mho$

$y_{21a} = \frac{i_{2a}}{v_{1a}}\Big|_{v_{2a}=0} = \frac{-\frac{a_v v_o}{R_o}}{-v_o} = \frac{a_v}{R_o} = \frac{10^3}{1M}$
$= 10^{-3}\mho$

$y_{21f} = 0$

$a = -\frac{y_{21a}+y_{21f}}{y_i y_o} = -\frac{10^{-3}+0}{3.5\times10^{-5}\times1.1\times10^{-5}}$
$= 2.6\times10^6\Omega$

$f = y_{12a} + y_{12f} = 0 + 10^{-5}\mho = 10^{-5}\mho$

$y_{12a} = 0$

$y_{12f} = \frac{i_{1f}}{v_{2f}}\Big|_{v_{1f}=0} = \frac{1}{R_2} = \frac{1}{100k} = 10^{-5}\mho$

$af = 26$

(c)

$R = \frac{R_1 \| R_i}{R_o + R_2 + (R_1 \| R_i)} a_v$

$= \frac{200k \| 50k}{1M + 100k + (200k \| 50k)} 10^3 = 35$

If v_i in Fig. 8.59 and i_i in Fig. 8.61 are disabled, the two circuits are the same, hence the same return ratio

(d)

Return ratios do not depend on feedback configurations, while loop gains do.

	Loop gain	Return ratio
Fig. 8.59	66	35
Fig. 8.61	26	35

CHAPTER 9

9.1

At low frequencies $T = a\mathfrak{f} = 10$
where $\mathfrak{f}$ is the feedback factor

$$T(jf) = \frac{10}{(1+j\frac{f}{f_1})(1+j\frac{f}{f_2})(1+j\frac{f}{f_3})}$$

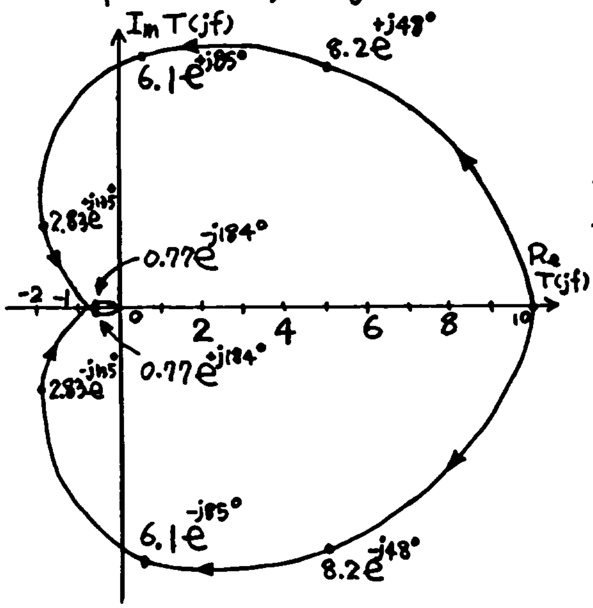
where f is the frequency

$f = 1\,\text{MHz}$

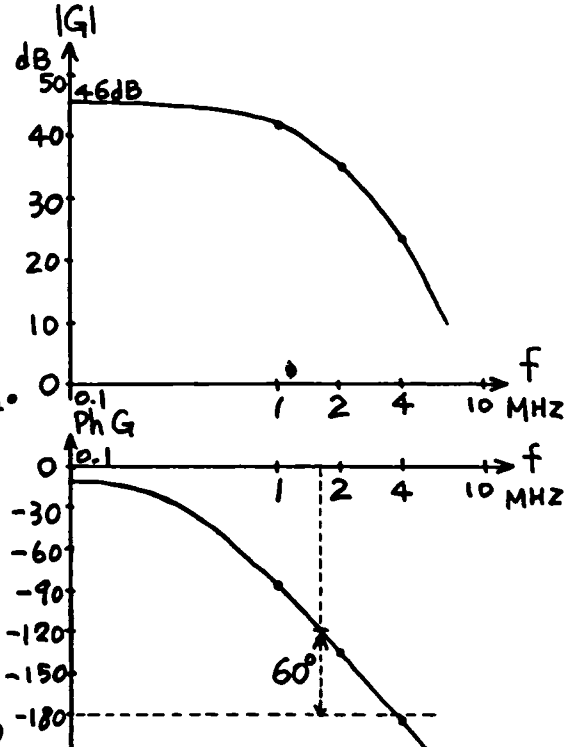
$T(jf) = 6.1\,e^{-85°}$

$f = 2\,\text{MHz}$, $T(jf) = 2.83\,e^{-135°}$

$f = 4\,\text{MHz}$, $T(jf) = 0.77\,e^{-184°}$



Does not encircle (−1,0)
∴ Stable



Ph G = −180° at $f \cong 4\,\text{MHz}$
where $G = 23.8\,\text{dB} = 15.4$

$\therefore \mathfrak{f} = \frac{1}{15.4} = 0.065$

just causes instability

Ph G = −120°, at $f = 1.7\,\text{MHz}$
where, $G = 71$

$\therefore \mathfrak{f} = \frac{1}{71} = 0.014$

gives 60° phase margin.

9.2

From 9.1

$$G(jf) = \frac{200}{(1+j\frac{f}{f_1})(1+j\frac{f}{f_2})(1+j\frac{f}{f_3})}$$

9.3

$|T(j\omega_0)| = 1$, $\angle T(j\omega_0) = -160°$

$$\therefore A(j\omega_0) = \frac{a(j\omega_0)}{1 + T(j\omega_0)}$$

$$A(j\omega_o) = \frac{a(j\omega_o)}{1+e^{-j160^\circ}} = \frac{a(j\omega_o)}{1-0.940-0.342j}$$

$$= \frac{a(j\omega_o)}{0.06-0.342j}$$

But $|T(j\omega_o)| = |a(j\omega_o)f| = 1$

$\therefore \quad |a(j\omega_o)| = \frac{1}{f}$

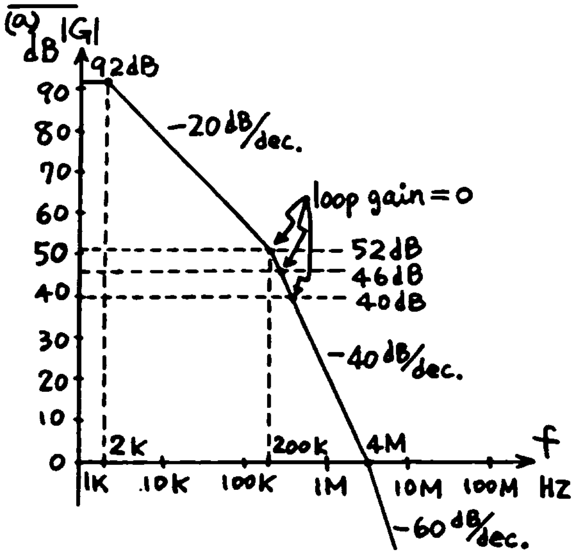
$\therefore \quad |A(j\omega_o)| = \frac{2.88}{f}$

$$= 20\log_{10}\frac{1}{f} + 9.2\,dB$$

Thus the gain peaks 9.2 dB above the low-frequency value.

9.4

(a)



Phase margin $\simeq 45^\circ$

At 200KHZ

$$T(jf) = \frac{100}{(1+j\frac{f}{f_1})(1+j\frac{f}{f_2})(1+\frac{f}{f_3})}$$

$|T(jf)| = 0.706$

$\angle T(jf) = -137^\circ$

At 150KHZ

$|T(jf)| = 1.07, \quad \angle T(jf) = -128^\circ$

$\therefore$ At 160KHZ

$|T(jf)| \simeq 1, \quad \angle T(jf) = -130^\circ$

$\therefore$ Phase margin = 50°

(b)

$A_o = 200$

$$\therefore T(jf) = \frac{200}{(1+j\frac{f}{f_1})(1+j\frac{f}{f_2})(1+j\frac{f}{f_3})}$$

at 300KHZ

$|T(jf)| = 0.74, \quad \angle T(jf) = -150^\circ$

at 250KHZ

$|T(jf)| = 1, \quad \angle T(jf) = -144^\circ$

$\therefore$ Phase margin = 36°

$A_o = 100$

$$\therefore T(jf) = \frac{400}{(1+j\frac{f}{f_1})(1+j\frac{f}{f_2})(1+j\frac{f}{f_3})}$$

at 300KHZ

$|T(jf)| = 1.48, \quad \angle T(jf) = -150^\circ$

at 350KHZ

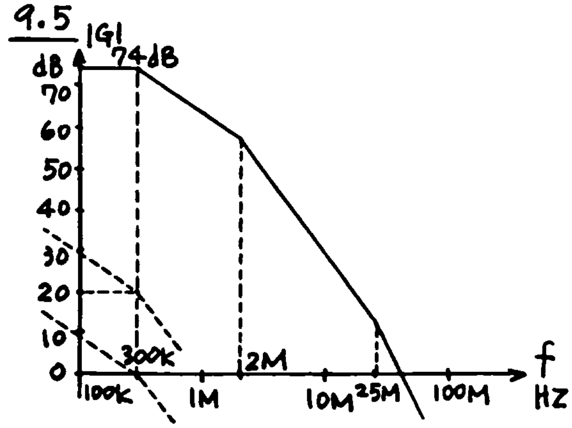
$|T(jf)| = 1.13, \quad \angle T(jf) = -155^\circ$

at 375KHZ

$|T(jf)| = 1, \quad \angle T(jf) = -157^\circ$

$\therefore$ Phase margin = 23°

9.5



(a) Dominant pole $= \frac{300{,}000}{5000} = 60\,HZ$

Bandwidth of feedback circuit $\simeq 300\,KHZ$

(b) Dominant pole $= \frac{300{,}000}{500} = 600\,HZ$

Bandwidth of feedback circuit $\simeq 300\,KHZ$

9.6

(a) Dominant pole $= \frac{2MHZ}{5000} = 400\,HZ$

Bandwidth of feedback circuit $\simeq 400 \times 5000 = 2\,MHZ$

(b) Dominant pole $= \frac{2MHZ}{500} = 4\,KHZ$

Bandwidth of feedback $\simeq 2\,MHZ$

9.7

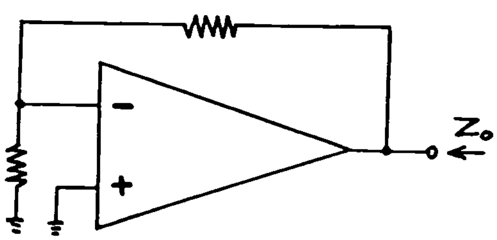
(a) Dominant pole $= \frac{200KHZ}{40{,}000} = 5\,HZ$

Bandwidth of feedback circuit $\simeq 200\,KHZ$

(b) Dominant pole $= \frac{200KHZ}{4000} = 50\,HZ$

Bandwidth $\simeq 200\,KHZ$

9.8



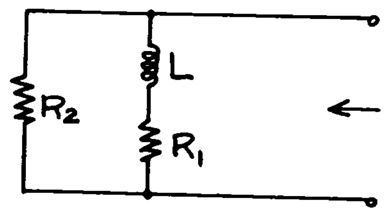
$$Z_o = \frac{R_o}{1+T(S)} = \frac{R_o}{1+af}$$

$$f = 0.01\ , \quad a = \frac{a_o}{1+\frac{s}{\omega_1}}$$

$$a_o = 100{,}000\ , \quad \omega_1 = 5 \times 2\pi \text{ rad/sec}$$

$$\therefore Z_o = \frac{R_o}{1+\frac{a_o f}{1+\frac{s}{\omega_1}}} = \frac{R_o\left(1+\frac{s}{\omega_1}\right)}{1+\frac{s}{\omega_1}+a_o f}$$

$$= \frac{R_o}{1+a_o f} \cdot \frac{1+\frac{s}{\omega_1}}{1+\frac{s}{(1+a_o f)\,\omega_1}} \quad \text{----(A)}$$



$$Z = \frac{R_2(R_1+LS)}{R_1+R_2+LS} = \frac{R_1 R_2}{R_1+R_2} \cdot \frac{1+\frac{L}{R_1}S}{1+\frac{LS}{R_1+R_2}} \quad \text{-----(B)}$$

From (A) and (B)

$$\frac{R_1 R_2}{R_1+R_2} = \frac{R_o}{1+a_o f} = \frac{100}{1001} = 0.1\,\Omega$$

$$\frac{L}{R_1} = \frac{1}{\omega_1}$$

$$\frac{L}{R_1+R_2} = \frac{1}{(1+a_o f)\,\omega_1}$$

$$\therefore \frac{R_1}{R_1+R_2} = \frac{1}{1+a_o f} = \frac{1}{1001}$$

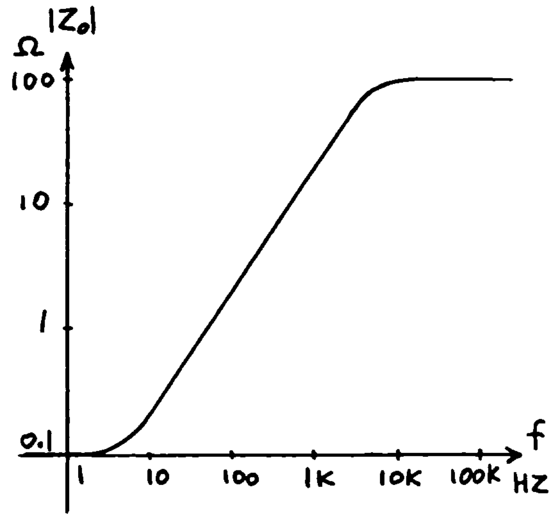
$$\therefore R_2 = \frac{R_1+R_2}{R_1} \times 0.1\,\Omega = 100\,\Omega$$

$$1+\frac{R_2}{R_1} = 1001$$

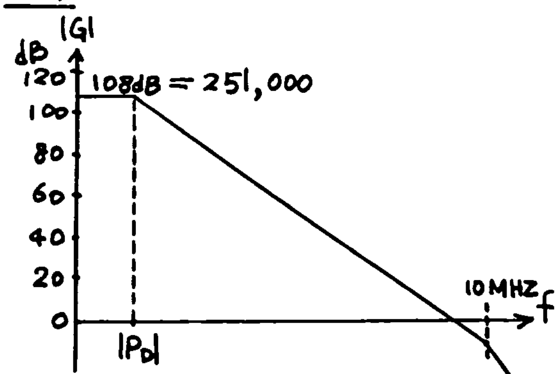
$$\therefore R_2 = 1000 R_1$$

$$\therefore R_1 = 0.1\,\Omega$$

$$L = \frac{1}{\omega_1} R_1 = \frac{1}{5 \times 2\pi} \times 0.1 = 3.18\ mH$$



9.9



Calculate dominant pole freq. required

$$|P_D| < \frac{10\,\text{MHZ}}{251{,}000} = 40\,\text{HZ}$$

when compensated

$$a = \frac{251{,}000}{(1 + j\frac{f}{f_1})(1 + j\frac{f}{f_2})}$$

$f_2 = 10\,\text{MHZ}$, $f_1 = |P_D|$

at the unity gain frequency

$$a \simeq \frac{251{,}000}{j\frac{f}{f_1}(1 + j\frac{f}{f_2})}$$

Try $f_1 = 30\,\text{HZ}$

By trial

$|a| = 1$ at $f = 6.5\,\text{MHZ}$

where $\angle a = -123°$

→ Phase margin = 57°

Try $f_1 = 25\,\text{HZ}$

By trial

$|a| = 1$ at $f = 5.5\,\text{MHZ}$

where $\angle a = -119°$

→ Phase margin = 61°

By interpolation we need $f_1 = 26\,\text{HZ}$, giving a unity gain frequency of 5.7 MHZ

From Chapter 7

$$f_1 = \frac{1}{2\pi}\frac{1}{C_M R_{ic}}$$

where $C_M = (1 + G_{mc} R_{oc}) C_c$

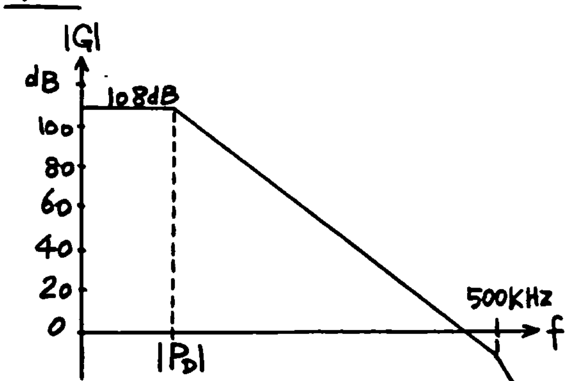
$= 552\, C_c$

and $R_{ic} = 1.95 \times 10^6$

$$\therefore 26 = \frac{1}{2\pi}\frac{1}{552 C_c \times 1.95 \times 10^6}$$

$\therefore C_c = 5.7\,\text{PF}$

9.10



Dominant pole freq. required

$$|P_D| < \frac{500\,\text{KHZ}}{251{,}000} = 2\,\text{HZ}$$

when compensated

$$a = \frac{251{,}000}{(1+j\frac{f}{f_1})(1+j\frac{f}{f_2})}$$

$f_2 = 500\,KHZ$, $f_1 = |P_D|$

at the unity gain frequency

$$a \simeq \frac{251{,}000}{j\frac{f}{f_1}(1+j\frac{f}{f_2})}$$

From problem 9.9, we found for 60° phase margin that

$$\frac{f_2}{f_1} = \frac{10\,MHZ}{26\,HZ} = 3.85\times10^5$$

∴ we now need

$$f_1 = \frac{500\,KHZ}{3.85\times10^5} = 1.3\,HZ$$

In problem 9.9 unity gain freq. $= 5.7\,MHZ$

∴ In this case unity gain freq.

$$= \frac{5.7\,MHZ}{20} = 285\,KHZ$$

From Section (9.4) for this compensation

$$f_1 = \frac{1}{2\pi RC}$$

$$\therefore\ 1.3 = \frac{1}{2\pi\times1.95\times10^6\times C}$$

$\therefore\ C = 0.063\,\mu F$

9.11

Breakaway between P_1 and P_2

$$\frac{1}{\sigma_i+1} + \frac{1}{\sigma_i+3} + \frac{1}{\sigma_i+4} = 0$$

$$\therefore (\sigma_i+3)(\sigma_i+4) + (\sigma_i+1)(\sigma_i+4) + (\sigma_i+1)(\sigma_i+3) = 0$$

$$\therefore 3\sigma_i^2 + 16\sigma_i + 19 = 0$$

$$\therefore \sigma_i = \frac{-16\pm\sqrt{16^2-12\times19}}{6}$$

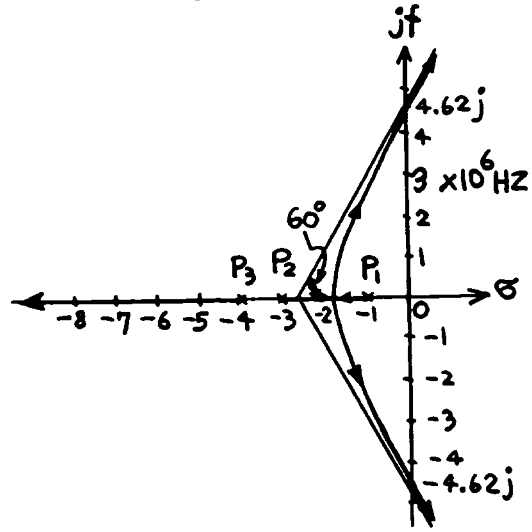
$$= -1.78 \text{ or } -3.55$$

$\therefore \sigma_i = -1.78$

Angle of asymptotes to axis = 60°

Asymptotes meet real axis at

$$\sigma_a = \frac{-1-3-4+0}{3} = -2.67$$



Root locus crosses axis at $s = j4.62$ (normalized to 10^6 HZ)

Then

$|s-P_1| = 4.73$,

$|s-P_2| = 5.51$,

$|s-P_3| = 6.11$.

Using (9.60)

$$T_0 \times \frac{1\times3\times4}{4.73\times5.51\times6.11} = 1$$

$\therefore T_0 = 13.3$

Since $a_0 = 200$, we have

$$f = \frac{13.3}{200} = 0.067$$

for instability.

9.12

Breakaway point between P_1 and P_2

$$\frac{1}{\sigma_i+2}+\frac{1}{\sigma_i+200}+\frac{1}{\sigma_i+4000}=0$$

↑ neglect (the $\frac{1}{\sigma_i+4000}$ term)

$\therefore \sigma_i+200+\sigma_i+2=0$

$\therefore \sigma_i=-101$

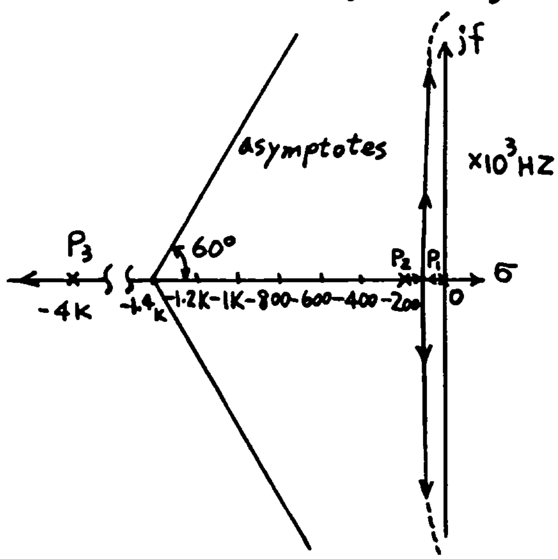
Angle of asymptotes to axis = 60°

Asymptotes meet real axis at

$$\sigma_a=\frac{-2-200-4000}{3}=-1400$$

Root locus crosses axis at

$s=1400\tan 60°\, j=2425j$



Then $|s-P_1|=2425$,

$|s-P_2|=2433$, $|s-P_3|=4677$

Using (9.60)

$$T_o\times\frac{2\times200\times4000}{2425\times2433\times4677}=1$$

$\therefore T_o=17{,}250$

Since $a_o=40{,}000$

the value of f causing instability is

$40{,}000 f=17{,}250$

$\therefore f=0.43$

Using Nyquist calculate $T(j\omega)$

$$T(jf)=\frac{17{,}250}{(1+j\frac{f}{2})(1+j\frac{f}{200})(1+j\frac{f}{4000})}$$

Put $f=2425$

$|T(jf)|=1$, $\angle T(jf)=-206°$

Unstable, but since $\angle T(jf)$ is less than $-180°$, the circuit would be unstable for smaller values of f.

9.13

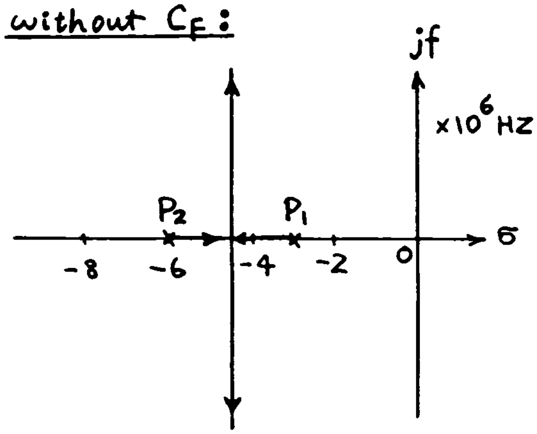
Zero freq. $\omega_Z=\frac{1}{R_F C_F}$

$=\frac{1}{5000\times1.5\times10^{-12}}$

$=1.33\times10^{8}$ rad/sec

$\therefore f_Z=21.2$ MHz

<u>without C_F:</u>



$$A=\frac{a}{1+af}\qquad a=\frac{a_o}{(1-\frac{s}{P_1})(1-\frac{s}{P_2})}$$

$$=\frac{a_o}{(1-\frac{s}{P_1})(1-\frac{s}{P_2})+a_o f}$$

For $f=0.01$, $a_o f=40$

and poles are

$(1+\frac{S}{3})(1+\frac{S}{6})+40=0$

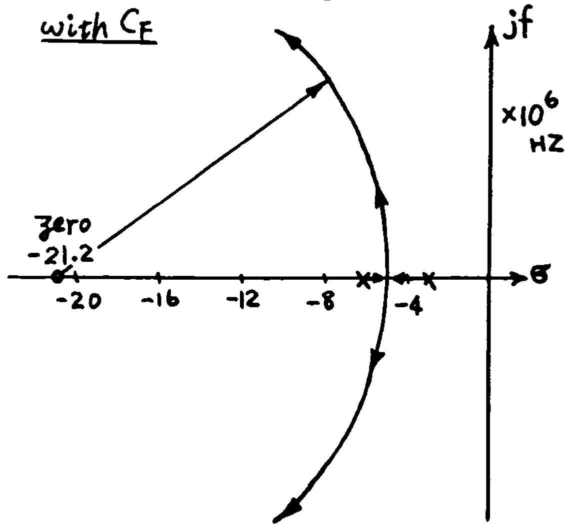
$\therefore S^2+9S+738=0$

$\therefore s=\frac{-9\pm\sqrt{81-4\times 738}}{2}$

$=-4.5\pm j26.8$

$\therefore$ for $f=0.01$, poles P_a and P_b are at $(-4.5\pm j26.8)$ MHZ

<u>with C_F</u>



Breakaway point

$$\frac{1}{\sigma_i+3}+\frac{1}{\sigma_i+6}=\frac{1}{\sigma_i+21.2}$$

$\therefore \sigma_i \simeq -4.5$ as for previous case.

$$A=\frac{a}{1+af} \qquad a=\frac{a_o}{(1-\frac{S}{P_1})(1-\frac{S}{P_2})}$$

$$f=f_o(1-\frac{S}{Z})$$

$$\therefore A=\frac{a_o}{(1-\frac{S}{P_1})(1-\frac{S}{P_2})+a_of_o(1-\frac{S}{Z})}$$

For $f_o=0.01$, $a_of_o=40$ and poles are

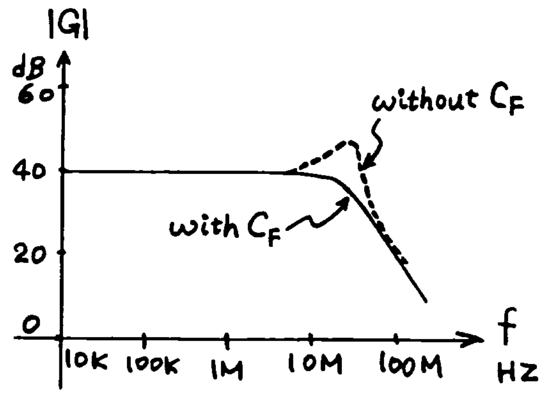
$$(1+\frac{S}{3})(1+\frac{S}{6})+40(1+\frac{S}{21.2})=0$$

$\therefore S^2+43S+738=0$

$\therefore S=\frac{-43\pm\sqrt{43^2-4\times 738}}{2}$

$=-21.5\pm j16.6$

$\therefore$ poles P_a and P_b are at $(-21.5\pm j16.6)$ MHZ

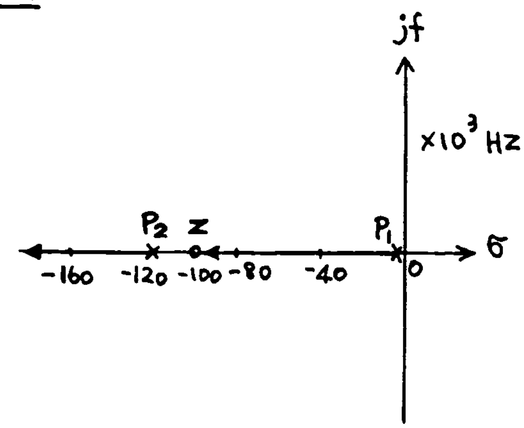


For the feedback amplifier

$$G=\frac{100}{(1-\frac{S}{P_a})(1-\frac{S}{P_b})}$$

where P_a and P_b are calculated above.

<u>9.14</u>



$$A(s)=\frac{a(s)}{1+af(s)}$$

$$a(s) = \frac{a_o(1-\frac{s}{z})}{(1-\frac{s}{P_1})(1-\frac{s}{P_2})}$$

$$\therefore A(s) = \frac{a_o(1-\frac{s}{z})}{(1-\frac{s}{P_1})(1-\frac{s}{P_2})+a_o f(1-\frac{s}{z})}$$

Poles are the solutions of

$$(1-\frac{s}{P_1})(1-\frac{s}{P_2})+a_o f(1-\frac{s}{z}) = 0$$

$$\therefore 1-(\frac{1}{P_1}+\frac{1}{P_2}+\frac{a_o f}{z})s+\frac{s^2}{P_1P_2}+a_o f=0$$

$$\therefore s^2-P_1P_2(\frac{1}{P_1}+\frac{1}{P_2}+\frac{a_o f}{z})s+P_1P_2(1+a_o f)=0$$

Normalized to KHZ

$\therefore P_1 = -0.1$, $P_2 = -120$

$Z = -100.$ $a_o = 10^5$

$f = 10^{-3}$

$$s^2-12(-10-\frac{1}{120}-\frac{100}{100})s+12\times 101=0$$

$$\therefore s^2+132s+1212=0$$

$$\therefore s = \frac{-132\pm\sqrt{132^2-4\times 1212}}{2}$$

$$= -66\pm 56 = -10 \text{ or } -122$$

$\therefore$ Poles are at -10 KHZ and -122 kHZ

Zero is at -100 KHZ

$f=1$

$$s^2-12(-10-\frac{1}{120}-\frac{10^5}{100})s+12\times 10^5=0$$

$$\therefore s^2+12120s+12\times 10^5=0$$

$$\therefore s = \frac{-12120\pm\sqrt{12120^2-12\times 10^5\times 4}}{2}$$

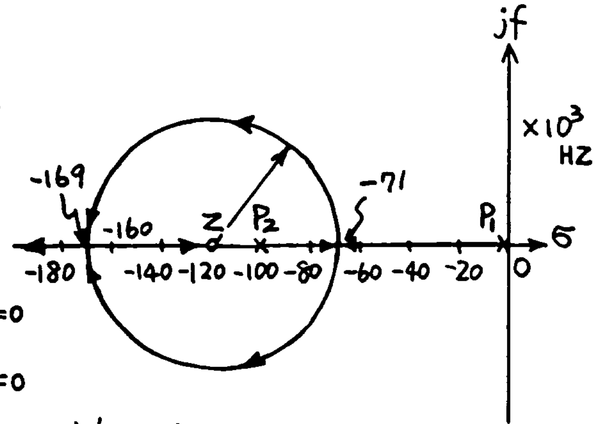
$$= -6060\pm 5960.2$$

$$= -99.8 \text{ or } -12020$$

$\therefore$ Poles are at -99.8 KHZ and -12 MHZ

Zero is at -100 KHZ

9.15



Normalize to KHZ

Breakaway point

$$\frac{1}{\sigma_i+0.1}+\frac{1}{\sigma_i+100}=\frac{1}{\sigma_i+120}$$

$$\therefore (\sigma_i+100)(\sigma_i+120)+(\sigma_i+0.1)(\sigma_i+120)$$
$$= (\sigma_i+0.1)(\sigma_i+100)$$

$$\therefore \sigma_i^2+240\sigma_i+12002=0$$

$$\therefore \sigma_i = \frac{-240\pm\sqrt{240^2-4\times 12002}}{2}$$

$$= -120\pm 49$$
$$= -169 \text{ or } -71$$

From 9.14 poles of feedback amplifier are given by solutions of

$$s^2-P_1P_2(\frac{1}{P_1}+\frac{1}{P_2}+\frac{a_o f}{z})s+P_1P_2(1+a_o f)=0$$

$\therefore P_1=-0.1$, $P_2=-100$, $Z=-120$

$a_o = 10^5$

$f=10^{-3}$

$$s^2-10(-10-\frac{1}{100}-\frac{100}{120})s+10\times 101=0$$

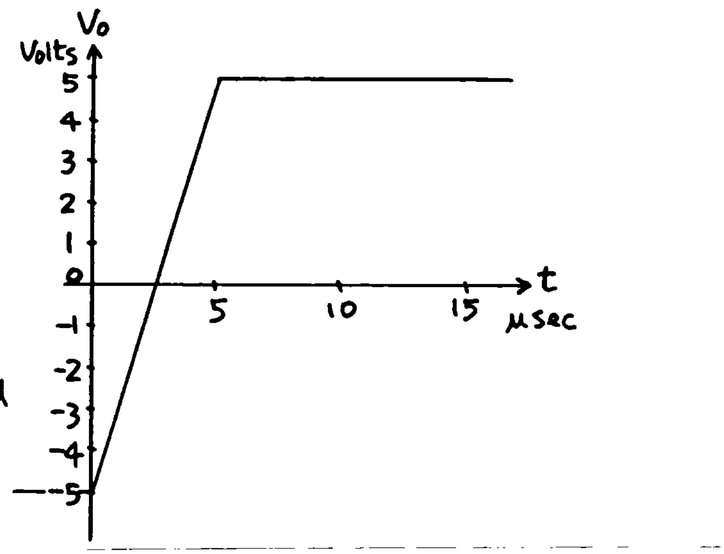
$$\therefore s^2+108.4s+1010=0$$

$$\therefore s = \frac{-108.4\pm\sqrt{108.4^2-4040}}{2}$$

$$= -98.1 \text{ or } -10.3$$

$\therefore$ Poles are at -10.3 kHz and -98.1 kHz

Zero is at -120 KHz



$f = 1$

$$s^2 - 10\left(-10 - \frac{1}{100} - \frac{10^5}{120}\right)s + 10\times10^5 = 0$$

$$\therefore S^2 + 84335 + 10^6 = 0$$

$$\therefore S = -4216.5 \pm 4096$$

$$= -8313 \text{ or } -120.5$$

$\therefore$ Poles are at -120.5 KHz and -8.3 MHz

Zero is at -120 kHz

9.16

(a) $\frac{\Delta V_o}{\Delta V_i}(j\omega) \simeq -G_m \frac{1}{j\omega C}$

at high frequencies where

$$G_m = g_{m1} = \frac{I_{C1}}{V_T} = \frac{10\times10^{-6}}{26\times10^{-3}} \text{ A/V}$$

$C = 10$ pF

$\therefore$ unity gain frequency ω_o is given by

$$G_m \frac{1}{\omega_o C} = 1$$

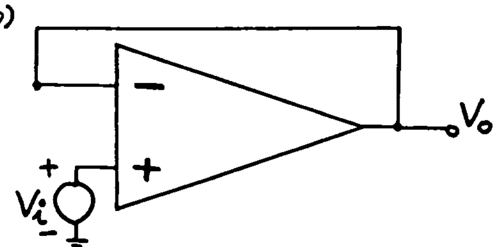
$$\therefore \omega_o = \frac{G_m}{C} = \frac{10^{-5}}{26\times10^{-3}} \frac{10^{12}}{10}$$

$$\therefore f_o = 6.12 \text{ MHz}$$

$$\text{Slew rate} = \frac{2I_{C1}}{C} = \frac{20\times10^{-6}}{10\times10^{-12}}$$

$$= 2 \text{ V}/\mu\text{s}$$

(b)



```
OP AMP
VCC 1 0 15V
VSS 2 0 -15V
IEE 1 9 200A
Q1 5 3 9 P
Q2 6 4 9 P
Q3 5 5 2 N
Q4 6 5 2 N
Q5 1 6 7 N
RES 7 2 50K
Q6 8 7 2 N
I6 1 8 300U
CCOMP 6 8 10P
VIN2 4 0 0V
VIN 3 0 0V AC
.MODEL N NPN BF=100 VAF=130 IS=1E-15
.MODEL P PNP BF=100 VAF=130 IS=1E-15
.PLOT AC V(8)
.AC DEC 40 1MEG 10MEG
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.END
```

```
****** AC ANALYSIS                              TNOM=  27.000 TEMP=  27.000
   FREQ       V(8)
(A      )      0.          2.000E+00    4.000E+00    6.000E+00    8.000E+00
                    +            +            +            +            +
 2.985E+06  2.02E+00 +      +      A      +      +      +      +      +      +
 1.162E+06  1.91E+00-+------+-----A+------+------+------+------+------+------+-
 3.349E+06  1.80E+00 +      +     A+      +      +      +      +      +      +
 3.548E+06  1.70E+00 +      +    A +      +      +      +      +      +      +
 3.758E+06  1.61E+00 +      +   A  +      +      +      +      +      +      +
 3.981E+06  1.52E+00 +      +   A  +      +      +      +      +      +      +
 4.217E+06  1.43E+00 +      + A    +      +      +      +      +      +      +
 4.466E+06  1.35E+00 +      + A    +      +      +      +      +      +      +
 4.731E+06  1.27E+00 +      + A    +      +      +      +      +      +      +
 5.011E+06  1.20E+00 +      +A     +      +      +      +      +      +      +
 5.300E+06  1.14E+00 +      +A     +      +      +      +      +      +      +
 5.623E+06  1.07E+00-+------+A-----+------+------+------+------+------+------+-
 5.956E+06  1.01E+00 +      A      +      +      +      +      +      +      +
 6.309E+06  9.60E-01 +      A      +      +      +      +      +      +      +
 6.683E+06  9.06E-01 +     A+      +      +      +      +      +      +      +
 7.079E+06  8.55E-01 +     A+      +      +      +      +      +      +      +
 7.498E+06  8.08E-01 +     A+      +      +      +      +      +      +      +
                    +            +            +            +            +
*****
UNITY GAIN FREQUENCY = 6 MEGAHERTZ
```

```
*****
OP AMP
VCC 1 0 15V
VSS 2 0 -15V
IEE 1 9 200A
Q1 5 8 9 P
Q2 6 4 9 P
Q3 5 5 2 N
Q4 6 5 2 N
Q5 1 6 7 N
RES 7 2 50K
Q6 8 7 2 N
I6 1 8 300U
CCOMP 6 8 10P
VIN 4 0 PULSE -5 5 0 0 0 30US
.MODEL N NPN BF=100 VAF=130 IS=1E-15
.MODEL P PNP BF=100 VAF=130 IS=1E-15
.PLOT TRAN V(8)
.TRAN 0.25U 10U
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END
****** OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
+0:1        = 1.500E+01 0:2        =-1.500E+01 0:4        =-5.000E+00
+0:5        =-1.440E+01 0:6        =-1.371E+01 0:7        =-1.431E+01
+0:8        =-4.999E+00 0:9        =-4.406E+00
**** BIPOLAR JUNCTION TRANSISTORS
```

ELEMENT	0:Q1	0:Q2	0:Q3	0:Q4	0:Q5	0:Q6
MODEL	0:P	0:P	0:N	0:N	0:N	0:N
IB	-9.243E-08	-9.281E-08	9.718E-08	9.718E-08	1.335E-07	2.800E-06
IC	-9.912E-06	-9.903E-06	9.718E-06	9.769E-06	1.630E-05	3.001E-04
VBE	-5.935E-01	-5.936E-01	5.948E-01	5.948E-01	6.030E-01	6.817E-01
VCE	-9.998E+00	-9.308E+00	5.948E-01	1.284E+00	2.931E+01	1.000E+01
VBC	9.405E+00	8.715E+00	0.	-6.899E-01	-2.871E+01	-9.318E+00
VS	4.999E+00	5.000E+00	1.440E+01	1.371E+01	-1.500E+01	4.999E+00
POWER	9.916E-05	9.224E-05	5.838E-06	1.261E-05	4.780E-04	3.003E-03
BETAD	1.072E+02	1.067E+02	1.000E+02	1.005E+02	1.220E+02	1.071E+02
GM	3.832E-04	3.828E-04	3.756E-04	3.776E-04	6.302E-04	1.160E-02
RPI	2.798E+05	2.786E+05	2.661E+05	2.661E+05	1.937E+05	9.236E+03
RX	0.	0.	0.	0.	0.	0.
RO	1.406E+07	1.400E+07	1.337E+07	1.337E+07	9.736E+06	4.642E+05
CPI	0.	0.	0.	0.	0.	0.
CMU	0.	0.	0.	0.	0.	0.
CBX	0.	0.	0.	0.	0.	0.
CCS	0.	0.	0.	0.	0.	0.
BETAAC	1.072E+02	1.066E+02	9.998E+01	1.005E+02	1.220E+02	1.071E+02
FT	6.098E+10	6.092E+10	5.978E+10	6.010E+10	1.002E+11	1.846E+12

```
****** TRANSIENT ANALYSIS                         TNOM=  27.000 TEMP=  27.000
   TIME       V(8)
(A      )    -5.000E+00     0.         5.000E+00    1.000E+01    1.500E+01
                    +            +            +            +            +
 0.         -5.00E+00-A------+------+------+------+------+------+------+------+-
 2.500E-07 -4.51E+00 +A     +      +      +      +      +      +      +      +
 5.000E-07 -4.01E+00 +  A   +      +      +      +      +      +      +      +
 7.500E-07 -3.52E+00 +   A  +      +      +      +      +      +      +      +
 1.000E-06 -3.03E+00 +    A +      +      +      +      +      +      +      +
 1.250E-06 -2.54E+00 +      A      +      +      +      +      +      +      +
 1.500E-06 -2.05E+00 +      +A     +      +      +      +      +      +      +
 1.750E-06 -1.56E+00 +      + A    +      +      +      +      +      +      +
 2.000E-06 -1.07E+00 +      +  A   +      +      +      +      +      +      +
 2.250E-06 -5.79E-01 +      +    A +      +      +      +      +      +      +
 2.500E-06 -8.78E-02-+------+------A------+------+------+------+------+------+-
 2.750E-06  4.04E-01 +      +      +A     +      +      +      +      +      +
 3.000E-06  8.95E-01 +      +      +  A   +      +      +      +      +      +
 3.250E-06  1.38E+00 +      +      +   A  +      +      +      +      +      +
 3.500E-06  1.87E+00 +      +      +    A +      +      +      +      +      +
 3.750E-06  2.37E+00 +      +      +      A      +      +      +      +      +
 4.000E-06  2.86E+00 +      +      +      +A     +      +      +      +      +
 4.250E-06  3.35E+00 +      +      +      + A    +      +      +      +      +
 4.500E-06  3.84E+00 +      +      +      +   A  +      +      +      +      +
 4.750E-06  4.33E+00 +      +      +      +    A +      +      +      +      +
 5.000E-06  4.82E+00-+------+------+------+------A------+------+------+------+-
 5.250E-06  5.00E+00 +      +      +      +      A      +      +      +      +
 5.500E-06  5.00E+00 +      +      +      +      A      +      +      +      +
 5.750E-06  5.00E+00 +      +      +      +      A      +      +      +      +
 6.000E-06  5.00E+00 +      +      +      +      A      +      +      +      +
 6.250E-06  5.00E+00 +      +      +      +      A      +      +      +      +
 6.500E-06  5.00E+00 +      +      +      +      A      +      +      +      +
 6.750E-06  5.00E+00 +      +      +      +      A      +      +      +      +
 7.000E-06  5.00E+00 +      +      +      +      A      +      +      +      +
 7.250E-06  5.00E+00 +      +      +      +      A      +      +      +      +
 7.500E-06  5.00E+00-+------+------+------+------A------+------+------+------+-
 7.750E-06  5.00E+00 +      +      +      +      A      +      +      +      +
 8.000E-06  5.00E+00 +      +      +      +      A      +      +      +      +
 8.250E-06  5.00E+00 +      +      +      +      A      +      +      +      +
 8.500E-06  5.00E+00 +      +      +      +      A      +      +      +      +
 8.750E-06  5.00E+00 +      +      +      +      A      +      +      +      +
 9.000E-06  5.00E+00 +      +      +      +      A      +      +      +      +
 9.250E-06  5.00E+00 +      +      +      +      A      +      +      +      +
 9.500E-06  5.00E+00 +      +      +      +      A      +      +      +      +
 9.750E-06  5.00E+00 +      +      +      +      A      +      +      +      +
 1.000E-05  5.00E+00-+------+------+------+------A------+------+------+------+-
                    +            +            +            +            +
*****
SLEW RATE = 10V/5.25US = 1.9V/US
```

9.17

(a) $\frac{\Delta V_o}{\Delta V_i}(j\omega) \simeq -G_m \frac{1}{j\omega C} A_v$

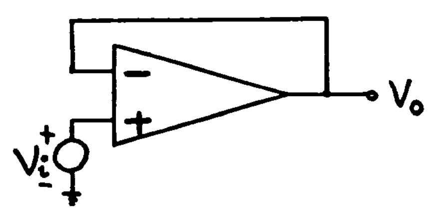
where $A_v = 500$, $C = 0.05\,\mu F$

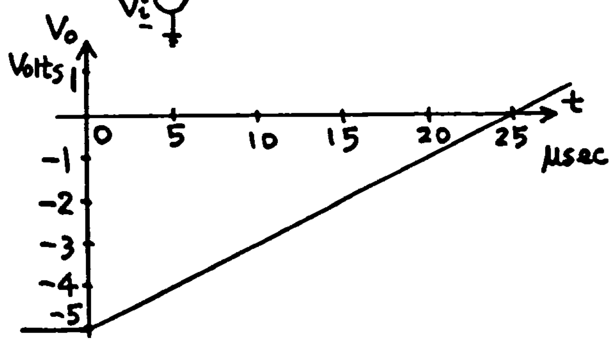
$\therefore 1 = \frac{10^{-5}}{26\times10^{-3}} \frac{10^6}{\omega_o \times 0.05} \times 500$

$\therefore f_o = 612\text{ KHz}$

Slew rate $= \frac{2 I_{c1}}{C} A_v$

$= \frac{20\times10^{-6}}{0.05\times10^{-6}} \times 500 = 0.2\ V/\mu s$





9.18

$$\frac{\Delta V_o}{\Delta V_i}(j\omega) = -G_m \frac{1}{j\omega C}$$

where $G_m = \dfrac{g_{m1}}{1 + g_{m1} R_E}$

$$= \frac{g_{m1}}{1 + \frac{10^{-5}}{26\times 10^{-3}}\times 10^{4}} = \frac{g_{m1}}{4.85}$$

For same unity gain freq.

$$C = \frac{10}{4.85}\ pF = 2.06\ pF$$

$$\text{Slew rate} = \frac{2 I_{C1}}{C}$$

$$= \frac{20\times 10^{-6}}{2.06\times 10^{-12}} = 9.7\ V/\mu s$$

Slew rate improves by a factor 4.85

```
OP AMP WITH EMITTER-DEGENERATED INPUT STAGE
VCC 1 0 15V
VSS 2 0 -15V
IEE 1 9 20UA
RE1 9 13 10K
RE2 9 14 10K
Q1 5 3 13 P
Q2 6 4 14 P
Q3 5 5 2 N
Q4 6 5 2 N
Q5 1 6 7 N
RE5 7 2 50K
Q6 8 7 2 N
I6 1 8 300U
CCOMP 6 8 2.06P
VIN2 3 0 0V
VIN 4 0 0V AC
.MODEL N NPN BF=100 VAF=130 IS=1E-15
.MODEL P PNP BF=100 VAF=130 IS=1E-15
.PLOT AC V(8)
.AC DEC 40 1MEG 10MEG
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.END

******  AC ANALYSIS                         TNOM=  27.000 TEMP=  27.000

   FREQ       V(8)
A                0.        2.000E+00    4.000E+00    6.000E+00    8.000E+00

1.778E+06  3.39E+00
1.883E+06  3.20E+00
1.995E+06  3.02E+00
2.113E+06  2.85E+00
2.239E+06  2.69E+00
2.371E+06  2.54E+00
2.511E+06  2.40E+00
2.660E+06  2.26E+00
2.818E+06  2.14E+00
2.985E+06  2.02E+00
3.162E+06  1.90E+00
3.349E+06  1.80E+00
3.548E+06  1.70E+00
3.758E+06  1.60E+00
3.981E+06  1.51E+00
4.217E+06  1.43E+00
4.466E+06  1.35E+00
4.731E+06  1.27E+00
5.011E+06  1.20E+00
5.308E+06  1.13E+00
5.623E+06  1.07E+00
5.956E+06  1.01E+00
6.309E+06  9.57E-01
6.683E+06  9.03E-01
7.079E+06  8.53E-01
7.499E+06  8.05E-01

*****
UNITY GAIN FREQUENCY = 6 MEGAHERTZ
```

```
*****
OP AMP WITH EMITTER-DEGENERATED INPUT STAGE
VCC 1 0 15V
VSS 2 0 -15V
IEE 1 9 20UA
RE1 9 13 10K
RE2 9 14 10K
Q1 5 8 13 P
Q2 6 4 14 P
Q3 5 5 2 N
Q4 6 5 2 N
Q5 1 6 7 N
RE5 7 2 50K
Q6 8 7 2 N
I6 1 8 300U
CCOMP 6 8 2.06P
VIN 4 0 PULSE -5 5 0 0 0 30US
.MODEL N NPN BF=100 VAF=130 IS=1E-15
.MODEL P PNP BF=100 VAF=130 IS=1E-15
.PLOT TRAN V(8)
.TRAN 0.05U 1.8U
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.END

******  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000

+0:1     = 1.500E+01 0:2      =-1.500E+01 0:4      =-5.000E+00
+0:5     =-1.440E+01 0:6      =-1.371E+01 0:7      =-1.431E+01
+0:8     =-5.000E+00 0:9      =-4.306E+00 0:13     =-4.406E+00
+0:14    =-4.406E+00

******  TRANSIENT ANALYSIS                  TNOM=  27.000 TEMP=  27.000

   TIME      V(8)
(A       )   -1.000E+01   -5.000E+00    0.         5.000E+00   1.000E+01

 0.         -5.00E+00
5.000E-08   -4.52E+00
1.000E-07   -4.04E+00
1.500E-07   -3.57E+00
2.000E-07   -3.09E+00
2.500E-07   -2.61E+00
3.000E-07   -2.14E+00
3.500E-07   -1.66E+00
4.000E-07   -1.18E+00
4.500E-07   -7.08E-01
5.000E-07   -2.31E-01
5.500E-07    2.46E-01
6.000E-07    7.23E-01
6.500E-07    1.20E+00
7.000E-07    1.67E+00
7.500E-07    2.15E+00
8.000E-07    2.63E+00
8.500E-07    3.10E+00
9.000E-07    3.59E+00
9.500E-07    4.06E+00
1.000E-06    4.54E+00
1.050E-06    4.90E+00
1.100E-06    4.98E+00
1.150E-06    4.99E+00
1.200E-06    5.00E+00
1.250E-06    5.00E+00
1.300E-06    5.00E+00
1.350E-06    5.00E+00
1.400E-06    5.00E+00
1.450E-06    5.00E+00
1.500E-06    5.00E+00
1.550E-06    5.00E+00
1.600E-06    5.00E+00
1.650E-06    5.00E+00
1.700E-06    5.00E+00
1.750E-06    5.00E+00
1.800E-06    5.00E+00

*****
SLEW RATE = 10V/1.2US = 8.33V/US
8.33/1.9 = 4.4 IMPROVEMENT
```

9.19

$G_m = 0.3\ mA/V$

$\frac{\Delta V_o}{\Delta V_i}(j\omega) = -G_m \frac{1}{j\omega C}$

$\therefore 1 = 0.3\times10^{-3} \frac{1}{6.12\times10^6 \times 2\pi \times C}$

$\therefore C = 7.8\ pF$

Slew rate $= \frac{2 I_{C1}}{C}$

$= \frac{600\times10^{-6}}{7.8\times10^{-12}} = 77\ V/\mu s$

Slew rate improves 38 times

9.20

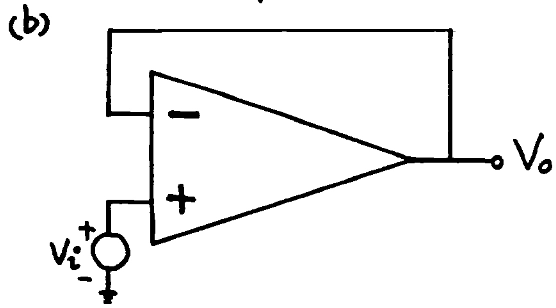
(a) $\left.\frac{dV_i}{dt}\right|_{MAX} = \omega V_M$

$\therefore \omega = \frac{2\ V/\mu s}{15 V} = 133\times10^3\ rad/sec$

$\therefore f = 21.2\ KHZ$

is the full-power bandwidth.

(b)



$V_i = 10 \sin 2\pi f t$

where $f = 45 KHZ$

$\frac{dV_i}{dt} = 2\pi f \times 10 \cos 2\pi f t$

$= 2.83\times10^6 \cos 2\pi f t$

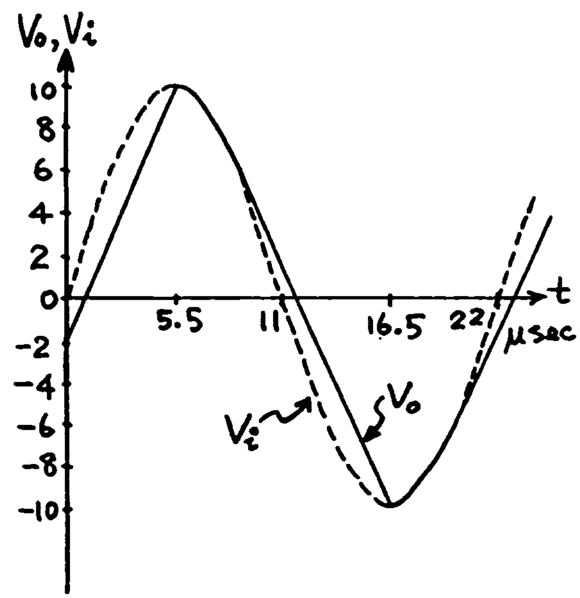
To find point of slew limiting put $\frac{dV_i}{dt} = 2\times10^6\ V/s$

$\therefore 2\times10^6 = 2.83\times10^6 \cos 2\pi f t$

$\therefore \cos 2\pi f t = 0.707$

$\therefore 2\pi f t = 0.786$

$\therefore t = 2.8\ \mu s$



9.21

$L_{eff} = L - 2L_d - X_d$

$= 8 - 2(0.3) - 1 = 6.4\mu$

$I_D = 20\mu A$ for m_8, m_5, m_7, m_6

$I_D = 10\mu A$ for m_1, m_2, m_3, m_4

$$\frac{1}{r_o} = \frac{\partial I_D}{\partial V_{DS}} = \frac{I_D}{L_{eff}} \frac{\partial X_d}{\partial V_{DS}}$$

nmos $\frac{\partial X_d}{\partial V_{DS}} = 0.2 \frac{\mu}{V}$

pmos $\frac{\partial X_d}{\partial V_{DS}} = 0.1 \frac{\mu}{V}$

$$\frac{1}{r_{o_2}} = \frac{10\mu}{6.4\mu} 0.1\,\mu = 156\,n$$

$$\frac{1}{r_{o_4}} = \frac{10\mu}{6.4\mu} 0.2\mu = 313\,n$$

$$g_{m_2} = \sqrt{2\,k_p' \frac{W}{L_{eff}} I_D}$$

$$= \sqrt{2(30.2\mu)\frac{100\mu}{6.4\mu} 10\mu}$$

$$= 97.1\mu$$

$k_p' = \mu_p\, C_{ox}$

$$= 350 \frac{cm^2}{Vs}\, 86.3\times 10^{-9} \frac{F}{cm^2}$$

$$= 30.2\times 10^{-6} \frac{C}{V^2 s}$$

$$= 30.2\,\mu \frac{A}{V^2}$$

$$C_{ox} = \frac{\epsilon_{ox}}{t_{ox}} = \frac{\epsilon_r \epsilon_0}{t_{ox}}$$

$$= \frac{3.9\,(8.85\times 10^{-14} \frac{F}{cm})}{40\times 10^{-7} cm}$$

$$= 86.3\times 10^{-9} \frac{F}{cm^2}$$

$$g_{m_6} = \sqrt{2\,k_n' \frac{W}{L_{eff}} I_D}$$

$$= \sqrt{2(60.4\mu)\frac{100}{6.4} 20\mu}$$

$$= 194\,\mu$$

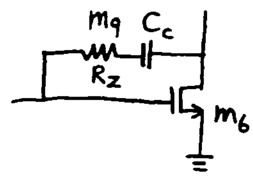
$$\frac{1}{r_{o_7}} = \frac{20\mu}{6.4\mu} 0.1\mu = 313\,n$$

$$\frac{1}{r_{o_6}} = \frac{20\mu}{6.4\mu} 0.2\mu = 625\,n$$

$$\frac{V_o}{V_i} = g_{m_2}(r_{o_2} \| r_{o_4})\, g_{m_6}(r_{o_6} \| r_{o_7})$$

$$= 97.1\mu\,(2.13\,M)(194\mu)(1.07M)$$

$= 4.28\times 10^4$ low frequency open loop gain



$$z = \frac{-1}{C_c\left(R_z - \frac{1}{g_{m6}}\right)}$$

cancel this zero by moving it to infinity : $R_z = \frac{1}{g_{m_6}} = 5.15\,k$

$$\frac{1}{R_z} = \frac{\partial I_D}{\partial V_{DS}} = k\,(V_{GS} - V_t - V_{DS})$$

$$\cong k\,(V_G - V_S - V_t)$$

assume $\gamma = 0$

$$= k' \frac{W}{L}(5V - V_{GS_6} - 0.7V)$$

$$\frac{1}{5.15k} = 60.4\mu \frac{W}{L}(5 - 0.906V - 0.7V)$$

$$= 205\mu \frac{W}{L}$$

$$0.95 = \frac{W}{L_{eff}} = \frac{6.1\mu}{6.4\mu}$$

$$\left(\frac{W}{L}\right)_9 = \frac{6.1\mu}{8\mu}$$

$$V_{GS_6} = \sqrt{\frac{2\,I_D}{k_n' \frac{W}{L_{eff}}}} + V_t$$

$$= \sqrt{\frac{2\,(20\mu)}{60.4\mu\, \frac{100\mu}{6.4\mu}}} + 0.7$$

$$= 0.906V$$

$$\frac{V_o}{V_i} = \frac{V_o}{i}\,\frac{i}{V_i} = \frac{1}{sC}\,g_{m_2} = \frac{g_{m_2}/C}{s}$$

$$\frac{V_o}{V_i}(j\omega) = \frac{g_m/C}{j\omega}$$

unity gain $\omega = \frac{g_{m_2}}{C} = \frac{97.1\mu}{5pF}$

$= 19.4\ M\ \frac{rad}{s}$

3.09 MHz

$$SR = \frac{dV_o}{dt}_{max} = \frac{I_{C\,max}}{C} = \frac{20\mu A}{5pF}$$

$$= 4\times10^6\ \frac{V}{s} = 4\ \frac{V}{\mu s}$$

```
CMOS AMP
VDD 1 0 5V
VSS 2 0 -5V
M1 7 5 4 4 P W=100U L=6.4U
M2 8 6 4 4 P W=100U L=6.4U
M3 7 7 2 2 N W=50U L=6.4U
M4 8 7 2 2 N W=50U L=6.4U
M5 4 3 1 1 P W=100U L=6.4U
M7 9 3 1 1 P W=100U L=6.4U
M8 3 3 1 1 P W=100U L=6.4U
M6 9 8 2 2 N W=100U L=6.4U
IBIAS 3 2 20UA
M9 10 1 8 2 N W=6.1U L=6.4U
CCOMP 10 9 5PF

*NMOS: LAMBDA=(DXD/DVDS)/LEFF=0.2U/6.4U=0.0313
*PMOS: LAMBDA=(DXD/DVDS)/LEFF=0.1U/6.4U=0.0156
.MODEL N NMOS KP=60.4U VTO=0.7 LAMBDA=0.0313
.MODEL P PMOS KP=30.2U VTO=-0.7 LAMBDA=0.0156
VI1 5 0 -48UV
VI2 6 0 0V AC
.TF V(9) VI1
.PLOT AC V(9)
.AC DEC 40 1MEG 10MEG
.OPTIONS NOPAGE NOMOD
.OPTIONS VNTOL=1N ABSTOL=1F RELTOL=1U
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END
```

```
****** OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000

+0:1     = 5.000E+00 0:2     =-5.000E+00 0:3     = 4.011E+00
+0:4     = 9.029E-01 0:5     =-4.800E-05 0:6     =   0.
+0:7     =-4.092E+00 0:8     =-4.102E+00 0:9     =-8.085E-03
+0:10    =-4.102E+00
```

**** MOSFETS

ELEMENT	0:M1	0:M2	0:M3	0:M4	0:M5	0:M7
MODEL	0:P	0:P	0:N	0:N	0:P	0:P
ID	-1.048E-05	-1.048E-05	1.048E-05	1.048E-05	-2.096E-05	-2.123E-05
IBS	0.	0.	0.	0.	0.	0.
IBD	4.995E-14	5.006E-14	-9.078E-15	-8.973E-15	4.097E-14	5.008E-14
VGS	-9.030E-01	-9.029E-01	9.078E-01	9.078E-01	-9.889E-01	-9.889E-01
VDS	-4.995E+00	-5.005E+00	9.078E-01	8.973E-01	-4.097E+00	-5.008E+00
VBS	0.	0.	0.	0.	0.	0.
VTH	-7.000E-01	-7.000E-01	7.000E-01	7.000E-01	-7.000E-01	-7.000E-01
VDSAT	-2.030E-01	-2.029E-01	2.078E-01	2.078E-01	-2.889E-01	-2.889E-01
BETA	5.086E-04	5.087E-04	4.853E-04	4.851E-04	5.020E-04	5.087E-04
GAM EFF	0.	0.	0.	0.	0.	0.
GM	1.032E-04	1.032E-04	1.009E-04	1.008E-04	1.451E-04	1.470E-04
GDS	1.517E-07	1.516E-07	3.189E-07	3.189E-07	3.073E-07	3.073E-07
GMB	0.	0.	0.	0.	0.	0.
CDTOT	0.	0.	0.	0.	0.	0.
CGTOT	0.	0.	0.	0.	0.	0.
CSTOT	0.	0.	0.	0.	0.	0.
CBTOT	0.	0.	0.	0.	0.	0.
CGS	0.	0.	0.	0.	0.	0.
CGD	0.	0.	0.	0.	0.	0.

ELEMENT	0:M8	0:M6	0:M9
MODEL	0:P	0:N	0:N
ID	-2.000E-05	2.123E-05	-9.063E-13
IBS	0.	0.	-8.973E-15
IBD	9.889E-15	-4.992E-14	-8.973E-15
VGS	-9.889E-01	8.973E-01	9.102E+00
VDS	-9.889E-01	4.991E+00	-1.873E-09
VBS	0.	0.	-8.973E-01
VTH	-7.000E-01	7.000E-01	7.000E-01
VDSAT	-2.889E-01	1.973E-01	1.873E-09
BETA	4.792E-04	1.091E-03	5.757E-05
GAM EFF	0.	0.	0.
GM	1.384E-04	2.153E-04	1.079E-13
GDS	3.073E-07	5.748E-07	4.837E-04
GMB	0.	0.	0.
CDTOT	0.	0.	0.
CGTOT	0.	0.	0.
CSTOT	0.	0.	0.
CBTOT	0.	0.	0.
CGS	0.	0.	0.
CGD	0.	0.	0.

```
****      SMALL-SIGNAL TRANSFER CHARACTERISTICS

     V(9)/VI1                                    = -5.345E+04
     INPUT RESISTANCE AT          VI1            =  9.999E+19
     OUTPUT RESISTANCE AT V(9)                   =  1.133E+06

****** AC ANALYSIS                          TNOM=  27.000 TEMP=  27.000

   FREQ       V(9)
(A       )    0.       1.000E-00 2.000E+00 3.000E+00 4.000E+00
              +         +         +         +         +
1.000E+06 3.26E+00-+----+----+----+----+----+----+--A-+----+
1.059E+06 3.08E+00 +    +    +    +    +    +    +A   +    +
1.122E+06 2.91E+00 +    +    +    +    +    +   A+    +    +
1.188E+06 2.75E+00 +    +    +    +    +    +  A +    +    +
1.258E+06 2.60E+00 +    +    +    +    +    +A   +    +    +
1.333E+06 2.45E+00 +    +    +    +    +   A+    +    +    +
1.412E+06 2.32E+00 +    +    +    +    +  A +    +    +    +
1.496E+06 2.19E+00 +    +    +    +    + A  +    +    +    +
1.584E+06 2.07E+00 +    +    +    +    +A   +    +    +    +
1.678E+06 1.95E+00 +    +    +    +   A+    +    +    +    +
1.778E+06 1.85E+00-+----+----+----+--A-+----+----+----+----+
1.883E+06 1.75E+00 +    +    +    +  A +    +    +    +    +
1.995E+06 1.65E+00 +    +    +    + A  +    +    +    +    +
2.113E+06 1.56E+00 +    +    +    +A   +    +    +    +    +
2.238E+06 1.47E+00 +    +    +    A    +    +    +    +    +
2.371E+06 1.39E+00 +    +    +   A+    +    +    +    +    +
2.511E+06 1.32E+00 +    +    +  A +    +    +    +    +    +
2.660E+06 1.25E+00 +    +    + A  +    +    +    +    +    +
2.818E+06 1.18E+00 +    +    + A  +    +    +    +    +    +
2.985E+06 1.12E+00 +    +    +A   +    +    +    +    +    +
3.162E+06 1.06E+00-+----+----+A---+----+----+----+----+----+
3.349E+06 1.00E+00 +    +    A    +    +    +    +    +    +
3.548E+06 9.55E-01 +    +   A+    +    +    +    +    +    +
3.758E+06 9.06E-01 +    +   A+    +    +    +    +    +    +
3.981E+06 8.60E-01 +    +  A +    +    +    +    +    +    +
4.217E+06 8.16E-01 +    +  A +    +    +    +    +    +    +
4.466E+06 7.76E-01 +    +  A +    +    +    +    +    +    +
4.731E+06 7.37E-01 +    + A  +    +    +    +    +    +    +
5.011E+06 7.02E-01 +    + A  +    +    +    +    +    +    +
5.308E+06 6.68E-01 +    + A  +    +    +    +    +    +    +
5.623E+06 6.37E-01-+----+A---+----+----+----+----+----+----+
5.956E+06 6.07E-01 +    + A  +    +    +    +    +    +    +
6.309E+06 5.80E-01 +    +A   +    +    +    +    +    +    +
6.683E+06 5.54E-01 +    +A   +    +    +    +    +    +    +
7.079E+06 5.30E-01 +    A    +    +    +    +    +    +    +
7.498E+06 5.08E-01 +    A    +    +    +    +    +    +    +
7.943E+06 4.88E-01 +    A    +    +    +    +    +    +    +
8.414E+06 4.69E-01 +    A    +    +    +    +    +    +    +
8.912E+06 4.51E-01 +   A+    +    +    +    +    +    +    +
9.440E+06 4.34E-01 +   A+    +    +    +    +    +    +    +
1.000E+07 4.19E-01-+---A+----+----+----+----+----+----+----+
              +         +         +         +         +
*****
```

```
CMOS AMP
VDD 1 0 5V
VSS 2 0 -5V
M1 7 9 4 4 P W=100U L=6.4U
M2 8 6 4 4 P W=100U L=6.4U
M3 7 7 2 2 N W=50U L=6.4U
M4 8 7 2 2 N W=50U L=6.4U
M5 4 3 1 1 P W=100U L=6.4U
M7 9 3 1 1 P W=100U L=6.4U
M8 3 3 1 1 P W=100U L=6.4U
M6 9 8 2 2 N W=100U L=6.4U
IBIAS 3 2 20UA
M9 10 1 8 2 N W=6.1U L=6.4U
CCOMP 10 9 5PF

*NMOS: LAMBDA=(DXD/DVDS)/LEFF=0.2U/6.4U=0.0313
*PMOS: LAMBDA=(DXD/DVDS)/LEFF=0.1U/6.4U=0.0156
.MODEL N NMOS KP=60.4U VTO=0.7 LAMBDA=0.0313
.MODEL P PMOS KP=30.2U VTO=-0.7 LAMBDA=0.0156
VI2 6 0 PULSE -2 2 0 0 0 30US
.PLOT TRAN V(9)
.TRAN 0.05U 1.8U
.OPTIONS NOPAGE NOMOD
.OPTIONS VNTOL=1N ABSTOL=1F RELTOL=1U
.WIDTH OUT=80
.OPTIONS SPICE
.END
```

```
****** TRANSIENT ANALYSIS                      TNOM=  27.000 TEMP=  27.000

    TIME       V(9)
(A        )   -4.000E+00   -2.000E+00      0.         2.000E+00   4.000E+00
                   +            +            +            +           +
  0.         -2.00E+00-+-----+-----A-----+-----+-----+-----+-----+-----+-
 5.000E-08 -1.91E+00 +     +     +A    +     +     +     +     +     +
 1.000E-07 -1.70E+00 +     +     + A   +     +     +     +     +     +
 1.500E-07 -1.49E+00 +     +     +   A +     +     +     +     +     +
 2.000E-07 -1.28E+00 +     +     +    A+     +     +     +     +     +
 2.500E-07 -1.07E+00 +     +     +     A     +     +     +     +     +
 3.000E-07 -8.60E-01 +     +     +     +A    +     +     +     +     +
 3.500E-07 -6.51E-01 +     +     +     + A   +     +     +     +     +
 4.000E-07 -4.42E-01 +     +     +     +   A +     +     +     +     +
 4.500E-07 -2.33E-01 +     +     +     +    A+     +     +     +     +
 5.000E-07 -2.57E-02-+-----+-----+-----+-----A-----+-----+-----+-----+-
 5.500E-07  1.81E-01 +     +     +     +     +A    +     +     +     +
 6.000E-07  3.88E-01 +     +     +     +     + A   +     +     +     +
 6.500E-07  5.94E-01 +     +     +     +     +   A +     +     +     +
 7.000E-07  7.99E-01 +     +     +     +     +    A+     +     +     +
 7.500E-07  1.00E+00 +     +     +     +     +     A     +     +     +
 8.000E-07  1.20E+00 +     +     +     +     +     +A    +     +     +
 8.500E-07  1.41E+00 +     +     +     +     +     + A   +     +     +
 9.000E-07  1.61E+00 +     +     +     +     +     +   A +     +     +
 9.500E-07  1.84E+00 +     +     +     +     +     +    A+     +     +
 1.000E-06  1.97E+00-+-----+-----+-----+-----+-----+-----A-----+-----+-
 1.050E-06  1.99E+00 +     +     +     +     +     +     A     +     +
 1.100E-06  1.99E+00 +     +     +     +     +     +     A     +     +
 1.150E-06  2.00E+00 +     +     +     +     +     +     A     +     +
 1.200E-06  2.00E+00 +     +     +     +     +     +     A     +     +
 1.250E-06  2.00E+00 +     +     +     +     +     +     A     +     +
 1.300E-06  2.00E+00 +     +     +     +     +     +     A     +     +
 1.350E-06  2.00E+00 +     +     +     +     +     +     A     +     +
 1.400E-06  2.00E+00 +     +     +     +     +     +     A     +     +
 1.450E-06  2.00E+00 +     +     +     +     +     +     A     +     +
 1.500E-06  2.00E+00-+-----+-----+-----+-----+-----+-----A-----+-----+-
 1.550E-06  2.00E+00 +     +     +     +     +     +     A     +     +
 1.600E-06  2.00E+00 +     +     +     +     +     +     A     +     +
 1.650E-06  2.00E+00 +     +     +     +     +     +     A     +     +
 1.700E-06  2.00E+00 +     +     +     +     +     +     A     +     +
 1.750E-06  2.00E+00 +     +     +     +     +     +     A     +     +
 1.800E-06  2.00E+00 +     +     +     +     +     +     A     +     +
                     +           +           +           +           +
```

9.22

$L_{eff} = L - 2L_d - X_d = 1 - 2\times 0.09 - 0.1$

$= 0.72\mu m$

$|I_D| = 200\mu A$ for M5–M8. $|I_D| = 100\mu A$ for M1–M4.

From Table 2.4, $\frac{dX_d}{dV_{DS}} = 0.02\ \mu m/V$ (NMOS)

$0.04\ \mu m/V$ (PMOS)

$$\frac{1}{r_o} = \frac{\partial I_D}{\partial V_{DS}} = \frac{I_D}{L_{eff}}\frac{dX_d}{dV_{DS}}$$

$$\frac{1}{r_{o2}} = \frac{100\mu A}{0.72\mu m}0.04\mu m/V = 5.55\mu A/V$$

$$\frac{1}{r_{o4}} = \frac{100\mu A}{0.72\mu m}0.02\mu m/V = 2.78\mu A/V$$

$$C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}} = \frac{3.9\times 8.854\times 10^{-12}}{80\times 10^{-10}} = 4.32\times 10^{-3} F/m^2$$

$$k_p' = \mu_p C_{ox} = 150\times 10^{-4}\times 4.32\times 10^{-3}$$

$$= 64.7\mu A/V^2$$

$$k_n' = \mu_n C_{ox} = 450\times 10^{-4}\times 4.32\times 10^{-3}$$

$$= 194\mu A/V^2$$

$$g_{m2} = \sqrt{2\times 64.7\times(150/0.72)\times 100} = 1.64 mA/V$$

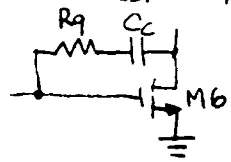
$$g_{m6} = \sqrt{2\times 194\times(100/0.72)\times 200} = 3.28 mA/V$$

$$\frac{1}{r_{o7}} = \frac{200\mu A}{0.72\mu m}0.04\mu m = 11.1\mu A/V$$

$$\frac{1}{r_{o6}} = \frac{200\mu A}{0.72\mu m}0.02\mu m = 5.55\mu A/V$$

$$\frac{V_o}{V_i} = g_{m2}(r_{o4}\|r_{o4})g_{m6}(r_{o6}\|r_{o7})$$

$$= \frac{1.64m}{8.33\mu}\frac{3.28m}{16.7\mu} = 38700$$



$$z = \frac{1}{(1/g_{m6} - R_q)C_c}$$

Cancel this zero by moving it to infinity.

$R_q = 1/g_{m6} = 305\Omega$

$$\frac{1}{R_q} = \frac{\partial I_D}{\partial V_{DS}} = k'\left(\frac{W}{L}\right)_q(V_{GSq} - V_{tq} - V_{DSq})$$

$$= k'\left(\frac{W}{L}\right)_q(V_{Gq} - V_{Sq} - V_{tq}) \quad (V_{DSq} = 0)$$

Assume $\gamma = 0$

$$\frac{1}{R_q} = k'\left(\frac{W}{L}\right)_q(V_{Gq} - V_{SS} - V_{GS6} - V_{tq})$$

$$= k'\left(\frac{W}{L}\right)_q(1.5 + 1.5 - V_{GS6} - V_{tq})$$

$$V_{ov6} = \sqrt{\frac{2\times 200}{194(100/0.72)}} = 0.122V$$

$$V_{GS6} = V_{t6} + V_{ov6} = 0.6 + 0.122 = 0.722V$$

$$\frac{1}{305} = 194\times 10^{-6}\left(\frac{W}{L}\right)_q(3 - 0.722 - 0.6)$$

$$\left(\frac{W}{L}\right)_q = 10.0$$

M9 is in the triode region, so $X_d = 0$

Use the same drawn length as for M6.

$L_q = 1 - 2\times 0.09 = 0.82\mu m$

$W_q = 8.2\mu m$.

At f_{unity}, $|A(\omega)| = \left|\frac{g_{m1}}{j\omega C_c}\right| = 1$

$$f_{unity} = \frac{g_{m1}}{2\pi C_c} = \frac{1.64\times 10^{-3}}{2\pi\times 5\times 10^{-12}} = 52.2MHz$$

$$SR = \frac{I_{max}}{C_c} = \frac{200\mu A}{5pF} = 40V/\mu s$$

9-16

```
CMOS AMP
VDD 1 0 1.5V
VSS 2 0 -1.5V
M1 7 5 4 4 P W=150U L=0.72U
M2 8 6 4 4 P W=150U L=0.72U
M3 7 7 2 2 N W=50U L=0.72U
M4 8 7 2 2 N W=50U L=0.72U
M5 4 3 1 1 P W=150U L=0.72U
M7 9 3 1 1 P W=150U L=0.72U
M8 3 3 1 1 P W=150U L=0.72U
M6 9 8 2 2 N W=100U L=0.72U
IBIAS 3 2 200UA
M9 10 1 8 2 N W=8.2U L=0.82U
CCOMP 10 9 5PF

* MODELS
.MODEL N NMOS LEVEL=1 KP=194U  VTO=0.6  LAMBDA=0.027778
.MODEL P PMOS LEVEL=1 KP=64.7U VTO=-0.8 LAMBDA=0.055556
*NMOS: LAMBDA=(DXD/DVDS)/LEFF=0.02U/0.72U=0.027778
*PMOS: LAMBDA=(DXD/DVDS)/LEFF=0.04U/0.72U=0.055556

VI1 5 0 0 AC 1 PULSE 0 1 0 1NS 1NS 1US 30US
VI2 6 0 0
.TF V(9) VI1
.PLOT AC VDB(9)
.AC DEC 5 10 100MEG
.TRAN 0.005U 0.1U
.PLOT TRAN V(9)
.OPTIONS NOPAGE NOMOD
.OPTIONS VNTOL=1N ABSTOL=1F RELTOL=1U
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END
```

```
 ******  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000

+0:1       = 1.500E+00 0:2       =-1.500E+00 0:3       = 5.322E-01
+0:4       = 9.153E-01 0:5       =   0.      0:6       =   0.
+0:7       =-7.806E-01 0:8       =-7.806E-01 0:9       = 3.454E-01
+0:10      =-7.806E-01
```

**** MOSFETS

ELEMENT	0:M1	0:M2	0:M3	0:M4	0:M5	0:M7
MODEL	0:P	0:P	0:N	0:N	0:P	0:P
ID	-9.798E-05	-9.798E-05	9.798E-05	9.798E-05	-1.960E-04	-2.020E-04
IBS	0.	0.	0.	0.	0.	0.
IBD	1.696E-14	1.696E-14	-7.194E-15	-7.194E-15	5.847E-15	1.155E-14
VGS	-9.153E-01	-9.153E-01	7.194E-01	7.194E-01	-9.678E-01	-9.678E-01
VDS	-1.695E+00	-1.695E+00	7.194E-01	7.194E-01	-5.847E-01	-1.154E+00
VBS	0.	0.	0.	0.	0.	0.
VTH	-8.000E-01	-8.000E-01	6.000E-01	6.000E-01	-8.000E-01	-8.000E-01
VDSAT	-1.153E-01	-1.153E-01	1.194E-01	1.194E-01	-1.678E-01	-1.678E-01
BETA	1.475E-02	1.475E-02	1.374E-02	1.374E-02	1.392E-02	1.434E-02
GAM EFF	0.	0.	0.	0.	0.	0.
GM	1.700E-03	1.700E-03	1.641E-03	1.641E-03	2.335E-03	2.407E-03
GDS	4.975E-06	4.975E-06	2.668E-06	2.668E-06	1.054E-05	1.054E-05
GMB	0.	0.	0.	0.	0.	0.
CDTOT	0.	0.	0.	0.	0.	0.
CGTOT	0.	0.	0.	0.	0.	0.
CSTOT	0.	0.	0.	0.	0.	0.
CBTOT	0.	0.	0.	0.	0.	0.
CGS	0.	0.	0.	0.	0.	0.
CGD	0.	0.	0.	0.	0.	0.

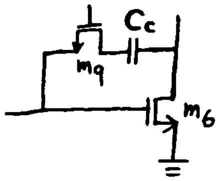
ELEMENT	0:M8	0:M6	0:M9
MODEL	0:P	0:N	0:N
ID	-2.000E-04	2.020E-04	-7.266E-13
IBS	0.	0.	-7.194E-15
IBD	9.678E-15	-1.845E-14	-7.194E-15
VGS	-9.678E-01	7.194E-01	2.280E+00
VDS	-9.678E-01	1.845E+00	-2.229E-10
VBS	0.	0.	-7.194E-01
VTH	-8.000E-01	6.000E-01	6.000E-01
VDSAT	-1.678E-01	1.194E-01	2.229E-10
BETA	1.420E-02	2.833E-02	1.940E-03
GAM EFF	0.	0.	0.
GM	2.384E-03	3.383E-03	4.324E-13
GDS	1.054E-05	5.337E-06	3.260E-03
GMB	0.	0.	0.
CDTOT	0.	0.	0.
CGTOT	0.	0.	0.
CSTOT	0.	0.	0.
CBTOT	0.	0.	0.
CGS	0.	0.	0.
CGD	0.	0.	0.

```
****     SMALL-SIGNAL TRANSFER CHARACTERISTICS

     V(9)/VI1                                = -4.733E+04
     INPUT RESISTANCE AT          VI1        =  9.999E+19
     OUTPUT RESISTANCE AT V(9)               =  6.296E+04
```

```
 ******  AC ANALYSIS                                    TNOM=  27.000 TEMP=  27.000

    FREQ       VDB(9)
(A        )   -5.000E+01    0.           5.000E+01     1.000E+02     1.500E+02
                    +             +             +             +             +
1.000E+01  9.35E+01-+------+------+------+------+------+----A-+------+------+-
1.584E+01  9.35E+01 +      +      +      +      +      +    A +      +      +
2.511E+01  9.35E+01 +      +      +      +      +      +    A +      +      +
3.981E+01  9.35E+01 +      +      +      +      +      +    A +      +      +
6.309E+01  9.34E+01 +      +      +      +      +      +    A +      +      +
1.000E+02  9.34E+01 +      +      +      +      +      +    A +      +      +
1.584E+02  9.34E+01 +      +      +      +      +      +    A +      +      +
2.511E+02  9.33E+01 +      +      +      +      +      +    A +      +      +
3.981E+02  9.30E+01 +      +      +      +      +      +    A +      +      +
6.309E+02  9.23E+01 +      +      +      +      +      +    A +      +      +
1.000E+03  9.10E+01-+------+------+------+------+------+---A--+------+------+-
1.584E+03  8.87E+01 +      +      +      +      +      +   A  +      +      +
2.511E+03  8.57E+01 +      +      +      +      +      +  A   +      +      +
3.981E+03  8.22E+01 +      +      +      +      +      + A    +      +      +
6.309E+03  7.84E+01 +      +      +      +      +      +A     +      +      +
1.000E+04  7.45E+01 +      +      +      +      +      A      +      +      +
1.584E+04  7.05E+01 +      +      +      +      +     A+      +      +      +
2.511E+04  6.65E+01 +      +      +      +      +    A +      +      +      +
3.981E+04  6.25E+01 +      +      +      +      +   A  +      +      +      +
6.309E+04  5.85E+01 +      +      +      +      + A    +      +      +      +
1.000E+05  5.45E+01-+------+------+------+------+A-----+------+------+------+-
1.584E+05  5.05E+01 +      +      +      +      A      +      +      +      +
2.511E+05  4.65E+01 +      +      +      +     A+      +      +      +      +
3.981E+05  4.25E+01 +      +      +      +    A +      +      +      +      +
6.309E+05  3.85E+01 +      +      +      +   A  +      +      +      +      +
1.000E+06  3.45E+01 +      +      +      +  A   +      +      +      +      +
1.584E+06  3.05E+01 +      +      +      + A    +      +      +      +      +
2.511E+06  2.65E+01 +      +      +      A      +      +      +      +      +
3.981E+06  2.25E+01 +      +      +     A+      +      +      +      +      +
6.309E+06  1.85E+01 +      +      +    A +      +      +      +      +      +
1.000E+07  1.45E+01-+------+------+---A--+------+------+------+------+------+-
1.584E+07  1.05E+01 +      +      +  A   +      +      +      +      +      +
2.511E+07  6.58E+00 +      +      + A    +      +      +      +      +      +
3.981E+07  2.58E+00 +      +      +A     +      +      +      +      +      +
6.309E+07 -1.41E+00 +      +      A      +      +      +      +      +      +
1.000E+08 -5.40E+00 +      +    A +      +      +      +      +      +      +
                    +             +             +             +             +
```

```
 ******  TRANSIENT ANALYSIS                             TNOM=  27.000 TEMP=  27.000

    TIME       V(9)
(A        )   -1.500E+00    -1.000E-00    -5.000E-01    0.            5.000E-01
                    +             +             +             +             +
    0.     3.45E-01-+------+------+------+------+------+------+------+---A--+-
5.000E-09  1.39E-01 +      +      +      +      +      +      +   A  +      +
1.000E-08 -5.57E-02 +      +      +      +      +      +    A +      +      +
1.500E-08 -2.50E-01 +      +      +      +      +      A      +      +      +
2.000E-08 -4.45E-01 +      +      +      +      + A    +      +      +      +
2.500E-08 -6.40E-01 +      +      +      +  A   +      +      +      +      +
3.000E-08 -8.34E-01 +      +      +    A +      +      +      +      +      +
3.500E-08 -1.02E+00 +      +     A+      +      +      +      +      +      +
4.000E-08 -1.22E+00 +      +A     +      +      +      +      +      +      +
4.500E-08 -1.39E+00 +  A   +      +      +      +      +      +      +      +
5.000E-08 -1.45E+00-+A-----+------+------+------+------+------+------+------+-
5.500E-08 -1.47E+00 +A     +      +      +      +      +      +      +      +
6.000E-08 -1.47E+00 +A     +      +      +      +      +      +      +      +
6.500E-08 -1.48E+00 A      +      +      +      +      +      +      +      +
7.000E-08 -1.48E+00 A      +      +      +      +      +      +      +      +
7.500E-08 -1.48E+00 A      +      +      +      +      +      +      +      +
8.000E-08 -1.49E+00 A      +      +      +      +      +      +      +      +
8.500E-08 -1.49E+00 A      +      +      +      +      +      +      +      +
9.000E-08 -1.49E+00 A      +      +      +      +      +      +      +      +
9.500E-08 -1.49E+00 A      +      +      +      +      +      +      +      +
1.000E-07 -1.49E+00-A------+------+------+------+------+------+------+------+-
                    +             +             +             +             +
```

9.23



zero $z = \dfrac{-1}{C_c\left(R_Z - \frac{1}{g_{m6}}\right)}$

set $R_Z = \dfrac{1}{g_{m6}} = \dfrac{1}{194\mu} = 5.15k$

$g_{m6} = \sqrt{2 k_n' \frac{W}{L_{eff}} I_D}$

$= \sqrt{2(60.4\mu)\frac{100}{6.4}20\mu}$

$= 194\mu$

$\dfrac{1}{R_Z} = \dfrac{\partial I_D}{\partial V_{DS}} = k(V_{GS} - V_t - V_{DS})$

$= k(V_{GS_9} - V_t)\Big|_{V_{DS}=0}$

$= g_{m9}$

$R_Z = \dfrac{1}{g_{m9}} = \dfrac{1}{g_{m6}}$

set $k_9(V_{GS_9} - V_t) = k_6(V_{GS_6} - V_t)$

$k_n'\left(\frac{W}{L}\right)_9(V_{GS_9} - V_t) = k_n'\left(\frac{W}{L}\right)_6(V_{GS_6} - V_t)$

assume $\gamma = 0$, $V_t = 0.7V$ for all devices

KVL

$V_{GS_{12}} + V_{GS_{11}} = V_{GS_9} + V_{GS_6}$

$V_{GS_{12}} = V_{GS_{11}} = V_{GS_6}$

$\therefore V_{GS_6} = V_{GS_9}$

$\left(\frac{W}{L}\right)_9(V_{GS_9} - V_t) = \left(\frac{W}{L}\right)_6(V_{GS_6} - V_t)$

$\left(\frac{W}{L}\right)_9 = \left(\frac{W}{L}\right)_6$

```
CMOS AMP WITHOUT M9, SEE RIGHT HALF PLANE ZERO
VDD 1 0 5V
VSS 2 0 -5V
M1 7 5 4 4 P W=100U L=6.4U
M2 8 6 4 4 P W=100U L=6.4U
M3 7 7 2 2 N W=50U L=6.4U
M4 8 7 2 2 N W=50U L=6.4U
M5 4 3 1 1 P W=100U L=6.4U
M7 9 3 1 1 P W=100U L=6.4U
M8 3 3 1 1 P W=100U L=6.4U
M6 9 8 2 2 N W=100U L=6.4U
IBIAS 3 2 20UA
CCOMP 8 9 5PF
*NMOS: LAMBDA=(DXD/DVDS)/LEFF=0.2U/6.4U=0.0313
*PMOS: LAMBDA=(DXD/DVDS)/LEFF=0.1U/6.4U=0.0156
.MODEL N NMOS KP=60.4U VTO=0.7 LAMBDA=0.0313
.MODEL P PMOS KP=30.2U VTO=-0.7 LAMBDA=0.0156
VI1 5 0 -48UV
VI2 6 0 0V AC
.TF V(9) VI1
.PLOT AC VP(9)
.AC DEC 10 100K 10GIG
.OPTIONS NOPAGE NOMOD
.OPTIONS VNTOL=1N ABSTOL=1F RELTOL=1U
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END
 ******  AC ANALYSIS                        TNOM=  27.000 TEMP=  27.000
    FREQ       VP(9)
(A        )   -2.000E+02    -1.500E+02    -1.000E+02    -5.000E+01     0.
                    +             +             +             +             +
1.000E+05 -9.08E+01-+------+------+------+------+--A---+------+------+------+-
1.258E+05 -9.10E+01 +      +      +      +      +  A   +      +      +      +
1.584E+05 -9.13E+01 +      +      +      +      + A    +      +      +      +
1.995E+05 -9.16E+01 +      +      +      +      + A    +      +      +      +
2.511E+05 -9.20E+01 +      +      +      +      + A    +      +      +      +
3.162E+05 -9.26E+01 +      +      +      +      + A    +      +      +      +
3.981E+05 -9.33E+01 +      +      +      +      + A    +      +      +      +
5.011E+05 -9.41E+01 +      +      +      +      + A    +      +      +      +
6.309E+05 -9.52E+01 +      +      +      +      +A     +      +      +      +
7.943E+05 -9.66E+01 +      +      +      +      +A     +      +      +      +
1.000E+06 -9.83E+01-+------+------+------+------A------+------+------+------+-
1.258E+06 -1.00E+02 +      +      +      +      A      +      +      +      +
1.584E+06 -1.03E+02 +      +      +      +     A+      +      +      +      +
1.995E+06 -1.06E+02 +      +      +      +    A +      +      +      +      +
2.511E+06 -1.10E+02 +      +      +      +   A  +      +      +      +      +
3.162E+06 -1.14E+02 +      +      +      +  A   +      +      +      +      +
3.981E+06 -1.20E+02 +      +      +      +A     +      +      +      +      +
5.011E+06 -1.26E+02 +      +      +      A      +      +      +      +      +
6.309E+06 -1.32E+02 +      +      +    A +      +      +      +      +      +
7.943E+06 -1.39E+02 +      +      +  A   +      +      +      +      +      +
1.000E+07 -1.45E+02-+------+------+A-----+------+------+------+------+------+-
1.258E+07 -1.51E+02 +      +      A      +      +      +      +      +      +
1.584E+07 -1.56E+02 +      +    A +      +      +      +      +      +      +
1.995E+07 -1.61E+02 +      +   A  +      +      +      +      +      +      +
2.511E+07 -1.64E+02 +      +  A   +      +      +      +      +      +      +
3.162E+07 -1.67E+02 +      + A    +      +      +      +      +      +      +
3.981E+07 -1.70E+02 +      +A     +      +      +      +      +      +      +
5.011E+07 -1.72E+02 +      +A     +      +      +      +      +      +      +
6.309E+07 -1.73E+02 +      A      +      +      +      +      +      +      +
7.943E+07 -1.75E+02 +      A      +      +      +      +      +      +      +
1.000E+08 -1.76E+02-+------A------+------+------+------+------+------+------+-
1.258E+08 -1.76E+02 +     A+      +      +      +      +      +      +      +
1.584E+08 -1.77E+02 +     A+      +      +      +      +      +      +      +
1.995E+08 -1.78E+02 +     A+      +      +      +      +      +      +      +
2.511E+08 -1.78E+02 +     A+      +      +      +      +      +      +      +
3.162E+08 -1.78E+02 +     A+      +      +      +      +      +      +      +
3.981E+08 -1.79E+02 +     A+      +      +      +      +      +      +      +
5.011E+08 -1.79E+02 +     A+      +      +      +      +      +      +      +
6.309E+08 -1.79E+02 +     A+      +      +      +      +      +      +      +
7.943E+08 -1.79E+02 +     A+      +      +      +      +      +      +      +
1.000E+09 -1.79E+02-+-----A+------+------+------+------+------+------+------+-
                    +             +             +             +             +
*****
CMOS AMP WITH M9 TO MOVE RIGHT HALF PLANE ZERO TO INFINITY
VDD 1 0 5V
VSS 2 0 -5V
M1 7 5 4 4 P W=100U L=6.4U
M2 8 6 4 4 P W=100U L=6.4U
M3 7 7 2 2 N W=50U L=6.4U
M4 8 7 2 2 N W=50U L=6.4U
M5 4 3 1 1 P W=100U L=6.4U
M7 9 3 1 1 P W=100U L=6.4U
M8 3 3 1 1 P W=100U L=6.4U
M6 9 8 2 2 N W=100U L=6.4U
IBIAS 3 2 20UA
M9 10 12 8 2 N W=100U L=6.4U
CCOMP 10 9 5PF
* BIAS CIRCUITRY FOR M9
M10 12 3 1 1 P W=100U L=6.4U
M11 12 12 13 2 N W=100U L=6.4U
M12 13 13 2 2 N W=100U L=6.4U
*NMOS: LAMBDA=(DXD/DVDS)/LEFF=0.2U/6.4U=0.0313
*PMOS: LAMBDA=(DXD/DVDS)/LEFF=0.1U/6.4U=0.0156
.MODEL N NMOS KP=60.4U VTO=0.7 LAMBDA=0.0313
.MODEL P PMOS KP=30.2U VTO=-0.7 LAMBDA=0.0156
VI1 5 0 -48UV
VI2 6 0 0V AC
.TF V(9) VI1
.PLOT AC VP(9)
.AC DEC 10 100K 1GIG
.OPTIONS NOPAGE NOMOD
.OPTIONS VNTOL=1N ABSTOL=1F RELTOL=1U
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END
 ******  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
+0:1      = 5.000E+00 0:2       =-5.000E+00 0:3       = 4.011E+00
+0:4      = 9.029E-01 0:5       =-4.800E-05 0:6       =   0.
+0:7      =-4.092E+00 0:8       =-4.102E+00 0:9       =-8.085E-03
+0:10     =-4.102E+00 0:12      =-3.172E+00 0:13      =-4.086E+00
**** MOSFETS
ELEMENT  0:M1       0:M2       0:M3       0:M4       0:M5       0:M7
MODEL    0:P        0:P        0:N        0:N        0:P        0:P
 ID      -1.048E-05 -1.048E-05  1.048E-05  1.048E-05 -2.096E-05 -2.123E-05
 IBS        0.         0.         0.         0.         0.         0.
 IBD      4.995E-14  5.006E-14 -9.078E-15 -8.973E-15  4.097E-14  5.008E-14
 VGS     -9.030E-01 -9.029E-01  9.078E-01  9.078E-01 -9.889E-01 -9.889E-01
 VDS     -4.995E+00 -5.005E+00  9.078E-01  8.973E-01 -4.097E+00 -5.008E+00
 VBS        0.         0.         0.         0.         0.         0.
 VTH     -7.000E-01 -7.000E-01  7.000E-01  7.000E-01 -7.000E-01 -7.000E-01
 VDSAT   -2.030E-01 -2.029E-01  2.078E-01  2.078E-01 -2.889E-01 -2.889E-01
 BETA     5.086E-04  5.087E-04  4.853E-04  4.851E-04  5.020E-04  5.087E-04
 GAM EFF    0.         0.         0.         0.         0.         0.
 GM       1.032E-04  1.032E-04  1.009E-04  1.008E-04  1.451E-04  1.470E-04
 GDS      1.517E-07  1.516E-07  3.189E-07  3.189E-07  3.073E-07  3.073E-07
 GMB        0.         0.         0.         0.         0.         0.
ELEMENT  0:M8       0:M6       0:M9       0:M10      0:M11      0:M12
MODEL    0:P        0:N        0:N        0:P        0:N        0:N
 ID      -2.000E-05  2.123E-05 -9.063E-13 -2.221E-05  2.221E-05  2.221E-05
 IBS        0.         0.     -8.973E-15    0.     -9.139E-15    0.
 IBD      9.889E-15 -4.992E-14 -8.973E-15  8.172E-14 -1.828E-14 -9.139E-15
 VGS     -9.889E-01  8.973E-01  9.305E-01 -9.889E-01  9.139E-01  9.139E-01
 VDS     -9.889E-01  4.991E+00 -4.166E-09 -8.172E+00  9.139E-01  9.139E-01
 VBS        0.         0.     -8.973E-01    0.     -9.139E-01    0.
 VTH     -7.000E-01  7.000E-01  7.000E-01 -7.000E-01  7.000E-01  7.000E-01
 VDSAT   -2.889E-01  1.973E-01  4.166E-09 -2.889E-01  2.139E-01  2.139E-01
 BETA     4.792E-04  1.091E-03  9.438E-04  5.320E-04  9.707E-04  9.707E-04
 GAM EFF    0.         0.         0.         0.         0.         0.
 GM       1.384E-04  2.153E-04  3.931E-12  1.537E-04  2.076E-04  2.076E-04
 GDS      3.073E-07  5.748E-07  2.175E-04  3.073E-07  6.758E-07  6.758E-07
 GMB        0.         0.         0.         0.         0.         0.
****     SMALL-SIGNAL TRANSFER CHARACTERISTICS
     V(9)/VI1                                  = -5.345E+04
     INPUT RESISTANCE AT           VI1          =  9.999E+19
     OUTPUT RESISTANCE AT V(9)                  =  1.133E+06
 ******  AC ANALYSIS                       TNOM=  27.000 TEMP=  27.000
    FREQ       VP(9)
(A        )   -1.600E+02    -1.400E+02    -1.200E+02    -1.000E+02    -8.000E+01
                    +             +             +             +             +
1.000E+05 -8.99E+01-+------+------+------+------+------+------+------A------+-
1.258E+05 -8.99E+01 +      +      +      +      +      +      +      A      +
1.584E+05 -8.99E+01 +      +      +      +      +      +      +      A      +
1.995E+05 -9.00E+01 +      +      +      +      +      +      +      A      +
2.511E+05 -9.00E+01 +      +      +      +      +      +      +      A      +
3.162E+05 -9.00E+01 +      +      +      +      +      +      +      A      +
3.981E+05 -9.00E+01 +      +      +      +      +      +      +      A      +
5.011E+05 -9.00E+01 +      +      +      +      +      +      +      A      +
6.309E+05 -9.00E+01 +      +      +      +      +      +      +      A      +
7.943E+05 -9.00E+01 +      +      +      +      +      +      +      A      +
1.000E+06 -9.00E+01-+------+------+------+------+------+------+------A------+-
1.258E+06 -9.01E+01 +      +      +      +      +      +      +      A      +
1.584E+06 -9.01E+01 +      +      +      +      +      +      +      A      +
1.995E+06 -9.01E+01 +      +      +      +      +      +      +      A      +
2.511E+06 -9.02E+01 +      +      +      +      +      +      +      A      +
3.162E+06 -9.02E+01 +      +      +      +      +      +      +      A      +
3.981E+06 -9.03E+01 +      +      +      +      +      +      +      A      +
5.011E+06 -9.04E+01 +      +      +      +      +      +      +      A      +
6.309E+06 -9.05E+01 +      +      +      +      +      +      +      A      +
7.943E+06 -9.06E+01 +      +      +      +      +      +      +      A      +
1.000E+07 -9.08E+01-+------+------+------+------+------+------+-----A+------+-
1.258E+07 -9.11E+01 +      +      +      +      +      +      +     A+      +
1.584E+07 -9.13E+01 +      +      +      +      +      +      +     A+      +
1.995E+07 -9.17E+01 +      +      +      +      +      +      +     A+      +
2.511E+07 -9.21E+01 +      +      +      +      +      +      +    A +      +
3.162E+07 -9.27E+01 +      +      +      +      +      +      +    A +      +
3.981E+07 -9.34E+01 +      +      +      +      +      +      +    A +      +
5.011E+07 -9.43E+01 +      +      +      +      +      +      +   A  +      +
6.309E+07 -9.55E+01 +      +      +      +      +      +      +  A   +      +
7.943E+07 -9.69E+01 +      +      +      +      +      +      + A    +      +
1.000E+08 -9.86E+01-+------+------+------+------+------+------+A-----+------+-
1.258E+08 -1.00E+02 +      +      +      +      +      +     A+      +      +
1.584E+08 -1.03E+02 +      +      +      +      +      +   A  +      +      +
1.995E+08 -1.06E+02 +      +      +      +      +      + A    +      +      +
2.511E+08 -1.11E+02 +      +      +      +      +     A+      +      +      +
3.162E+08 -1.15E+02 +      +      +      +      +  A   +      +      +      +
3.981E+08 -1.21E+02 +      +      +      +     A+      +      +      +      +
5.011E+08 -1.27E+02 +      +      +      + A    +      +      +      +      +
6.309E+08 -1.33E+02 +      +      +   A  +      +      +      +      +      +
7.943E+08 -1.40E+02 +      +      A      +      +      +      +      +      +
1.000E+09 -1.46E+02-+------+-A----+------+------+------+------+------+------+-
                    +             +             +             +             +
*****
THE POLE AT 6.3 MHZ HAS BEEN MOVED UP IN FREQUENCY.
```

9.24

From Problem 9.22,

$\frac{1}{R_9} = k'\left(\frac{W}{L}\right)_9 (V_{GS9} - V_{t9})$

Since $I_{D12} = I_{D6}$ and $(W/L)_{12} = (W/L)_6$, $V_{ov12} = V_{ov6}$.

Therefore $V_{SB11} = V_{GS12} = V_{t12} + V_{ov12}$
$= V_{SB9} = V_{GS6} = V_{t6} + V_{ov6}$,

because $V_{t12} = V_{t6}$ (no body effect).

Also, $V_{ov11} = V_{ov12}$ because $I_{D11} = I_{D12}$ and $(W/L)_{11} = (W/L)_{12}$

Therefore, $V_{GS9} = V_{GS11} + V_{GS12} - V_{GS6}$
$= V_{t11} + V_{ov11} + V_{t12} + V_{ov12} - V_{t6} - V_{ov6}$
$= V_{t11} + V_{ov}$,

where $V_{ov} = V_{ov6} = V_{ov11} = V_{ov12}$.

So $V_{GS9} - V_{t9} = V_{t11} + V_{ov} - V_{t9} = V_{ov}$.

Since $V_{GS9} - V_{t9} = V_{GS6} - V_{t6}$ and $\frac{1}{R_9}$ should equal g_{m6} to cancel the RHP zero,

$\frac{1}{R_9} = k'\left(\frac{W}{L}\right)_9 (V_{GS9} - V_{t9})$

$= g_{m6} = k'\left(\frac{W}{L}\right)_6 (V_{GS6} - V_{t6})$

$\left(\frac{W}{L}\right)_9 = \left(\frac{W}{L}\right)_6 = \frac{100}{1}$

9.25

To get 45° phase margin, set the 2nd pole = unity gain freq.

$$\left(|P_2| = \frac{g_{m6} C_c}{C_L C_1 + C_c C_L + C_1 C_c}\right) = \frac{g_{m2}}{C_c}$$

$g_{m2} = 97.1\,\mu A/V$

$g_{m6} = 194\,\mu A/V$

$C_c = 5\,pF$

$C_1 = C_{OL2} + C_{OL4} + C_{gs6} + C_{OL9}$

$= 0.35\,fF/\mu\,(100\mu + 50\mu)$

$+ \frac{2}{3}(100\mu)(8\mu)\,0.869\,fF/\mu^2$

$+ 0.35\,fF/\mu\,(100\mu)$

$= 551\,fF$

$\frac{g_{m2}}{C_c} = 19.4\,M\,rad/s$

$$19.4M = \frac{194\mu(5p)}{C_L 551f + C_L 5p + 551f(5p)}$$

solve for C_L

$C_L = 8.51\,pF$

9.26

To obtain 45° phase margin, set the 2nd pole to funity

$$|P_2| = \frac{g_{m6}C_c}{C_LC_1 + C_cC_L + C_1C_c} = \frac{g_{m2}}{C_c} = \frac{1.64\,mA/V}{5\,pF}$$

$= 328M$ rad/s

C_1 is dominated by the gate of M6

Minimum estimate for $C_1 = C_{gs6(i)} + C_{gs6(ol)}$

$= \frac{2}{3}100 \times 0.72 \times 4.3 + 0.35 \times 100 = 244\,fF$

Maximum estimate for C_1

$= C_{gs6(i)} + C_{gs6(ol)} + C_{gs9(i)} + C_{gs9(ol)} + C_{gd2(ol)} + C_{gd4(ol)}$

$= \frac{2}{3}100 \times 0.72 \times 0.43 + 0.35 \times 100 + \frac{1}{2}100 \times 0.82 + 0.35 \times 100 + 0.35 \times 150 + 0.35 \times 50$

$= 387\,fF$

(M9 is in the triode region.)

$$328M\ \text{rad/s} = \frac{3.28m(5p)}{C_LC_1 + C_L(5p) + C_1(5p)}$$

Case 1 (min C_1)

$C_L(244fF) + C_L(5p) + 244f(5p) = 5 \times 10^{-23}$

$C_L = 9.3\,pF$

Case 2 (max C_1)

$C_L(387f) + C_L(5p) + 387f(5p) = 5 \times 10^{-23}$

$C_L = 8.9\,pF$

Therefore, C_L shoubl be less than about 8.9 pF

9.27

calculate capacitances for SPICE input

$W = 100\mu$

nmos

$C_{jsw} = 0.5\, \frac{fF}{\mu} (204\mu)$

$= 102 fF$

$C_j = 0.08\, \frac{fF}{\mu^2}\, 200\mu^2$

$= 16 fF$

$C_{db} = C_{sb} = 102 + 16$

$= 118 fF$

$W = 100\mu$

pmos

$C_{jsw} = 1.5\, \frac{fF}{\mu}\, 204\mu$

$= 306 fF$

$C_j = 0.2\, \frac{fF}{\mu^2}\, 200\mu^2$

$= 40 fF$

$C_{db} = C_{sb} = 346 fF$

$W = 50\mu$

nmos

$C_{jsw} = 0.5\, \frac{fF}{\mu}\, 104\mu$

$= 52 fF$

$C_j = 0.08\, \frac{fF}{\mu^2}\, 100\mu^2$

$= 8 fF$

$C_{db} = C_{sb} = 60 fF$

from SPICE output of forward path gain $a(j\omega)$

$\omega_1 = 1.26\, MHz$

$\measuredangle a(j\omega_1) = -100°$

set $f_o = \frac{1}{|a(j\omega_1)|} = \frac{1}{312} = 3.21m$

$\therefore |T(j\omega_1)| = |a(j\omega_1)|\, f_o = 1$

$\therefore$ phase margin $= 80°$

$f_o = \frac{R_x}{R_x + 1M}$, $R_x = 3.22k$

$\omega_2 = 3.98\, MHz$

$\measuredangle a(j\omega_2) = -120°$

set $f_o = \frac{1}{|a(j\omega_2)|} = \frac{1}{90.1} = 11.1m$

$\therefore |T(j\omega_2)| = |a(j\omega_2)|\, f_o = 1$

$\therefore$ phase margin $= 60°$

$f_o = \frac{R_x}{R_x + 1M}$, $R_x = 11.2k$

$\omega_3 = 6.31\, MHz$

$\measuredangle a(j\omega_3) = -135°$

set $f_o = \frac{1}{|a(j\omega_3)|} = \frac{1}{49.7} = 20.1m$

$\therefore |T(j\omega_3)| = |a(j\omega_3)|\, f_o = 1$

$\therefore$ phase margin $= 45°$

$f_o = \frac{R_x}{R_x + 1M}$, $R_x = 20.5k$

$\omega_4 = 12.6\, MHz$

$\measuredangle a(j\omega_4) = -160°$

set $f_o = \frac{1}{|a(j\omega_4)|} = \frac{1}{16.1} = 62.2m$

$\therefore |T(j\omega_4)| = |a(j\omega_4)|\, f_o = 1$

$\therefore$ phase margin $= 20°$

$f_o = \frac{R_x}{R_x + 1M}$, $R_x = 66.3k$

```
CMOS AMP, FORWARD PATH GAIN = A(JW)
VDD 1 0 5V
VSS 2 0 -5V
******
* ASSUME XD=1U. LEFF=L-XD-2LD=8U-1U-0.6U=6.4U
* ASSUME DRAIN/SOURCE REGIONS ARE 2U WIDE.
******
M1 7 5 4 4 P W=100U L=6.4U
M2 8 6 4 4 P W=100U L=6.4U
M3 7 7 2 2 N_50U W=50U L=6.4U
M4 8 7 2 2 N_50U W=50U L=6.4U
M5 4 3 1 1 P W=100U L=6.4U
M7 9 3 1 1 P W=100U L=6.4U
M8 3 3 1 1 P W=100U L=6.4U
M6 9 8 2 2 N_100U W=100U L=6.4U
IBIAS 3 2 200A
RL 9 0 1MEG

*NMOS: LAMBDA=(DXD/DVDS)/LEFF=0.2U/6.4U=0.0313
*PMOS: LAMBDA=(DXD/DVDS)/LEFF=0.1U/6.4U=0.0156
.MODEL N_50U NMOS KP=60.4U VTO=0.7 LAMBDA=0.0313 TOX=400E-10
+ CGSO=350PF CGDO=350PF CBD=60FF CBS=60FF
.MODEL N_100U NMOS KP=60.4U VTO=0.7 LAMBDA=0.0313 TOX=400E-10
+ CGSO=350PF CGDO=350PF CBD=118FF CBS=118FF
.MODEL P PMOS KP=30.2U VTO=-0.7 LAMBDA=0.0156 TOX=400E-10
+ CGSO=350PF CGDO=350PF CBD=346FF CBS=346FF
VI1 5 0 -48UV
VI2 6 0 0V AC
.TF V(9) VI2
.PLOT AC V(9)
.PLOT AC VP(9)
.AC DEC 10 1K 20MEG
.OPTIONS NOPAGE NOMOD
.OPTIONS VNTOL=1N ABSTOL=1F RELTOL=1U
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

 ******  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000

+0:1        = 5.000E+00 0:2        =-5.000E+00 0:3        = 4.011E+00
+0:4        = 9.029E-01 0:5        =-4.800E-05 0:6        =  0.
+0:7        =-4.092E+00 0:8        =-4.102E+00 0:9        =-4.230E-03

**** MOSFETS

ELEMENT  0:M1       0:M2       0:M3       0:M4       0:M5       0:M7
MODEL    0:P        0:P        0:N_50U    0:N_50U    0:P        0:P
 ID      -1.048E-05 -1.048E-05  1.048E-05  1.048E-05 -2.096E-05 -2.123E-05
 IBS       0.         0.         0.         0.         0.         0.
 IBD      4.995E-14  5.006E-14 -9.078E-15 -8.973E-15  4.097E-14  5.004E-14
 VGS     -9.030E-01 -9.029E-01  9.078E-01  9.078E-01 -9.889E-01 -9.889E-01
 VDS     -4.995E+00 -5.005E+00  9.078E-01  8.973E-01 -4.097E+00 -5.004E+00
 VBS       0.         0.         0.         0.         0.         0.
 VTH     -7.000E-01 -7.000E-01  7.000E-01  7.000E-01 -7.000E-01 -7.000E-01
 VDSAT   -2.030E-01 -2.029E-01  2.078E-01  2.078E-01 -2.889E-01 -2.889E-01
 BETA     5.086E-04  5.087E-04  4.853E-04  4.851E-04  5.020E-04  5.087E-04
 GAM EFF   0.         0.         0.         0.         0.         0.
 GM       1.032E-04  1.032E-04  1.009E-04  1.008E-04  1.451E-04  1.470E-04
 GDS      1.517E-07  1.516E-07  3.189E-07  3.189E-07  3.073E-07  3.073E-07
 GMB       0.         0.         0.         0.         0.         0.
 CDTOT    1.672E-13  1.671E-13  5.890E-14  5.902E-14  1.779E-13  1.671E-13
 CGTOT    4.872E-13  4.872E-13  2.416E-13  2.416E-13  4.729E-13  4.735E-13
 CSTOT    7.493E-13  7.493E-13  2.617E-13  2.617E-13  7.493E-13  7.493E-13
 CBTOT    5.197E-13  5.196E-13  1.231E-13  1.233E-13  5.174E-13  5.060E-13
 CGS      4.033E-13  4.033E-13  2.017E-13  2.017E-13  4.033E-13  4.033E-13
 CGD      3.868E-14  3.869E-14  1.783E-14  1.783E-14  3.802E-14  3.869E-14

ELEMENT  0:M8       0:M6
MODEL    0:P        0:N_100U
 ID      -2.000E-05  2.124E-05
 IBS       0.         0.
 IBD      9.889E-15 -4.996E-14
 VGS     -9.889E-01  8.973E-01
 VDS     -9.889E-01  4.995E+00
 VBS       0.         0.
 VTH     -7.000E-01  7.000E-01
 VDSAT   -2.889E-01  1.973E-01
 BETA     4.792E-04  1.091E-03
 GAM EFF   0.         0.
 GM       1.384E-04  2.153E-04
 GDS      3.073E-07  5.749E-07
 GMB       0.         0.
 CDTOT    2.671E-13  8.252E-14
 CGTOT    4.706E-13  4.885E-13
 CSTOT    7.493E-13  5.213E-13
 CBTOT    6.089E-13  2.083E-13
 CGS      4.033E-13  4.033E-13
 CGD      3.573E-14  3.868E-14
****      SMALL-SIGNAL TRANSFER CHARACTERISTICS

     V(9)/VI2                                  =  2.505E+04
     INPUT RESISTANCE AT          VI2          =  9.999E+19
     OUTPUT RESISTANCE AT V(9)                 =  5.313E+05

 ******  AC ANALYSIS                       TNOM=  27.000 TEMP=  27.000
```

```
     FREQ        V(9)
(A         )     0.            1.000E+04     2.000E+04     3.000E+04     4.000E+04
                 +             +             +             +             +
 9.999E+02  2.50E+04-+------+------+------+------+------A------+------+------+-
 1.258E+03  2.49E+04 +      +      +      +      +      A      +      +      +
 1.584E+03  2.49E+04 +      +      +      +      +      A      +      +      +
 1.995E+03  2.48E+04 +      +      +      +      +      A      +      +      +
 2.511E+03  2.46E+04 +      +      +      +      +      A      +      +      +
 3.162E+03  2.44E+04 +      +      +      +      +     A+      +      +      +
 3.981E+03  2.41E+04 +      +      +      +      +     A+      +      +      +
 5.011E+03  2.36E+04 +      +      +      +      +    A +      +      +      +
 6.309E+03  2.29E+04 +      +      +      +      +   A  +      +      +      +
 7.943E+03  2.19E+04 +      +      +      +      +  A   +      +      +      +
 9.999E+03  2.05E+04-+------+------+------+------+A-----+------+------+------+-
 1.258E+04  1.88E+04 +      +      +      +    A +      +      +      +      +
 1.584E+04  1.68E+04 +      +      +      +  A   +      +      +      +      +
 1.995E+04  1.46E+04 +      +      +     A+      +      +      +      +      +
 2.511E+04  1.24E+04 +      +      +  A   +      +      +      +      +      +
 3.162E+04  1.03E+04 +      +      +A     +      +      +      +      +      +
 3.981E+04  8.50E+03 +      +    A +      +      +      +      +      +      +
 5.011E+04  6.90E+03 +      +  A   +      +      +      +      +      +      +
 6.309E+04  5.56E+03 +      +A     +      +      +      +      +      +      +
 7.943E+04  4.45E+03 +     A+      +      +      +      +      +      +      +
 1.000E+05  3.56E+03-+----A-+------+------+------+------+------+------+------+-
 1.258E+05  2.84E+03 +   A  +      +      +      +      +      +      +      +
 1.584E+05  2.26E+03 +  A   +      +      +      +      +      +      +      +
 1.995E+05  1.79E+03 +  A   +      +      +      +      +      +      +      +
 2.511E+05  1.43E+03 + A    +      +      +      +      +      +      +      +
 3.162E+05  1.13E+03 + A    +      +      +      +      +      +      +      +
 3.981E+05  9.02E+02 +A     +      +      +      +      +      +      +      +
 5.011E+05  7.16E+02 +A     +      +      +      +      +      +      +      +
 6.309E+05  5.68E+02 +A     +      +      +      +      +      +      +      +
 7.943E+05  4.51E+02 +A     +      +      +      +      +      +      +      +
 1.000E+06  3.57E+02-+A-----+------+------+------+------+------+------+------+-
 1.258E+06  2.82E+02 A      +      +      +      +      +      +      +      +
 1.584E+06  2.23E+02 A      +      +      +      +      +      +      +      +
 1.995E+06  1.75E+02 A      +      +      +      +      +      +      +      +
 2.511E+06  1.37E+02 A      +      +      +      +      +      +      +      +
 3.162E+06  1.06E+02 A      +      +      +      +      +      +      +      +
 3.981E+06  8.16E+01 A      +      +      +      +      +      +      +      +
 5.011E+06  6.13E+01 A      +      +      +      +      +      +      +      +
 6.309E+06  4.48E+01 A      +      +      +      +      +      +      +      +
 7.943E+06  3.17E+01 A      +      +      +      +      +      +      +      +
 1.000E+07  2.16E+01-A------+------+------+------+------+------+------+------+-
 1.258E+07  1.42E+01 A      +      +      +      +      +      +      +      +
 1.584E+07  9.19E+00 A      +      +      +      +      +      +      +      +
 1.995E+07  5.86E+00 A      +      +      +      +      +      +      +      +
 2.511E+07  3.72E+00 A      +      +      +      +      +      +      +      +
                     +             +             +             +             +
```

```
     FREQ        VP(9)
(A         )    -2.000E+02    -1.000E+02     0.            1.000E+02     2.000E+02
                     +             +             +             +             +
 9.999E+02 -3.99E+00-+------+------+------+-----A+------+------+------+------+-
 1.258E+03 -5.01E+00 +      +      +      +     A+      +      +      +      +
 1.584E+03 -6.30E+00 +      +      +      +     A+      +      +      +      +
 1.995E+03 -7.92E+00 +      +      +      +     A+      +      +      +      +
 2.511E+03 -9.93E+00 +      +      +      +     A+      +      +      +      +
 3.162E+03 -1.24E+01 +      +      +      +    A +      +      +      +      +
 3.981E+03 -1.55E+01 +      +      +      +    A +      +      +      +      +
 5.011E+03 -1.92E+01 +      +      +      +   A  +      +      +      +      +
 6.309E+03 -2.37E+01 +      +      +      +   A  +      +      +      +      +
 7.943E+03 -2.90E+01 +      +      +      +  A   +      +      +      +      +
 9.999E+03 -3.49E+01-+------+------+------+-A----+------+------+------+------+-
 1.258E+04 -4.13E+01 +      +      +      +A     +      +      +      +      +
 1.584E+04 -4.79E+01 +      +      +      A      +      +      +      +      +
 1.995E+04 -5.44E+01 +      +      +     A+      +      +      +      +      +
 2.511E+04 -6.04E+01 +      +      +     A+      +      +      +      +      +
 3.162E+04 -6.56E+01 +      +      +    A +      +      +      +      +      +
 3.981E+04 -7.04E+01 +      +      +   A  +      +      +      +      +      +
 5.011E+04 -7.44E+01 +      +      +   A  +      +      +      +      +      +
 6.309E+04 -7.76E+01 +      +      +  A   +      +      +      +      +      +
 7.943E+04 -8.03E+01 +      +      +  A   +      +      +      +      +      +
 1.000E+05 -8.26E+01-+------+------+-A----+------+------+------+------+------+-
 1.258E+05 -8.45E+01 +      +      + A    +      +      +      +      +      +
 1.584E+05 -8.61E+01 +      +      + A    +      +      +      +      +      +
 1.995E+05 -8.74E+01 +      +      + A    +      +      +      +      +      +
 2.511E+05 -8.87E+01 +      +      + A    +      +      +      +      +      +
 3.162E+05 -9.99E+01 +      +      +A     +      +      +      +      +      +
 3.981E+05 -9.11E+01 +      +      +A     +      +      +      +      +      +
 5.011E+05 -9.23E+01 +      +      +A     +      +      +      +      +      +
 6.309E+05 -9.37E+01 +      +      +A     +      +      +      +      +      +
 7.943E+05 -9.53E+01 +      +      +A     +      +      +      +      +      +
 1.000E+06 -9.72E+01-+------+------A------+------+------+------+------+------+-
 1.258E+06 -9.94E+01 +      +      A      +      +      +      +      +      +
 1.584E+06 -1.02E+02 +      +      A      +      +      +      +      +      +
 1.995E+06 -1.05E+02 +      +     A+      +      +      +      +      +      +
 2.511E+06 -1.09E+02 +      +     A+      +      +      +      +      +      +
 3.162E+06 -1.14E+02 +      +    A +      +      +      +      +      +      +
 3.981E+06 -1.20E+02 +      +   A  +      +      +      +      +      +      +
 5.011E+06 -1.27E+02 +      +  A   +      +      +      +      +      +      +
 6.309E+06 -1.35E+02 +      + A    +      +      +      +      +      +      +
 7.943E+06 -1.44E+02 +      +A     +      +      +      +      +      +      +
 1.000E+07 -1.53E+02-+------A------+------+------+------+------+------+------+-
 1.258E+07 -1.61E+02 +    A +      +      +      +      +      +      +      +
 1.584E+07 -1.68E+02 +   A  +      +      +      +      +      +      +      +
 1.995E+07 -1.75E+02 +  A   +      +      +      +      +      +      +      +
 2.511E+07  1.79E+02 +      +      +      +      +      +      +    A +      +
                     +             +             +             +             +
```

```
*****
CMOS AMP WITH FB, EXPECT PHASE MARGIN = 80 DEGREES
VDD 1 0 5V
VSS 2 0 -5V
M1 7 5 4 4 P W=100U L=6.4U
M2 8 6 4 4 P W=100U L=6.4U
M3 7 7 2 2 N_50U W=50U L=6.4U
M4 8 7 2 2 N_50U W=50U L=6.4U
M5 4 3 1 1 P W=100U L=6.4U
M7 9 3 1 1 P W=100U L=6.4U
M8 3 3 1 1 P W=100U L=6.4U
M6 9 8 2 2 N_100U W=100U L=6.4U
IBIAS 3 2 20UA
RL 9 5 1MEG
RX 5 0 3.22K

.MODEL N_50U NMOS KP=60.4U VTO=0.7 LAMBDA=0.0313 TOX=400E-10
+ CGSO=350PF CGDO=350PF CBD=60FF CBS=60FF
.MODEL N_100U NMOS KP=60.4U VTO=0.7 LAMBDA=0.0313 TOX=400E-10
+ CGSO=350PF CGDO=350PF CBD=118FF CBS=118FF
.MODEL P PMOS KP=30.2U VTO=-0.7 LAMBDA=0.0156 TOX=400E-10
+ CGSO=350PF CGDO=350PF CBD=346FF CBS=346FF
VI2 6 0 0V AC PULSE 0V 0.39MV 0N 0N 0N 3U
.PLOT TRAN V(9)
.TRAN 0.01U 0.5U
.TF V(9) VI2
.PLOT AC V(9)
.AC DEC 10 100K 20MEG
.OPTIONS NOPAGE NOMOD
.OPTIONS VNTOL=1N ABSTOL=1F RELTOL=1U
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

 ******  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000

+0:1      = 5.000E+00 0:2      =-5.000E+00 0:3      = 4.011E+00
+0:4      = 9.029E-01 0:5      =-4.758E-05 0:6      =  0.
+0:7      =-4.092E+00 0:8      =-4.102E+00 0:9      =-1.482E-02

****      SMALL-SIGNAL TRANSFER CHARACTERISTICS

      V(9)/VI2                                 =  3.077E+02
      INPUT RESISTANCE AT         VI2          =  9.999E+19
      OUTPUT RESISTANCE AT V(9)                =  6.524E+03

 ******  AC ANALYSIS                          TNOM=  27.000 TEMP=  27.000

   FREQ       V(9)
(A       )         0.           1.000E+02     2.000E+02     3.000E+02     4.000E+02
                    +             +             +             +             +
1.000E+05  3.07E+02-+------+------+------+------+------+------+A-----+------+-
1.258E+05  3.06E+02 +      +      +      +      +      +      +A     +      +
1.584E+05  3.05E+02 +      +      +      +      +      +      +A     +      +
1.995E+05  3.04E+02 +      +      +      +      +      +      +A     +      +
2.511E+05  3.03E+02 +      +      +      +      +      +      A      +      +
3.162E+05  3.00E+02 +      +      +      +      +      +      A      +      +
3.981E+05  2.96E+02 +      +      +      +      +      +     A+      +      +
5.011E+05  2.90E+02 +      +      +      +      +      +     A+      +      +
6.309E+05  2.81E+02 +      +      +      +      +      +   A  +      +      +
7.943E+05  2.68E+02 +      +      +      +      +      + A    +      +      +
1.000E+06  2.51E+02-+------+------+------+------+------A------+------+------+-
1.258E+06  2.29E+02 +      +      +      +      +   A  +      +      +      +
1.584E+06  2.03E+02 +      +      +      +      +A     +      +      +      +
1.995E+06  1.75E+02 +      +      +      +  A   +      +      +      +      +
2.511E+06  1.46E+02 +      +      +     A-      +      +      +      +      +
3.162E+06  1.18E+02 +      +      + A    +      +      +      +      +      +
3.981E+06  9.27E+01 +      +     A+      +      +      +      +      +      +
5.011E+06  7.00E+01 +      +  A   +      +      +      +      +      +      +
6.309E+06  5.09E+01 +      A      +      +      +      +      +      +      +
7.943E+06  3.52E+01 +    A +      +      +      +      +      +      +      +
1.000E+07  2.33E+01-+--A---+------+------+------+------+------+------+------+-
1.258E+07  1.49E+01 + A    +      +      +      +      +      +      +      +
1.584E+07  9.36E+00 +A     +      +      +      +      +      +      +      +
1.995E+07  5.82E+00 +A     +      +      +      +      +      +      +      +
2.511E+07  3.63E+00 +A     +      +      +      +      +      +      +      +
                    +             +             +             +             +
```

```
 ******  TRANSIENT ANALYSIS                   TNOM=  27.000 TEMP=  27.000

   TIME       V(9)
(A       )   -5.000E-02       0.            5.000E-02     1.000E-01     1.500E-01
                    +             +             +             +             +
    0.     -1.48E-02-+------+--A---+------+------+------+------+------+------+-
1.000E-08 -1.45E-02 +      + A    +      +      +      +      +      +      +
2.000E-08 -1.18E-02 +      +  A   +      +      +      +      +      +      +
3.000E-08 -7.23E-03 +      +    A +      +      +      +      +      +      +
4.000E-08 -1.20E-03 +      +      A      +      +      +      +      +      +
5.000E-08  5.68E-03 +      +      + A    +      +      +      +      +      +
6.000E-08  1.29E-02 +      +      +   A  +      +      +      +      +      +
7.000E-08  2.01E-02 +      +      +     A+      +      +      +      +      +
8.000E-08  2.70E-02 +      +      +      +A     +      +      +      +      +
9.000E-08  3.36E-02 +      +      +      + A    +      +      +      +      +
1.000E-07  3.97E-02-+------+------+------+---A--+------+------+------+------+-
1.100E-07  4.53E-02 +      +      +      +     A+      +      +      +      +
1.200E-07  5.05E-02 +      +      +      +      A      +      +      +      +
1.300E-07  5.53E-02 +      +      +      +      +A     +      +      +      +
1.400E-07  5.97E-02 +      +      +      +      + A    +      +      +      +
1.500E-07  6.36E-02 +      +      +      +      +   A  +      +      +      +
1.600E-07  6.73E-02 +      +      +      +      +    A +      +      +      +
1.700E-07  7.06E-02 +      +      +      +      +     A+      +      +      +
1.800E-07  7.36E-02 +      +      +      +      +      A      +      +      +
1.900E-07  7.63E-02 +      +      +      +      +      A      +      +      +
2.000E-07  7.89E-02-+------+------+------+------+------+A-----+------+------+-
2.100E-07  8.12E-02 +      +      +      +      +      + A    +      +      +
2.200E-07  8.33E-02 +      +      +      +      +      + A    +      +      +
2.300E-07  8.52E-02 +      +      +      +      +      +  A   +      +      +
2.400E-07  8.69E-02 +      +      +      +      +      +  A   +      +      +
2.500E-07  8.85E-02 +      +      +      +      +      +   A  +      +      +
2.600E-07  9.00E-02 +      +      +      +      +      +   A  +      +      +
2.700E-07  9.13E-02 +      +      +      +      +      +    A +      +      +
2.800E-07  9.25E-02 +      +      +      +      +      +    A +      +      +
2.900E-07  9.36E-02 +      +      +      +      +      +    A +      +      +
3.000E-07  9.46E-02-+------+------+------+------+------+----A-+------+------+-
3.100E-07  9.55E-02 +      +      +      +      +      +     A+      +      +
3.200E-07  9.64E-02 +      +      +      +      +      +     A+      +      +
3.300E-07  9.71E-02 +      +      +      +      +      +     A+      +      +
3.400E-07  9.78E-02 +      +      +      +      +      +     A+      +      +
3.500E-07  9.85E-02 +      +      +      +      +      +      A      +      +
3.600E-07  9.91E-02 +      +      +      +      +      +      A      +      +
3.700E-07  9.96E-02 +      +      +      +      +      +      A      +      +
3.800E-07  1.00E-01 +      +      +      +      +      +      A      +      +
3.900E-07  1.01E-01 +      +      +      +      +      +      A      +      +
4.000E-07  1.01E-01-+------+------+------+------+------+------A------+------+-
4.100E-07  1.01E-01 +      +      +      +      +      +      A      +      +
4.200E-07  1.02E-01 +      +      +      +      +      +      A      +      +
4.300E-07  1.02E-01 +      +      +      +      +      +      +A     +      +
4.400E-07  1.02E-01 +      +      +      +      +      +      +A     +      +
4.500E-07  1.02E-01 +      +      +      +      +      +      +A     +      +
4.600E-07  1.03E-01 +      +      +      +      +      +      +A     +      +
4.700E-07  1.03E-01 +      +      +      +      +      +      +A     +      +
4.800E-07  1.03E-01 +      +      +      +      +      +      +A     +      +
4.900E-07  1.03E-01 +      +      +      +      +      +      +A     +      +
5.000E-07  1.03E-01-+------+------+------+------+------+------+A-----+------+-
                    +             +             +             +             +

*****
STEP RESPONSE SHOWS NO OVERSHOOT

CMOS AMP WITH FB, EXPECT PHASE MARGIN = 60 DEGREES
VDD 1 0 5V
VSS 2 0 -5V
M1 7 5 4 4 P W=100U L=6.4U
M2 8 6 4 4 P W=100U L=6.4U
M3 7 7 2 2 N_50U W=50U L=6.4U
M4 8 7 2 2 N_50U W=50U L=6.4U
M5 4 3 1 1 P W=100U L=6.4U
M7 9 3 1 1 P W=100U L=6.4U
M8 3 3 1 1 P W=100U L=6.4U
M6 9 8 2 2 N_100U W=100U L=6.4U
IBIAS 3 2 20UA
RL 9 5 1MEG
RX 5 0 11.2K

.MODEL N_50U NMOS KP=60.4U VTO=0.7 LAMBDA=0.0313 TOX=400E-10
+ CGSO=350PF CGDO=350PF CBD=60FF CBS=60FF
.MODEL N_100U NMOS KP=60.4U VTO=0.7 LAMBDA=0.0313 TOX=400E-10
+ CGSO=350PF CGDO=350PF CBD=118FF CBS=118FF
.MODEL P PMOS KP=30.2U VTO=-0.7 LAMBDA=0.0156 TOX=400E-10
+ CGSO=350PF CGDO=350PF CBD=346FF CBS=346FF
VI2 6 0 0V AC PULSE 0V 1.11MV 0N 0N 0N 3U
.PLOT TRAN V(9)
.TRAN 0.01U 0.5U
.TF V(9) VI2
.PLOT AC V(9)
.AC DEC 10 100K 20MEG
.OPTIONS NOPAGE NOMOD
.OPTIONS VNTOL=1N ABSTOL=1F RELTOL=1U
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

****      SMALL-SIGNAL TRANSFER CHARACTERISTICS
```

```
     V(9)/VI2                                  =  8.996E+01
     INPUT RESISTANCE AT          VI2          =  9.999E+19
     OUTPUT RESISTANCE AT V(9)                 =  1.907E+03

 ******  AC ANALYSIS                         TNOM=  27.000 TEMP=  27.000

   FREQ       V(9)
(A       )   -5.000E+01       0.          5.000E+01    1.000E+02    1.500E+02
                  +             +             +            +            +
1.000E+05  8.99E+01-+------+------+------+------+------+---A--+------+------+-
1.258E+05  8.99E+01 +      +      +      +      +      +   A  +      +      +
1.584E+05  8.99E+01 +      +      +      +      +      +   A  +      +      +
1.995E+05  8.99E+01 +      +      +      +      +      +   A  +      +      +
2.511E+05  8.99E+01 +      +      +      +      +      +   A  +      +      +
3.162E+05  9.00E+01 +      +      +      +      +      +   A  +      +      +
3.981E+05  9.00E+01 +      +      +      +      +      +   A  +      +      +
5.011E+05  9.00E+01 +      +      +      +      +      +   A  +      +      +
6.309E+05  9.01E+01 +      +      +      +      +      +   A  +      +      +
7.943E+05  9.02E+01 +      +      +      +      +      +   A  +      +      +
1.000E+06  9.03E+01-+------+------+------+------+------+---A--+------+------+-
1.258E+06  9.05E+01 +      +      +      +      +      +   A  +      +      +
1.584E+06  9.08E+01 +      +      +      +      +      +   A  +      +      +
1.995E+06  9.13E+01 +      +      +      +      +      +    A +      +      +
2.511E+06  9.19E+01 +      +      +      +      +      +    A +      +      +
3.162E+06  9.24E+01 +      +      +      +      +      +    A +      +      +
3.981E+06  9.18E+01 +      +      +      +      +      +    A +      +      +
5.011E+06  8.66E+01 +      +      +      +      +      +  A   +      +      +
6.309E+06  7.15E+01 +      +      +      +      +     A+      +      +      +
7.943E+06  4.86E+01 +      +      +      +      A      +      +      +      +
1.000E+07  2.89E+01-+------+------+------+A-----+------+------+------+------+-
1.258E+07  1.64E+01 +      +      +    A +      +      +      +      +      +
1.584E+07  9.29E+00 +      +      +  A   +      +      +      +      +      +
1.995E+07  5.32E+00 +      +      +A     +      +      +      +      +      +
2.511E+07  3.12E+00 +      +      +A     +      +      +      +      +      +
                  +             +             +            +            +

 ******  TRANSIENT ANALYSIS                  TNOM=  27.000 TEMP=  27.000

   TIME       V(9)
(A       )   -5.000E-02       0.          5.000E-02    1.000E-01    1.500E-01
                  +             +             +            +            +
0.        -4.33E-03-+------+-----A+------+------+------+------+------+------+-
1.000E-08 -3.57E-03 +      +     A+      +      +      +      +      +      +
2.000E-08  3.14E-03 +      +      +A     +      +      +      +      +      +
3.000E-08  1.48E-02 +      +      +   A  +      +      +      +      +      +
4.000E-08  3.03E-02 +      +      +      +A     +      +      +      +      +
5.000E-08  4.74E-02 +      +      +      +     A+      +      +      +      +
6.000E-08  6.40E-02 +      +      +      +      +   A  +      +      +      +
7.000E-08  7.85E-02 +      +      +      +      +      +A     +      +      +
8.000E-08  9.00E-02 +      +      +      +      +      +   A  +      +      +
9.000E-08  9.81E-02 +      +      +      +      +      +     A+      +      +
1.000E-07  1.03E-01-+------+------+------+------+------+------+A-----+------+-
1.100E-07  1.05E-01 +      +      +      +      +      +      + A    +      +
1.200E-07  1.06E-01 +      +      +      +      +      +      + A    +      +
1.300E-07  1.04E-01 +      +      +      +      +      +      +A     +      +
1.400E-07  1.02E-01 +      +      +      +      +      +      +A     +      +
1.500E-07  1.00E-01 +      +      +      +      +      +      A      +      +
1.600E-07  9.83E-02 +      +      +      +      +      +      A      +      +
1.700E-07  9.65E-02 +      +      +      +      +      +     A+      +      +
1.800E-07  9.52E-02 +      +      +      +      +      +     A+      +      +
1.900E-07  9.44E-02 +      +      +      +      +      +    A +      +      +
2.000E-07  9.40E-02-+------+------+------+------+------+----A-+------+------+-
2.100E-07  9.39E-02 +      +      +      +      +      +    A +      +      +
2.200E-07  9.41E-02 +      +      +      +      +      +    A +      +      +
2.300E-07  9.44E-02 +      +      +      +      +      +    A +      +      +
2.400E-07  9.47E-02 +      +      +      +      +      +     A+      +      +
2.500E-07  9.50E-02 +      +      +      +      +      +     A+      +      +
2.600E-07  9.53E-02 +      +      +      +      +      +     A+      +      +
2.700E-07  9.55E-02 +      +      +      +      +      +     A+      +      +
2.800E-07  9.57E-02 +      +      +      +      +      +     A+      +      +
2.900E-07  9.57E-02 +      +      +      +      +      +     A+      +      +
3.000E-07  9.58E-02-+------+------+------+------+------+-----A+------+------+-
3.100E-07  9.58E-02 +      +      +      +      +      +     A+      +      +
3.200E-07  9.57E-02 +      +      +      +      +      +     A+      +      +
3.300E-07  9.57E-02 +      +      +      +      +      +     A+      +      +
3.400E-07  9.56E-02 +      +      +      +      +      +     A+      +      +
3.500E-07  9.56E-02 +      +      +      +      +      +     A+      +      +
3.600E-07  9.55E-02 +      +      +      +      +      +     A+      +      +
3.700E-07  9.55E-02 +      +      +      +      +      +     A+      +      +
3.800E-07  9.55E-02 +      +      +      +      +      +     A+      +      +
3.900E-07  9.55E-02 +      +      +      +      +      +     A+      +      +
4.000E-07  9.55E-02-+------+------+------+------+------+-----A+------+------+-
4.100E-07  9.55E-02 +      +      +      +      +      +     A+      +      +
4.200E-07  9.55E-02 +      +      +      +      +      +     A+      +      +
4.300E-07  9.55E-02 +      +      +      +      +      +     A+      +      +
4.400E-07  9.55E-02 +      +      +      +      +      +     A+      +      +
4.500E-07  9.55E-02 +      +      +      +      +      +     A+      +      +
4.600E-07  9.55E-02 +      +      +      +      +      +     A+      +      +
4.700E-07  9.55E-02 +      +      +      +      +      +     A+      +      +
4.800E-07  9.55E-02 +      +      +      +      +      +     A+      +      +
4.900E-07  9.55E-02 +      +      +      +      +      +     A+      +      +
5.000E-07  9.55E-02-+------+------+------+------+------+-----A+------+------+-
                  +             +             +            +            +
```

*****
STEP RESPONSE SHOWS SLIGHT OVERSHOOT

CMOS AMP WITH FB, EXPECT PHASE MARGIN = 45 DEGREES

```
VDD 1 0 5V
VSS 2 0 -5V
M1 7 5 4 4 P W=100U L=6.4U
M2 8 6 4 4 P W=100U L=6.4U
M3 7 7 2 2 N_50U W=50U L=6.4U
M4 8 7 2 2 N_50U W=50U L=6.4U
M5 4 3 1 1 P W=100U L=6.4U
M7 9 3 1 1 P W=100U L=6.4U
M8 3 3 1 1 P W=100U L=6.4U
M6 9 8 2 2 N_100U W=100U L=6.4U
IBIAS 3 2 20UA
RL 9 5 1MEG
RX 5 0 20.5K

.MODEL N_50U NMOS KP=60.4U VTO=0.7 LAMBDA=0.0313 TOX=400E-10
+ CGSO=350PF CGDO=350PF CBD=60FF CBS=60FF
.MODEL N_100U NMOS KP=60.4U VTO=0.7 LAMBDA=0.0313 TOX=400E-10
+ CGSO=350PF CGDO=350PF CBD=118FF CBS=118FF
.MODEL P PMOS KP=30.2U VTO=-0.7 LAMBDA=0.0156 TOX=400E-10
+ CGSO=350PF CGDO=350PF CBD=346FF CBS=346FF
VI2 6 0 0V AC PULSE 0V 2MV 0N 0N 0N 3U
.PLOT TRAN V(9)
.TRAN 0.01U 0.5U
.TF V(9) VI2
.PLOT AC V(9)
.AC DEC 10 100K 20MEG
.OPTIONS NOPAGE NOMOD
.OPTIONS VNTOL=1N ABSTOL=1F RELTOL=1U
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

****     SMALL-SIGNAL TRANSFER CHARACTERISTICS

     V(9)/VI2                                  =  4.968E+01
     INPUT RESISTANCE AT          VI2          =  9.999E+19
     OUTPUT RESISTANCE AT V(9)                 =  1.053E+03

 ******  AC ANALYSIS                         TNOM=  27.000 TEMP=  27.000

   FREQ       V(9)
(A       )   -5.000E+01       0.          5.000E+01    1.000E+02    1.500E+02
                  +             +             +            +            +
1.000E+05  4.96E+01-+------+------+------+------A------+------+------+------+-
1.258E+05  4.96E+01 +      +      +      +      A      +      +      +      +
1.584E+05  4.97E+01 +      +      +      +      A      +      +      +      +
1.995E+05  4.97E+01 +      +      +      +      A      +      +      +      +
2.511E+05  4.97E+01 +      +      +      +      A      +      +      +      +
3.162E+05  4.97E+01 +      +      +      +      A      +      +      +      +
3.981E+05  4.97E+01 +      +      +      +      A      +      +      +      +
5.011E+05  4.98E+01 +      +      +      +      A      +      +      +      +
6.309E+05  4.98E+01 +      +      +      +      A      +      +      +      +
7.943E+05  5.00E+01 +      +      +      +      A      +      +      +      +
1.000E+06  5.01E+01-+------+------+------+------A------+------+------+------+-
1.258E+06  5.05E+01 +      +      +      +      A      +      +      +      +
1.584E+06  5.10E+01 +      +      +      +      A      +      +      +      +
1.995E+06  5.18E+01 +      +      +      +      +A     +      +      +      +
2.511E+06  5.32E+01 +      +      +      +      +A     +      +      +      +
3.162E+06  5 57E+01 +      +      +      +      + A    +      +      +      +
3.981E+06  6.05E+01 +      +      +      +      +  A   +      +      +      +
5.011E+06  7.04E+01 +      +      +      +      +     A+      +      +      +
6.309E+06  9.10E+01 +      +      +      +      +      +   A  +      +      +
7.943E+06  8.84E+01 +      +      +      +      +      +   A  +      +      +
1.000E+07  3.88E+01-+------+------+------+---A--+------+------+------+------+-
1.258E+07  1.71E+01 +      +      +    A +      +      +      +      +      +
1.584E+07  8 35E+00 +      +      + A    +      +      +      +      +      +
1.995E+07  4.36E+00 +      +      +A     +      +      +      +      +      +
2.511E+07  2.47E+00 +      +      +A     +      +      +      +      +      +
                  +             +             +            +            +
```

9-25

```
******  TRANSIENT ANALYSIS                    TNOM=  27.000 TEMP=  27.000

   TIME      V(9)
(A       )  -5.000E-02     0.           5.000E-02     1.000E-01     1.500E-01
                    +             +             +             +             +
 0.       -2.39E-03-+------+-----A+------+------+------+------+------+------+-
 1.000E-08 -1.22E-03 +      +      A      +      +      +      +      +      +
 2.000E-08 9.46E-03 +      +      +  A   +      +      +      +      +      +
 3.000E-08 2.82E-02 +      +      +      +A     +      +      +      +      +
 4.000E-08 5.34E-02 +      +      +      +      +A     +      +      +      +
 5.000E-08 8.08E-02 +      +      +      +      +      + A    +      +      +
 6.000E-08 1.06E-01 +      +      +      +      +      +      + A    +      +
 7.000E-08 1.24E-01 +      +      +      +      +      +      +      A      +
 8.000E-08 1.33E-01 +      +      +      +      +      +      +      + A    +
 9.000E-08 1.34E-01 +      +      +      +      +      +      +      +  A   +
 1.000E-07 1.27E-01-+------+------+------+------+------+------+------+A-----+-
 1.100E-07 1.15E-01 +      +      +      +      +      +      +   A  +      +
 1.200E-07 1.02E-01 +      +      +      +      +      +      +A     +      +
 1.300E-07 8.98E-02 +      +      +      +      +      +   A  +      +      +
 1.400E-07 8.11E-02 +      +      +      +      +      + A    +      +      +
 1.500E-07 7.70E-02 +      +      +      +      +      +A     +      +      +
 1.600E-07 7.74E-02 +      +      +      +      +      +A     +      +      +
 1.700E-07 8.16E-02 +      +      +      +      +      + A    +      +      +
 1.800E-07 8.81E-02 +      +      +      +      +      +   A  +      +      +
 1.900E-07 9.52E-02 +      +      +      +      +      +     A+      +      +
 2.000E-07 1.01E-01-+------+------+------+------+------+------A------+------+-
 2.100E-07 1.06E-01 +      +      +      +      +      +      + A    +      +
 2.200E-07 1.08E-01 +      +      +      +      +      +      + A    +      +
 2.300E-07 1.07E-01 +      +      +      +      +      +      + A    +      +
 2.400E-07 1.05E-01 +      +      +      +      +      +      +A     +      +
 2.500E-07 1.01E-01 +      +      +      +      +      +      A      +      +
 2.600E-07 9.74E-02 +      +      +      +      +      +     A+      +      +
 2.700E-07 9.42E-02 +      +      +      +      +      +    A +      +      +
 2.800E-07 9.21E-02 +      +      +      +      +      +    A +      +      +
 2.900E-07 9.13E-02 +      +      +      +      +      +    A +      +      +
 3.000E-07 9.17E-02-+------+------+------+------+------+----A-+------+------+-
 3.100E-07 9.31E-02 +      +      +      +      +      +    A +      +      +
 3.200E-07 9.50E-02 +      +      +      +      +      +     A+      +      +
 3.300E-07 9.70E-02 +      +      +      +      +      +     A+      +      +
 3.400E-07 9.86E-02 +      +      +      +      +      +      A      +      +
 3.500E-07 9.97E-02 +      +      +      +      +      +      A      +      +
 3.600E-07 1.00E-01 +      +      +      +      +      +      A      +      +
 3.700E-07 9.97E-02 +      +      +      +      +      +      A      +      +
 3.800E-07 9.89E-02 +      +      +      +      +      +      A      +      +
 3.900E-07 9.79E-02 +      +      +      +      +      +     A+      +      +
 4.000E-07 9.68E-02-+------+------+------+------+------+-----A+------+------+-
 4.100E-07 9.60E-02 +      +      +      +      +      +     A+      +      +
 4.200E-07 9.55E-02 +      +      +      +      +      +     A+      +      +
 4.300E-07 9.54E-02 +      +      +      +      +      +     A+      +      +
 4.400E-07 9.56E-02 +      +      +      +      +      +     A+      +      +
 4.500E-07 9.60E-02 +      +      +      +      +      +     A+      +      +
 4.600E-07 9.66E-02 +      +      +      +      +      +     A+      +      +
 4.700E-07 9.71E-02 +      +      +      +      +      +     A+      +      +
 4.800E-07 9.75E-02 +      +      +      +      +      +     A+      +      +
 4.900E-07 9.78E-02 +      +      +      +      +      +     A+      +      +
 5.000E-07 9.78E-02-+------+------+------+------+------+-----A+------+------+-
                    +             +             +             +             +
*****
STEP RESPONSE SHOWS SIGNIFICANT OVERSHOOT AND LONG SETTLING TIME

CMOS AMP WITH FB, EXPECT PHASE MARGIN = 20 DEGREES
VDD 1 0 5V
VSS 2 0 -5V
M1 7 5 4 4 P W=100U L=6.4U
M2 8 6 4 4 P W=100U L=6.4U
M3 7 7 2 2 N_50U W=50U L=6.4U
M4 8 7 2 2 N_50U W=50U L=6.4U
M5 4 3 1 1 P W=100U L=6.4U
M7 9 3 1 1 P W=100U L=6.4U
M8 3 3 1 1 P W=100U L=6.4U
M6 9 8 2 2 N_100U W=100U L=6.4U
IBIAS 3 2 20UA
RL 9 5 1MEG
RX 5 0 30K

.MODEL N_50U NMOS KP=60.4U VTO=0.7 LAMBDA=0.0313 TOX=400E-10
+ CGSO=350PF CGDO=350PF CBD=60FF CBS=60FF
.MODEL N_100U NMOS KP=60.4U VTO=0.7 LAMBDA=0.0313 TOX=400E-10
+ CGSO=350PF CGDO=350PF CBD=118FF CBS=118FF
.MODEL P PMOS KP=30.2U VTO=-0.7 LAMBDA=0.0156 TOX=400E-10
+ CGSO=350PF CGDO=350PF CBD=346FF CBS=346FF
VI2 6 0 0V AC PULSE 0V 2.92MV 0N 0N 0N 3U
.PLOT TRAN V(9)
.TRAN 0.01U 1.5U
.TF V(9) VI2
.PLOT AC V(9)
.AC DEC 10 100K 20MEG
.OPTIONS NOPAGE NOMOD
.OPTIONS VNTOL=1N ABSTOL=1F RELTOL=1U
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

****     SMALL-SIGNAL TRANSFER CHARACTERISTICS

      V(9)/VI2                                  =  3.428E+01

      INPUT RESISTANCE AT           VI2         =  9.999E+19
      OUTPUT RESISTANCE AT V(9)                 =  7.270E+02

******  AC ANALYSIS                           TNOM=  27.000 TEMP=  27.000

   FREQ      V(9)
(A       )      0.          1.000E+02     2.000E+02     3.000E+02     4.000E+02
                    +             +             +             +             +
 1.000E+05 3.42E+01-+----A-+------+------+------+------+------+------+------+-
 1.258E+05 3.42E+01 +    A +      +      +      +      +      +      +      +
 1.584E+05 3.42E+01 +    A +      +      +      +      +      +      +      +
 1.995E+05 3.43E+01 +    A +      +      +      +      +      +      +      +
 2.511E+05 3.43E+01 +    A +      +      +      +      +      +      +      +
 3.162E+05 3.43E+01 +    A +      +      +      +      +      +      +      +
 3.981E+05 3.43E+01 +    A +      +      +      +      +      +      +      +
 5.011E+05 3.43E+01 +    A +      +      +      +      +      +      +      +
 6.309E+05 3.44E+01 +    A +      +      +      +      +      +      +      +
 7.943E+05 3.44E+01 +    A +      +      +      +      +      +      +      +
 1.000E+06 3.45E+01-+----A-+------+------+------+------+------+------+------+-
 1.258E+06 3.47E+01 +    A +      +      +      +      +      +      +      +
 1.584E+06 3.50E+01 +    A +      +      +      +      +      +      +      +
 1.995E+06 3.55E+01 +    A +      +      +      +      +      +      +      +
 2.511E+06 3.64E+01 +    A +      +      +      +      +      +      +      +
 3.162E+06 3.79E+01 +    A +      +      +      +      +      +      +      +
 3.981E+06 4.10E+01 +     A+      +      +      +      +      +      +      +
 5.011E+06 4.77E+01 +      A      +      +      +      +      +      +      +
 6.309E+06 6.82E+01 +      +  A   +      +      +      +      +      +      +
 7.943E+06 2.76E+02 +      +      +      +      +      +   A  +      +      +
 1.000E+07 4.98E+01-+------A------+------+------+------+------+------+------+-
 1.258E+07 1.58E+01 + A    +      +      +      +      +      +      +      +
 1.584E+07 6.94E+00 +A     +      +      +      +      +      +      +      +
 1.995E+07 3.51E+00 A      +      +      +      +      +      +      +      +
 2.511E+07 2.06E+00 A      +      +      +      +      +      +      +      +
                    +             +             +             +             +

******  TRANSIENT ANALYSIS                    TNOM=  27.000 TEMP=  27.000

   TIME      V(9)
(A       )  -1.000E-01     0.           1.000E-01     2.000E-01     3.000E-01
                    +             +             +             +             +
 0.       -1.65E-03-+------+------A------+------+------+------+------+------+-
 1.000E-08 -1.13E-04 +      +      A      +      +      +      +      +      +
 2.000E-08 1.41E-02 +      +      + A    +      +      +      +      +      +
 3.000E-08 3.91E-02 +      +      +    A +      +      +      +      +      +
 4.000E-08 7.18E-02 +      +      +      +  A   +      +      +      +      +
 5.000E-08 1.03E-01 +      +      +      +      A      +      +      +      +
 6.000E-08 1.32E-01 +      +      +      +      +    A +      +      +      +
 7.000E-08 1.54E-01 +      +      +      +      +      +A     +      +      +
 8.000E-08 1.57E-01 +      +      +      +      +      +A     +      +      +
 9.000E-08 1.55E-01 +      +      +      +      +      +A     +      +      +
 1.000E-07 1.32E-01-+------+------+------+------+----A-+------+------+------+-
 1.100E-07 1.09E-01 +      +      +      +      +A     +      +      +      +
 1.200E-07 8.04E-02 +      +      +      +   A  +      +      +      +      +
 1.300E-07 5.58E-02 +      +      +      +A     +      +      +      +      +
 1.400E-07 4.59E-02 +      +      +     A+      +      +      +      +      +
 1.500E-07 4.07E-02 +      +      +     A+      +      +      +      +      +
 1.600E-07 5.63E-02 +      +      +      +A     +      +      +      +      +
 1.700E-07 7.39E-02 +      +      +      +  A   +      +      +      +      +
 1.800E-07 1.01E-01 +      +      +      +      A      +      +      +      +
 1.900E-07 1.25E-01 +      +      +      +      +    A +      +      +      +
 2.000E-07 1.41E-01-+------+------+------+------+-----A+------+------+------+-
 2.100E-07 1.53E-01 +      +      +      +      +      A      +      +      +
 2.200E-07 1.44E-01 +      +      +      +      +     A+      +      +      +
 2.300E-07 1.34E-01 +      +      +      +      +    A +      +      +      +
 2.400E-07 1.10E-01 +      +      +      +      +A     +      +      +      +
 2.500E-07 8.67E-02 +      +      +      +    A +      +      +      +      +
 2.600E-07 6.80E-02 +      +      +      +  A   +      +      +      +      +
 2.700E-07 5.15E-02 +      +      +      A      +      +      +      +      +
 2.800E-07 5.33E-02 +      +      +      A      +      +      +      +      +
 2.900E-07 5.67E-02 +      +      +      +A     +      +      +      +      +
 3.000E-07 7.63E-02-+------+------+------+---A--+------+------+------+------+-
 3.100E-07 9.60E-02 +      +      +      +     A+      +      +      +      +
 3.200E-07 1.16E-01 +      +      +      +      + A    +      +      +      +
 3.300E-07 1.35E-01 +      +      +      +      +    A +      +      +      +
 3.400E-07 1.39E-01 +      +      +      +      +     A+      +      +      +
 3.500E-07 1.43E-01 +      +      +      +      +     A+      +      +      +
 3.600E-07 1.28E-01 +      +      +      +      +   A  +      +      +      +
 3.700E-07 1.13E-01 +      +      +      +      + A    +      +      +      +
 3.800E-07 9.28E-02 +      +      +      +     A+      +      +      +      +
 3.900E-07 7.28E-02 +      +      +      +  A   +      +      +      +      +
 4.000E-07 6.42E-02-+------+------+------+-A----+------+------+------+------+-
 4.100E-07 5.57E-02 +      +      +      +A     +      +      +      +      +
 4.200E-07 6.52E-02 +      +      +      + A    +      +      +      +      +
 4.300E-07 7.47E-02 +      +      +      +  A   +      +      +      +      +
 4.400E-07 9.33E-02 +      +      +      +     A+      +      +      +      +
 4.500E-07 1.12E-01 +      +      +      +      + A    +      +      +      +
 4.600E-07 1.24E-01 +      +      +      +      +  A   +      +      +      +
 4.700E-07 1.36E-01 +      +      +      +      +    A +      +      +      +
 4.800E-07 1.32E-01 +      +      +      +      +    A +      +      +      +
 4.900E-07 1.28E-01 +      +      +      +      +   A  +      +      +      +
 5.000E-07 1.12E-01-+------+------+------+------+-A----+------+------+------+-
 5.100E-07 9.61E-02 +      +      +      +     A+      +      +      +      +
 5.200E-07 8.19E-02 +      +      +      +   A  +      +      +      +      +
 5.300E-07 6.79E-02 +      +      +      +  A   +      +      +      +      +
 5.400E-07 6.67E-02 +      +      +      + A    +      +      +      +      +
 5.500E-07 6.65E-02 +      +      +      + A    +      +      +      +      +
 5.600E-07 7.83E-02 +      +      +      +   A  +      +      +      +      +
 5.700E-07 9.12E-02 +      +      +      +     A+      +      +      +      +
```

5.800E-07	1.06E-01
5.900E-07	1.20E-01
6.000E-07	1.26E-01
6.100E-07	1.30E-01
6.200E-07	1.22E-01
6.300E-07	1.13E-01
6.400E-07	9.96E-02
6.500E-07	8.53E-02
6.600E-07	7.70E-02
6.700E-07	6.98E-02
6.800E-07	7.32E-02
6.900E-07	7.87E-02
7.000E-07	9.03E-02
7.100E-07	1.03E-01
7.200E-07	1.13E-01
7.300E-07	1.22E-01
7.400E-07	1.23E-01
7.500E-07	1.21E-01
7.600E-07	1.12E-01
7.700E-07	1.01E-01
7.800E-07	9.07E-02
7.900E-07	8.03E-02
8.000E-07	7.68E-02
8.100E-07	7.56E-02
8.200E-07	8.14E-02
8.300E-07	8.98E-02
8.400E-07	9.97E-02
8.500E-07	1.10E-01
8.600E-07	1.16E-01
8.700E-07	1.20E-01
8.800E-07	1.17E-01
8.900E-07	1.11E-01
9.000E-07	1.03E-01
9.100E-07	9.29E-02
9.200E-07	8.57E-02
9.300E-07	7.99E-02
9.400E-07	7.99E-02
9.500E-07	8.29E-02
9.600E-07	8.96E-02
9.700E-07	9.84E-02
9.800E-07	1.06E-01
9.900E-07	1.13E-01
1.000E-06	1.15E-01
1.010E-06	1.15E-01
1.020E-06	1.10E-01
1.030E-06	1.03E-01
1.040E-06	9.58E-02
1.050E-06	8.83E-02
1.060E-06	8.41E-02
1.070E-06	8.25E-02
1.080E-06	8.48E-02
1.090E-06	9.01E-02
1.100E-06	9.66E-02
1.110E-06	1.04E-01
1.120E-06	1.09E-01
1.130E-06	1.13E-01
1.140E-06	1.13E-01
1.150E-06	1.09E-01
1.160E-06	1.04E-01
1.170E-06	9.71E-02
1.180E-06	9.13E-02
1.190E-06	8.68E-02
1.200E-06	8.52E-02
1.210E-06	8.67E-02
1.220E-06	9.03E-02
1.230E-06	9.62E-02
1.240E-06	1.02E-01
1.250E-06	1.07E-01
1.260E-06	1.10E-01
1.270E-06	1.10E-01
1.280E-06	1.08E-01
1.290E-06	1.04E-01
1.300E-06	9.87E-02
1.310E-06	9.32E-02
1.320E-06	8.93E-02
1.330E-06	8.76E-02
1.340E-06	8.79E-02
1.350E-06	9.12E-02
1.360E-06	9.53E-02
1.370E-06	1.01E-01
1.380E-06	1.05E-01
1.390E-06	1.09E-01
1.400E-06	1.09E-01
1.410E-06	1.07E-01
1.420E-06	1.04E-01
1.430E-06	9.92E-02
1.440E-06	9.49E-02
1.450E-06	9.14E-02
1.460E-06	8.92E-02
1.470E-06	8.98E-02
1.480E-06	9.14E-02
1.490E-06	9.54E-02
1.500E-06	9.96E-02

*****

TRANSFER FUNCTION HAS PEAKING
THE EXPECTED RX=66.3K CAUSES OSCILLATION
(I.E. NEGATIVE PHASE MARGIN), BECAUSE WE DID NOT TAKE
INTO ACCOUNT THE PHASE CONTRIBUTION FROM THE POLE
IN THE FEEDBACK PATH BY RX AND INPUT CAPACITANCE
OF M1.
WE USE RX=30K HERE.
FINDING THE EXACT RX VALUE FOR THE PHASE MARGIN OF 20 DEGREES
IS NOT AS IMPORTANT AS OBSERVING THIS GENERAL TREND:
THE SMALLER THE PHASE MARGIN,
THE HIGHER THE OVERSHOOT & THE LONGER THE SETTLING TIME
IN THE STEP RESPONSE.

9.28

dc bias

$I_D = 20\mu A = I_1$

in all devices

gain

$A_V = G_m R_o$

$g_{m3} = \sqrt{2 k_n' \frac{W}{L} I_3}$

$= \sqrt{2(60\mu)(\frac{20}{1})(20\mu)}$

$= 219 \mu A/V$

$g_{m6} = \sqrt{2(20\mu)(\frac{60}{1})(20\mu)}$

$= 219 \mu A/V$

$V_{GS_3} = \sqrt{\frac{2 I_3}{k_n'(\frac{W}{L})_3}} + V_{t_3}$

$|V_{GS_6}| = \sqrt{\frac{2 I_6}{k_p'(\frac{W}{L})_6}} + |V_{t_6}|$

$V_{t_3} = |V_{t_6}|$

$k_n'(\frac{W}{L})_3 = k_p'(\frac{W}{L})_6$

$\mu_n C_{ox}(\frac{W}{L})_n = \mu_p C_{ox}(\frac{W}{L})_p$

$\therefore V_{GS_3} = |V_{GS_6}|$

$\therefore$ m_3 & m_6 share V_i equally

$\therefore A_V = G_m R_o$

$= g_{m3}(R_{o14} \| R_{o15})$

$g_{m14} = \sqrt{2(20\mu)(\frac{300\mu}{1\mu})(20\mu)}$

$= 490 \mu A/V$

$g_{m15} = \sqrt{2(60\mu)(\frac{100}{1})(20\mu)}$

$= 490 \mu A/V$

$R_{o14} = r_{o14}(1 + g_{m14} r_{o13})$

$= 1M(1 + 490\mu \, 1M)$

$= 491 M$

$r_{o14} = r_{o13} = \frac{1}{\lambda I_D}$

$= \frac{1}{0.05(20\mu)} = 1M$

$R_{o14} \| R_{o15} = 245 M$

$A_V = g_{m3}(245 M)$

$= 219\mu(245 M)$

$= 53700$

high freq gain

$A_V = g_{m3} \frac{1}{j\omega C_L}$

$|A_V| = 1 = \frac{g_{m3}}{\omega_1 C_L}$

unity gain $\omega_1 = \frac{g_{m3}}{C_L} = \frac{219\mu}{10p}$

$= 21.9 M \text{ rad/s}$

$\to$ 3.5 MHz unity gain freq

m_2, m_3, m_6, m_7 on

$I_o = |I_{14}| - I_{15} = |I_{10}| - I_{11}$

$= I_3 - |I_7|$

$= \frac{\mu_n C_{ox}(\frac{W}{L})_3}{2}(V_{GS_{3bias}} + \frac{V_i}{2} - V_{t_3})^2$

$- \frac{\mu_p C_{ox}(\frac{W}{L})_7}{2}(V_{GS_{7bias}} - \frac{V_i}{2} - V_{t_7})^2$

$= \frac{\mu_n C_{ox}(\frac{W}{L})_3}{2}\Big(2\frac{V_i}{2}(V_{GS_{3bias}} - V_{t_3})$

$- -2\frac{V_i}{2}(V_{GS_{7bias}} - V_{t_7})\Big)$

$I_o = \mu_n C_{ox}(\frac{W}{L})_3 (V_{GS_{3bias}} - V_{t_3}) V_i$

$= g_{m3} V_i$

$= (219 \mu A/V) V_i$

linear relation

$G_m = \frac{I_o}{V_i} = g_{m3}$

$\mu_n C_{ox}(\frac{W}{L})_3 = \mu_p C_{ox}(\frac{W}{L})_7$

$V_{t_3} = V_{t_7}$

$V_{GS_{3bias}} = V_{GS_{7bias}}$

m_2, m_7 cut off

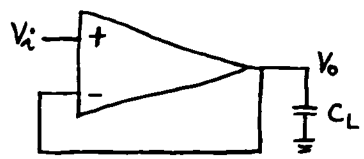
$I_7 = 0$ for $V_{GS_{7bias}} - V_{t7} \le \frac{V_i}{2}$

$2(V_{GS_{bias}} - V_{t7}) \le V_i$

$2\sqrt{\frac{2 I_7}{\mu_p C_{ox} (\frac{W}{L})_7}} = 0.365V \le V_i$

$I_0 = I_3 = \frac{1}{2}\mu_n C_{ox} (\frac{W}{L})_3 (V_{GS_{3bias}} + \frac{V_i}{2} - V_t)^2$

square relation

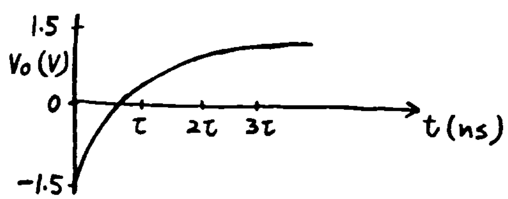


$\frac{V_0}{V_i} = \frac{1}{1+s\tau}$

$\tau = \frac{1}{\omega_1} = \frac{1}{21.9M\,rad/s} = 45.7\ ns$

↑ unity gain freq

$V_0 = -1.5 + 3(1 - e^{-\frac{t}{45.7ns}})$



t	V_0
45.7ns(1τ)	0.4V
91.4ns(2τ)	1.1V
137ns(3τ)	1.4V

peak current to C_L

$\Delta V_i = 3V$

$I_{D3} = \frac{\mu_n C_{ox}}{2} (\frac{W}{L})_3 (V_{GS_{3bias}} + \frac{\Delta V_i}{2} - V_t)^2$

$= \frac{60\mu}{2} \frac{20}{1} (0.183 + 1.5)^2$

$= 1.7mA$

$V_{GS_{3bias}} - V_t = \sqrt{\frac{2 I_3}{\mu_n C_{ox} (\frac{W}{L})_3}} = 0.183V$

```
CROSS-COUPLED MOS QUAD
VDD 1 0 5V
VSS 2 0 -5V
M1 1 19 5 2 N W=20U L=1U
M2 1 19 7 2 N W=20U L=1U
M3 14 4 8 2 N W=20U L=1U
M4 1 4 6 2 N W=20U L=1U
M5 9 9 5 1 P W=60U L=1U
M6 2 9 8 1 P W=60U L=1U
M7 11 12 7 1 P W=60U L=1U
M8 12 12 6 1 P W=60U L=1U
M11 11 11 17 2 N W=100U L=1U
M12 17 17 2 2 N W=100U L=1U
M15 19 11 18 2 N W=100U L=1U
M16 18 17 2 2 N W=100U L=1U
M9 15 15 1 1 P W=300U L=1U
M10 14 14 15 1 P W=300U L=1U
M13 16 15 1 1 P W=300U L=1U
M14 29 14 16 1 P W=300U L=1U
VDUMMY 29 19 0V
IBIAS1 9 2 20UA
IBIAS2 12 2 20UA
CL 19 0 10PF
.MODEL N NMOS KP=60U VTO=0.7 LAMBDA=0.05
.MODEL P PMOS KP=20U VTO=-0.7 LAMBDA=0.05
VI2 4 0 PULSE -1.5 1.5 0N 0N 0N 3US
.PLOT TRAN V(19)
.PLOT TRAN I(VDUMMY)
.TRAN 0.005U 0.25U
.OPTIONS NOPAGE NOMOD
.OPTIONS VNTOL=1N ABSTOL=1F RELTOL=1U
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END
```

****** OPERATING POINT INFORMATION   TNOM= 27.000 TEMP= 27.000

+0:1 = 5.000E+00	0:2 =-5.000E+00	0:4 =-1.500E+00	
+0:5 =-2.355E+00	0:6 =-2.356E+00	0:7 =-2.356E+00	
+0:8 =-2.361E+00	0:9 =-3.234E+00	0:11 =-3.439E+00	
+0:12 =-3.234E+00	0:14 = 3.439E+00	0:15 = 4.219E+00	
+0:16 = 4.211E+00	0:17 =-4.219E+00	0:18 =-4.216E+00	
+0:19 =-1.499E+00	0:29 =-1.499E+00		

**** MOSFETS

ELEMENT	0:M1	0:M2	0:M3	0:M4	0:M5	0:M6
MODEL	0:N	0:N	0:N	0:N	0:P	0:P
ID	2.000E-05	2.020E-05	2.020E-05	2.000E-05	-2.000E-05	-2.020E-05
IBS	-2.645E-14	-2.644E-14	-2.638E-14	-2.644E-14	7.355E-14	7.362E-14
IBD	-1.000E-13	-1.000E-13	-8.439E-14	-1.000E-13	8.234E-14	1.000E-13
VGS	8.561E-01	8.569E-01	8.615E-01	8.561E-01	-8.787E-01	-8.725E-01
VDS	7.355E+00	7.356E+00	5.800E+00	7.356E+00	-8.787E-01	-2.638E+00
VBS	-2.644E+00	-2.643E+00	-2.638E+00	-2.643E+00	7.355E+00	7.361E+00
VTH	7.000E-01	7.000E-01	7.000E-01	7.000E-01	-7.000E-01	-7.000E-01
VDSAT	1.561E-01	1.569E-01	1.615E-01	1.561E-01	-1.787E-01	-1.725E-01
BETA	1.641E-03	1.641E-03	1.548E-03	1.641E-03	1.253E-03	1.358E-03
GAM EFF	0.	0.	0.	0.	0.	0.
GM	2.562E-04	2.575E-04	2.501E-04	2.562E-04	2.239E-04	2.342E-04
GDS	7.311E-07	7.385E-07	7.828E-07	7.311E-07	9.579E-07	8.922E-07
GMB	0.	0.	0.	0.	0.	0.
CDTOT	0.	0.	0.	0.	0.	0.
CGTOT	0.	0.	0.	0.	0.	0.
CSTOT	0.	0.	0.	0.	0.	0.
CBTOT	0.	0.	0.	0.	0.	0.
CGS	0.	0.	0.	0.	0.	0.
CGD	0.	0.	0.	0.	0.	0.

ELEMENT	0:M7	0:M8	0:M11	0:M12	0:M15	0:M16
MODEL	0:P	0:P	0:N	0:N	0:N	0:N
ID	-2.020E-05	-2.000E-05	2.020E-05	2.020E-05	2.021E-05	2.021E-05
IBS	7.356E-14	7.356E-14	-7.805E-15	0.	-7.840E-15	0.
IBD	8.439E-14	8.235E-14	-1.561E-14	-7.805E-15	-3.501E-14	-7.840E-15
VGS	-8.787E-01	-8.787E-01	7.805E-01	7.805E-01	7.770E-01	7.805E-01
VDS	-1.082E+00	-8.787E-01	7.805E-01	7.805E-01	2.716E+00	7.840E-01
VBS	7.356E+00	7.356E+00	-7.805E-01	0.	-7.840E-01	0.
VTH	-7.000E-01	-7.000E-01	7.000E-01	7.000E-01	7.000E-01	7.000E-01
VDSAT	-1.787E-01	-1.787E-01	8.050E-02	8.050E-02	7.700E-02	8.050E-02
BETA	1.265E-03	1.253E-03	6.234E-03	6.234E-03	6.815E-03	6.235E-03
GAM EFF	0.	0.	0.	0.	0.	0.
GM	2.261E-04	2.239E-04	5.019E-04	5.019E-04	5.248E-04	5.020E-04
GDS	9.582E-07	9.579E-07	9.722E-07	9.722E-07	8.894E-07	9.722E-07
GMB	0.	0.	0.	0.	0.	0.
CDTOT	0.	0.	0.	0.	0.	0.
CGTOT	0.	0.	0.	0.	0.	0.
CSTOT	0.	0.	0.	0.	0.	0.
CBTOT	0.	0.	0.	0.	0.	0.
CGS	0.	0.	0.	0.	0.	0.
CGD	0.	0.	0.	0.	0.	0.

ELEMENT	0:M9	0:M10	0:M13	0:M14
MODEL	0:P	0:P	0:P	0:P
ID	-2.020E-05	-2.020E-05	-2.021E-05	-2.021E-05
IBS	0.	7.805E-15	0.	7.886E-15
IBD	7.805E-15	1.561E-14	7.886E-15	6.499E-14
VGS	-7.805E-01	-7.805E-01	-7.805E-01	-7.724E-01
VDS	-7.805E-01	-7.805E-01	-7.886E-01	-5.710E+00
VBS	0.	7.805E-01	0.	7.886E-01
VTH	-7.000E-01	-7.000E-01	-7.000E-01	-7.000E-01
VDSAT	-8.050E-02	-8.050E-02	-8.050E-02	-7.238E-02
BETA	6.234E-03	6.234E-03	6.237E-03	7.713E-03
GAM EFF	0.	0.	0.	0.
GM	5.018E-04	5.018E-04	5.020E-04	5.583E-04
GDS	9.719E-07	9.719E-07	9.719E-07	7.859E-07
GMB	0.	0.	0.	0.
CDTOT	0.	0.	0.	0.
CGTOT	0.	0.	0.	0.
CSTOT	0.	0.	0.	0.
CBTOT	0.	0.	0.	0.
CGS	0.	0.	0.	0.
CGD	0.	0.	0.	0.

****** TRANSIENT ANALYSIS   TNOM= 27.000 TEMP= 27.000

```
   TIME       V(19)
(A        )   -2.000E+00    -1.000E-00      0.          1.000E-00    2.000E+00
                     +             +             +             +             +

  0.        -1.49E+00-+------A------+------+------+------+------+------+------+-
5.000E-09 -1.17E+00 +      +    A +      +      +      +      +      +      +
1.000E-08 -5.48E-01 +      +      +     A+      +      +      +      +      +
1.500E-08 -1.21E-01 +      +      +      +    A +      +      +      +      +
2.000E-08  1.75E-01 +      +      +      +      + A    +      +      +      +
2.500E-08  3.94E-01 +      +      +      +      +     A+      +      +      +
3.000E-08  5.61E-01 +      +      +      +      +      +A     +      +      +
3.500E-08  6.94E-01 +      +      +      +      +      +  A   +      +      +
4.000E-08  8.02E-01 +      +      +      +      +      +   A  +      +      +
4.500E-08  8.92E-01 +      +      +      +      +      +    A +      +      +
5.000E-08  9.67E-01-+------+------+------+------+------+------A------+------+-
5.500E-08  1.03E+00 +      +      +      +      +      +      A      +      +
6.000E-08  1.08E+00 +      +      +      +      +      +      +A     +      +
6.500E-08  1.13E+00 +      +      +      +      +      +      + A    +      +
7.000E-08  1.17E+00 +      +      +      +      +      +      + A    +      +
7.500E-08  1.21E+00 +      +      +      +      +      +      +  A   +      +
8.000E-08  1.24E+00 +      +      +      +      +      +      +  A   +      +
8.500E-08  1.27E+00 +      +      +      +      +      +      +   A  +      +
9.000E-08  1.30E+00 +      +      +      +      +      +      +   A  +      +
9.500E-08  1.32E+00 +      +      +      +      +      +      +    A +      +
1.000E-07  1.34E+00-+------+------+------+------+------+------+----A-+------+-
1.050E-07  1.36E+00 +      +      +      +      +      +      +    A +      +
1.100E-07  1.38E+00 +      +      +      +      +      +      +    A +      +
1.150E-07  1.39E+00 +      +      +      +      +      +      +     A+      +
1.200E-07  1.40E+00 +      +      +      +      +      +      +     A+      +
1.250E-07  1.41E+00 +      +      +      +      +      +      +     A+      +
1.300E-07  1.42E+00 +      +      +      +      +      +      +     A+      +
1.350E-07  1.43E+00 +      +      +      +      +      +      +     A+      +
1.400E-07  1.44E+00 +      +      +      +      +      +      +     A+      +
1.450E-07  1.45E+00 +      +      +      +      +      +      +     A+      +
1.500E-07  1.45E+00-+------+------+------+------+------+------+-----A+------+-
1.550E-07  1.46E+00 +      +      +      +      +      +      +     A+      +
1.600E-07  1.46E+00 +      +      +      +      +      +      +      A      +
1.650E-07  1.47E+00 +      +      +      +      +      +      +      A      +
1.700E-07  1.47E+00 +      +      +      +      +      +      +      A      +
1.750E-07  1.47E+00 +      +      +      +      +      +      +      A      +
1.800E-07  1.47E+00 +      +      +      +      +      +      +      A      +
1.850E-07  1.48E+00 +      +      +      +      +      +      +      A      +
1.900E-07  1.48E+00 +      +      +      +      +      +      +      A      +
1.950E-07  1.48E+00 +      +      +      +      +      +      +      A      +
2.000E-07  1.48E+00-+------+------+------+------+------+------+------A------+-
                     +             +             +             +             +
```

```
   TIME       I(VDUMMY)
(A        )    0.           5.000E-04     1.000E-03     1.500E-03    2.000E-03
                     +             +             +             +             +

  0.         2.02E-05-+A-----+------+------+------+------+------+------+------+-
5.000E-09  1.61E-03 +      +      +      +      +      +      +  A   +      +
1.000E-08  1.02E-03 +      +      +      +      A      +      +      +      +
1.500E-08  6.89E-04 +      +      +    A +      +      +      +      +      +
2.000E-08  4.98E-04 +      +      A      +      +      +      +      +      +
2.500E-08  3.76E-04 +      +  A   +      +      +      +      +      +      +
3.000E-08  2.95E-04 +      +A     +      +      +      +      +      +      +
3.500E-08  2.37E-04 +      A      +      +      +      +      +      +      +
4.000E-08  1.95E-04 +    A +      +      +      +      +      +      +      +
4.500E-08  1.63E-04 +    A +      +      +      +      +      +      +      +
5.000E-08  1.38E-04-+---A--+------+------+------+------+------+------+------+-
5.500E-08  1.19E-04 +  A   +      +      +      +      +      +      +      +
6.000E-08  1.03E-04 +  A   +      +      +      +      +      +      +      +
6.500E-08  9.05E-05 +  A   +      +      +      +      +      +      +      +
7.000E-08  8.00E-05 + A    +      +      +      +      +      +      +      +
7.500E-08  7.13E-05 + A    +      +      +      +      +      +      +      +
8.000E-08  6.40E-05 + A    +      +      +      +      +      +      +      +
8.500E-08  5.78E-05 + A    +      +      +      +      +      +      +      +
9.000E-08  5.27E-05 +A     +      +      +      +      +      +      +      +
9.500E-08  4.83E-05 +A     +      +      +      +      +      +      +      +
1.000E-07  4.46E-05-+A-----+------+------+------+------+------+------+------+-
                     +             +             +             +             +
```

9.29

$\Delta V_o = \pm 1V$ into $R_L = 1k\Omega$

need $I_{D8} > 1mA$

set $I_{D8} \simeq 2mA$ (say 1.6 mA)

this lowers R_o

run m_1, m_2, m_3 at low I_D with no FB

$$r_{oa} = \frac{1}{g_{m8} + g_{mb8}} \simeq \frac{1}{g_{m8}}$$

set $V_{GS8} \simeq 2.5V$

bias m_2 & m_3 equally

$$V_{t8} = V_{t0} + \gamma\left(\sqrt{V_{SB} + 2\phi_f} - \sqrt{2\phi_f}\right)$$
$$= 0.7 + 0.5\left(\sqrt{5+0.6} - \sqrt{0.6}\right)$$
$$= 1.5V$$

$$I_{D8} = \frac{\mu_n C_{ox}}{2}\frac{W}{L}(V_{GS} - V_t)^2$$

$$1.6mA = \frac{60\mu}{2}\frac{W}{L}(2.5 - 1.5)^2$$

$$53 = \left(\frac{W}{L}\right)_8 = \frac{159\mu}{3\mu}$$

$$g_{m8} = \mu_n C_{ox}\frac{W}{L}(V_{GS} - V_t)$$
$$= 60\mu(53)(1)$$
$$= 3.18\ m$$

$$r_{oa} = \frac{1}{g_{m8}} = 315\,\Omega$$

$$R_o = \frac{r_{oa}}{1+T}$$

$$30 = \frac{315}{1+T}$$

$T = 9.5$

series shunt FB

$$T = \frac{R_2}{R_2+R_1}\frac{g_{m2}}{2}(2r_{o2} \| r_{o3})$$

$$\text{gain} = A = 10 \simeq \frac{R_2+R_1}{R_2}$$

$$9.5 = \frac{1}{10}\frac{g_{m2}}{2}(2r_{o2} \| r_{o3})$$

$$190 = g_{m2}(2r_{o2} \| r_{o3})$$

for large r_{o3}, make L_3 large

9-30

$$r_{o2} = \frac{1}{\frac{I_D}{L}\frac{\partial X_d}{\partial V_{DS}}}$$

$$g_m = k(V_{GS} - V_t)$$

$$g_{m2} r_{o2} = \frac{2L_2}{(V_{GS} - V_t)\frac{\partial X_d}{\partial V_{DS}}}$$

need L_2 large, $(V_{GS2} - V_{t2})$ small

if $g_{m2} r_{o2} = 200$

$$200 = \frac{2L}{V_{GS} - V_t}\frac{1}{0.2\mu}$$

$$L_2 = 20(V_{GS2} - V_{t2})\mu$$

if $(V_{GS2} - V_{t2})$ is too small, g_{m2} is small

can ↑ g_{m2} by ↑ W_2

but cap ↑ ∴ ↓BW

if $(V_{GS2} - V_{t2}) = 0.2$

$$L_2 = 4\mu$$

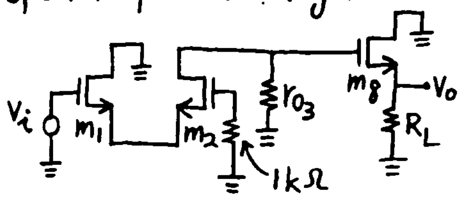
set $L_2 = L_3 = 10\mu = L_1$

$$g_{m2}(2r_{o2} \| r_{o3})$$
$$= \frac{2I_{D2}}{V_{GS2} - V_{t2}}\left(2\frac{V_{A2}}{I_{D2}} \Big\| \frac{V_{A3}}{I_{D2}}\right)$$
$$= \frac{2I_{D2}}{V_{GS2} - V_{t2}} \cdot \frac{2\frac{V_{A2}}{I_{D2}}\frac{V_{A3}}{I_{D2}}}{2\frac{V_{A2}}{I_{D2}} + \frac{V_{A3}}{I_{D2}}}$$
$$= \frac{2}{V_{GS2} - V_{t2}} \cdot \frac{2V_{A2}V_{A3}}{2V_{A2} + V_{A3}}$$
$$= \frac{2}{0.2}\,50 = 500 > 190$$

$$V_{A2} = r_{o2} I_{D2} = \frac{L}{\frac{\partial X_d}{\partial V_{DS}}} = \frac{10\mu}{0.2\mu} = 50V$$

$$V_{A3} = \frac{10\mu}{0.1\mu} = 100V$$

open loop forward gain



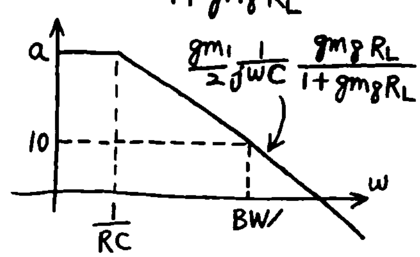
$$a = \frac{V_o}{V_i} \cong \frac{g_{m1}}{2}\underbrace{(2r_{o2} \| r_{o3})}_{R}\frac{g_{m8}R_L}{1+g_{m8}R_L}$$

at high freq

$$a \simeq \frac{g_{m1}}{2}\frac{R}{1+sRC}\frac{g_{m8}R_L}{1+g_{m8}R_L}$$

↑ dominant pole at m_2 drain by ZVTC

$$C = C_{dg2} + C_{db2} + C_{dg3} + C_{db3} + \frac{C_{gs8}}{1+g_{m8}R_L}$$



↑BW/ by ↑g_{m1} & ↓C

$$|GB| = \frac{g_{m1}}{2}R\frac{g_{m8}R_L}{1+g_{m8}R_L}\frac{1}{RC}$$

$$10\ BW/ = \frac{g_{m1}}{2}\frac{1}{C}\frac{g_{m8}R_L}{1+g_{m8}R_L}$$

$$BW/ = \frac{g_{m1}}{20}\frac{1}{C}\frac{1k/315}{1+1k/315}$$

$$= \frac{g_{m1}}{20}\frac{1}{C}\,0.76$$

set $W_1 = 200\mu$

$$I_{D1} = \frac{60\mu}{2}\frac{200\mu}{10\mu}(0.2)^2$$

$$= \frac{\mu_n C_{ox}}{2}\frac{W}{L}(V_{GS1}-V_{t1})^2$$

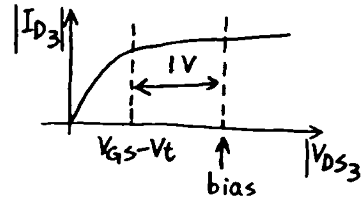
$$= 24\,\mu A$$

$g_{m1} = 240\,\mu A/V$

↓capacitance

want min W_3, but must allow

$\Delta V_{DS3} = 1V$ for $\Delta V_o = +1V$



$$2.5V = |V_{DS3}| = 1 + |V_{GS3} - V_t|$$

$$1.5V = |V_{GS3} - V_{t3}|$$

$$I_{D3} = \frac{\mu_p C_{ox}}{2}\frac{W}{L}(V_{GS}-V_t)^2$$

$$24\mu = \frac{30\mu}{2}\frac{W}{10\mu}1.5^2$$

$$7\mu = W_3$$

set $I_1 = 24\,\mu A$

$$\left(\frac{W}{L}\right)_3 = \left(\frac{W}{L}\right)_4 = \frac{7\mu}{10\mu}$$

$$\left(\frac{W}{L}\right)_1 = \left(\frac{W}{L}\right)_2 = \frac{200\mu}{10\mu}$$

$$\left(\frac{W}{L}\right)_5 = \frac{3\mu}{3\mu}$$

$$\left(\frac{W}{L}\right)_6 = \frac{6\mu}{3\mu}$$

$$\left(\frac{W}{L}\right)_7 = \frac{200\mu}{3\mu}$$

want $I_{D8} = I_{D7} = 1.6\,mA$

$$\frac{1.6mA}{24\mu A} = \frac{\left(\frac{W}{L}\right)_7}{\left(\frac{W}{L}\right)_5} = \frac{\frac{200\mu}{3\mu}}{\frac{3\mu}{3\mu}}$$

$$\left(\frac{W}{L}\right)_8 = \frac{159\mu}{3\mu}$$

set $R_1 \gg R_L$

$$\frac{R_2+R_1}{R_2} = 10 = \frac{2.22k + 20k}{2.22k}$$

m_2 dominates C

$$C \cong C_{dg2} + C_{db2} + \frac{C_{gs8}}{1+g_{m8}R_L}$$

$C_{jsw} = 0.5\,fF/\mu\,(418\mu) = 209\,fF$

$C_{jo} = 0.08\,fF/\mu^2\,(200\mu)(9\mu)$

$= 144\,fF$

$C_{db_2} = 144 + 209 = 353\,fF$

$C_{dgol} = 0.35\,fF/\mu\,(200\mu) = 70f$

$C_{gs_8} = \frac{2}{3} WLC_{ox}$

$= \frac{2}{3}(159)(3)\,0.86f$

$= 273\,fF$

$$C \simeq 353f + 70f + \frac{273f}{1 + 1k/315}$$

$= 488\,fF$

$$BW/ = \frac{g_{m_1}}{20}\,\frac{1}{C}\,0.76$$

$$= \frac{240\mu}{20}\,\frac{1}{488f}\,0.76$$

$= 18.7\ M\,rad/s$

↳ 3 MHz

```
CMOS FEEDBACK AMP
VDD 1 0 5V
VSS 9 0 -5V
M4 2 2 1 1 PMOS W=7U L=10U
I1 2 3 24UA
M5 3 3 9 9 NMOS W=3U L=3U
M6 6 3 9 9 NMOS W=6U L=3U
M1 1 4 6 9 NMOS2 W=200U L=10U
M2 5 7 6 9 NMOS2 W=200U L=10U
M3 5 2 1 1 PMOS W=7U L=10U
M8 1 5 8 9 NMOS W=159U L=3U
M7 8 3 9 9 NMOS2 W=200U L=3U
RLOAD 8 0 1K
R1 8 7 20K
R2 7 0 2.22K
VI 4 0 0V AC
.TF V(8) VI
.DC VI -0.4V 0.8V 0.1V
.PLOT DC V(8)
.AC DEC 10 100K 10MEG
.PLOT AC VDB(8)
.MODEL NMOS2 NMOS KP=60U VTO=0.8 LAMBDA=0.02 TOX=400E-10
+ CGSO=350PF CGDO=350PF CBD=353FF CBS=353FF
.MODEL NMOS NMOS KP=60U VTO=0.8 LAMBDA=0.02 TOX=400E-10
+ CGSO=350PF CGDO=350PF
.MODEL PMOS PMOS KP=30U VTO=-0.8 LAMBDA=0.02 TOX=400E-10
+ CGSO=350PF CGDO=350PF
.OPTIONS NOPAGE NOMOD
.OPTIONS VNTOL=1N ABSTOL=1F RELTOL=1U
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END
```

****** DC TRANSFER CURVES   TNOM= 27.000 TEMP= 27.000

```
   VOLT       V(8)
(A       )   -2.000E+00       0.          2.000E+00     4.000E+00     6.000E+00
                  +             +             +             +             +
-4.000E-01 -1.58E+00-+--A---+------+------+------+------+------+------+------+-
-3.000E-01 -1.58E+00 +  A   +      +      +      +      +      +      +      +
-2.000E-01 -1.58E+00 +  A   +      +      +      +      +      +      +      +
-1.000E-01 -9.20E-01 +      +A     +      +      +      +      +      +      +
 0.         6.61E-03 +      +      A      +      +      +      +      +      +
 1.000E-01  9.39E-01 +      +      +      A      +      +      +      +      +
 2.000E-01  1.71E+00 +      +      +      +    A +      +      +      +      +
 3.000E-01  2.11E+00 +      +      +      +      +A     +      +      +      +
 4.000E-01  2.38E+00 +      +      +      +      +  A   +      +      +      +
 5.000E-01  2.55E+00 +      +      +      +      +   A  +      +      +      +
 6.000E-01  2.56E+00-+------+------+------+------+---A--+------+------+------+-
 7.000E-01  2.56E+00 +      +      +      +      +   A  +      +      +      +
 8.000E-01  2.56E+00 +      +      +      +      +   A  +      +      +      +
                  +             +             +             +             +
```

****** OPERATING POINT INFORMATION   TNOM= 27.000 TEMP= 27.000

```
+0:1        = 5.000E+00 0:2        = 2.721E+00 0:3        =-3.320E+00
+0:4        =   0.      0:5        = 1.795E+00 0:6        =-9.957E-01
+0:7        = 6.601E-04 0:8        = 6.606E-03 0:9        =-5.000E+00
```

**** MOSFETS

ELEMENT	0:M4	0:M5	0:M6	0:M1	0:M2	0:M3
MODEL	0:PMOS	0:NMOS	0:NMOS	0:NMOS2	0:NMOS2	0:PMOS
ID	-2.400E-05	2.400E-05	5.016E-05	2.573E-05	2.443E-05	-2.443E-05
IBS	0.	0.	0.	-4.004E-14	-4.004E-14	0.
IBD	2.279E-14	-1.680E-14	-4.004E-14	-1.000E-13	-6.795E-14	3.205E-14
VGS	-2.278E+00	1.679E+00	1.679E+00	9.957E-01	9.964E-01	-2.278E+00
VDS	-2.278E+00	1.679E+00	4.004E+00	5.995E+00	2.791E+00	-3.204E+00
VBS	0.	0.	0.	-4.004E+00	-4.004E+00	0.
VTH	-8.000E-01	8.000E-01	8.000E-01	8.000E-01	8.000E-01	-8.000E-01
VDSAT	-1.478E+00	8.798E-01	8.798E-01	1.957E-01	1.964E-01	-1.478E+00
BETA	2.196E-05	6.202E-05	1.296E-04	1.344E-03	1.267E-03	2.235E-05
GAM EFF	0.	0.	0.	0.	0.	0.
GM	3.246E-05	5.456E-05	1.140E-04	2.630E-04	2.488E-04	3.304E-05
GDS	4.591E-07	4.644E-07	9.288E-07	4.596E-07	4.627E-07	4.591E-07
GMB	0.	0.	0.	0.	0.	0.
CDTOT	2.634E-15	1.067E-15	2.183E-15	1.799E-13	1.910E-13	2.708E-15
CGTOT	4.588E-14	7.423E-15	1.489E-14	1.451E-12	1.443E-12	4.596E-14
CSTOT	4.274E-14	6.230E-15	1.246E-14	1.365E-12	1.365E-12	4.274E-14
CBTOT	5.123E-16	1.260E-16	2.519E-16	3.865E-13	4.045E-13	5.123E-16
CGS	4.274E-14	6.230E-15	1.246E-14	1.221E-12	1.221E-12	4.274E-14
CGD	2.634E-15	1.067E-15	2.183E-15	8.380E-14	7.643E-14	2.708E-15

ELEMENT	0:M8	0:M7
MODEL	0:NMOS	0:NMOS2
ID	1.710E-03	1.703E-03
IBS	-5.007E-14	0.
IBD	-1.000E-13	-5.007E-14
VGS	1.788E+00	1.679E+00
VDS	4.993E+00	5.006E+00
VBS	-5.006E+00	0.
VTH	8.000E-01	8.000E-01
VDSAT	9.888E-01	8.798E-01
BETA	3.498E-03	4.401E-03
GAM EFF	0.	0.
GM	3.458E-03	3.871E-03
GDS	3.109E-05	3.096E-05
GMB	0.	0.
CDTOT	5.839E-14	2.045E-13
CGTOT	3.944E-13	4.972E-13
CSTOT	3.302E-13	7.683E-13
CBTOT	5.789E-15	4.924E-13
CGS	3.302E-13	4.153E-13
CGD	5.839E-14	7.346E-14

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

```
     V(8)/VI                                 =  9.305E+00
     INPUT RESISTANCE AT          VI         =  9.999E+19
     OUTPUT RESISTANCE AT V(8)               =  1.470E+01
```

****** AC ANALYSIS   TNOM= 27.000 TEMP= 27.000

```
   FREQ       VDB(8)
(A       )    5.000E+00     1.000E+01     1.500E+01     2.000E+01     2.500E+01
                  +             +             +             +             +
 1.000E+05  1.93E+01-+------+------+------+------+------+----A-+------+------+-
 1.258E+05  1.93E+01 +      +      +      +      +      +    A +      +      +
 1.584E+05  1.93E+01 +      +      +      +      +      +    A +      +      +
 1.995E+05  1.93E+01 +      +      +      +      +      +    A +      +      +
 2.511E+05  1.93E+01 +      +      +      +      +      +    A +      +      +
 3.162E+05  1.93E+01 +      +      +      +      +      +    A +      +      +
 3.981E+05  1.93E+01 +      +      +      +      +      +    A +      +      +
 5.011E+05  1.93E+01 +      +      +      +      +      +    A +      +      +
 6.309E+05  1.92E+01 +      +      +      +      +      +    A +      +      +
 7.943E+05  1.92E+01 +      +      +      +      +      +    A +      +      +
 1.000E+06  1.91E+01-+------+------+------+------+------+----A-+------+------+-
 1.258E+06  1.89E+01 +      +      +      +      +      +   A  +      +      +
 1.584E+06  1.87E+01 +      +      +      +      +      +   A  +      +      +
 1.995E+06  1.84E+01 +      +      +      +      +      +  A   +      +      +
 2.511E+06  1.79E+01 +      +      +      +      +      +A     +      +      +
 3.162E+06  1.73E+01 +      +      +      +      +      A      +      +      +
 3.981E+06  1.64E+01 +      +      +      +      +   A  +      +      +      +
 5.011E+06  1.53E+01 +      +      +      +      +A     +      +      +      +
 6.309E+06  1.40E+01 +      +      +      +  A   +      +      +      +      +
 7.943E+06  1.26E+01 +      +      +      A      +      +      +      +      +
 1.000E+07  1.09E+01-+------+------+--A---+------+------+------+------+------+-
                  +             +             +             +             +
```

9.30

Assume the zero has been eliminated and $|P_3| \gg |P_2| \gg |P_1|$, at the op-amp unity-gain frequency, $|P_1|$ contributes $-90°$ phase shift. If $|P_2|$ contributes $-30°$ phase shift, the phase margin is $60°$.

phase shift due to $|P_2|$ =

$$-\tan^{-1}\frac{\omega_{unity}}{|P_2|} = -30° \text{ at } \omega_{unity}$$

$$\omega_{unity} = \tan 30° \cdot |P_2| = \frac{\sqrt{3}}{3}|P_2|$$

$$= a_0|P_1|$$

$$a_0|P_1| = \frac{\sqrt{3}}{3}|P_2|$$

$$g_{m1}R_1 g_{m6}R_2 \frac{1}{g_{m6}R_2R_1C} = \frac{\sqrt{3}}{3}\frac{g_{m6}}{C_1+C_2}$$

$$\frac{g_{m1}}{C} = \frac{\sqrt{3}}{3}\frac{g_{m6}}{C_1+C_2}$$

From the example in Section 9.4.3,

$g_{m1} = 1\text{mA/V}$, $g_{m6} = 1.55\text{mA/V}$, $C_1+C_2 \approx 5\text{PF}$

$$C = \sqrt{3}\frac{g_{m1}}{g_{m6}}(C_1+C_2) = 1.7\frac{1}{1.55}5 = 5.4\text{PF}$$

9.31

(a) Similar to Problem 9.30, the op-amp unity-gain frequency

$$\omega_{unity} = 2\cdot\tan 45°|P_2| = 2|P_2| = a_0|P_1|$$

$$\frac{g_{m1}}{C} = 2\frac{g_{m6}}{C_1+C_2}$$

$$\frac{0.5}{C} = 2\frac{2}{0.1+8}$$

$$C = 1\text{PF}$$

(b) $R_z = \frac{1}{g_{m6}} = 500\Omega$

9.32

Similar to Problem 9.31a,

$$|P_2| = \frac{g_{m6}}{C+C_2}\frac{C}{C_1}$$

$$a_0|P_1| = 2|P_2|$$

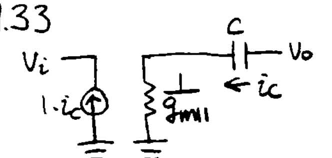
$$\frac{g_{m1}}{C} = 2\frac{g_{m6}}{C+C_2}\frac{C}{C_1}$$

$$\frac{0.5}{C} = 2\frac{2}{C+8}\frac{C}{0.1}$$

$$C = 0.32\text{PF}$$

It is smaller than the compensation capacitor in Problem 9.31a.

9.33



$$i_c = \frac{V_o}{\frac{1}{g_{m11}}+\frac{1}{sC}} = \frac{sg_{m11}C}{g_{m11}+sC}V_o$$

In (9.40a), (9.40b) and (9.41), C_1 can be ignored and sC replaced by $\frac{sg_{m11}C}{g_{m11}+sC}$;

$$\frac{V_o}{i_s} = \frac{g_{m6}R_1R_2}{1+sR_2C_2+s(1+g_{m6}R_1)R_2C} \text{ becomes}$$

$$\frac{V_o}{i_s} = \frac{g_{m6}R_1R_2}{1+sR_2C_2+s(1+g_{m6}R_1)R_2C\frac{g_{m11}}{g_{m11}+sC}}$$

$$= \frac{g_{m6}R_1R_2(g_{m11}+sC)}{g_{m11}+s[C+g_{m11}R_2C_2+(1+g_{m6}C_1)g_{m11}R_2C]+s^2R_2C_2C}$$

There is a zero at $-\frac{g_{m11}}{C}$

9.34

The denominator of (9.27) is

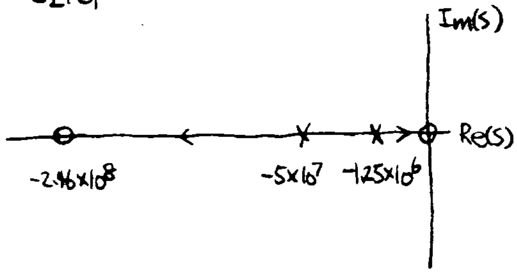
$$1+s(C_2R_2+C_1R_1)+s^2R_2R_1C_2C_1+$$
$$C[s(R_2+R_1+g_mR_2R_1)+s^2R_2R_1(C_2+C_1)]=0$$
$$1+C\frac{s(R_2+R_1+g_mR_2R_1)+s^2R_2R_1(C_2+C_1)}{1+s(C_2R_2+C_1R_1)+s^2R_2R_1C_2C_1}=0$$

Roots of the denominator:

$$-\frac{1}{R_2C_2}=-1.25\times10^6\ \text{rad/s}$$
$$-\frac{1}{R_1C_1}=-5\times10^7\ \text{rad/s}$$

Roots of the numerator:

$$0,$$
$$-\frac{g_m}{C_2+C_1}=-2.46\times10^8\ \text{rad/s}$$



9.35

$$P_1\approx-\frac{1}{g_{m1}R_1g_{m2}R_2R_oC_{m2}}$$
$$P_2\approx-\frac{g_{m1}}{C_{m1}}$$
$$P_3\approx-\frac{g_{m2}}{C_2}$$
$$a_o=g_{mo}R_og_{m1}R_1g_{m2}R_2$$
$$a_o\cdot|P_1|=1\cdot|P_2|$$
$$\therefore C_{m2}=\frac{g_{mo}}{g_{m1}}C_{m1}=C_{m1}$$

$C_{m1}, C_{m2} \gtrsim C_o, C_1, C_2$ should be satisfied.

One possible answer is $C_{m1}=C_{m2}=10\text{pF}$

$$|P_3|=\frac{6g_{m1}}{6\text{pF}}\gg|P_2|=\frac{g_{m1}}{10\text{pF}}\gg|P_1|=\frac{|P_2|}{a_o}$$

9.36

Assume $|P_2|\gg|P_1|$. At ω_{unity}, P_1 contributes -90° phase shift. If P_2 contributes -30°, the phase margin will be 60°.

$$-\tan^{-1}\frac{\omega_{unity}}{|P_2|}=-30^\circ$$
$$\omega_{unity}=\frac{\sqrt{3}}{3}|P_2|$$
$$a_o\cdot|P_1|=1\cdot\omega_{unity}=1\cdot\frac{\sqrt{3}}{3}|P_2|$$
$$P_1\approx-\frac{1}{g_{m1}R_1g_{m2}R_2R_oC_{m2}}$$
$$P_2\approx-\frac{g_{m1}}{C_{m1}}$$
$$a_o=g_{mo}R_og_{m1}R_1g_{m2}R_2$$
$$\therefore C_{m2}=\sqrt{3}C_{m1}$$

One possible answer is $C_{m1}=10\text{pF}$, $C_{m2}=17\text{pF}$.

9.37

$$|P_1|=\frac{1}{R_oC_L}$$

a_o, $|P_2|$ are constant.

To give a 45° phase margin,

$$a_o\cdot|P_1|=1\cdot\tan(90^\circ-45^\circ)|P_2|=1\cdot|P_2|$$
$$C_L=\frac{a_o}{|P_2|R_o}$$

To give a 60° phase margin,

$$a_o\cdot|P_1'|=1\cdot\tan(90^\circ-60^\circ)|P_2|=1\cdot\frac{\sqrt{3}}{3}|P_2|$$
$$C_L'=\sqrt{3}\frac{a_o}{|P_2|R_o}=\sqrt{3}C_L=3.4\text{pF}$$

9.38

(a) $a_0 \cdot \frac{1}{R_O C_L} = |P_2|$

$g_{m1} R_O \frac{1}{R_O C_L} = \frac{g_{m1}}{C_L} = |P_2|$

$\frac{0.3\times10^{-3}}{C_L} = 200\times10^{6}$

$C_L = 1.5\times10^{-12}F = 1.5PF$

(b) $SR = \frac{I_{TAIL}}{C_L} = \frac{0.5mA}{1.5PF}$

$= 330 V/\mu s$

9.39

(a) The equivalent load is

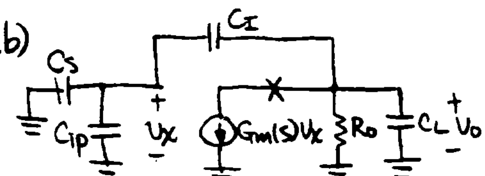
$C_L' = C_L + C_I \| (C_S + C_{ip})$

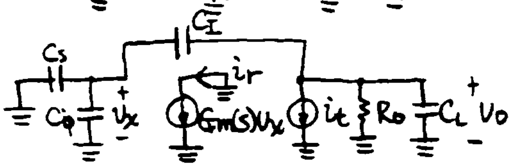
$= 1.5 + 4 \| (0.4 + 0.1)$

$= 1.9PF$

$SR = \frac{0.2mA}{1.9PF} = 105 V/\mu s$

(b)





$f = \frac{V_X}{V_O} = \frac{C_I}{C_I + (C_S + C_{ip})} = \frac{4}{4 + (0.4 + 0.1)}$

$= 0.89$

$G_m(s) = \frac{g_{m1}}{1 - S/P_2}$

$R = -\frac{i_r}{i_t} = -\left[-i_t \frac{1}{1/R_O + sC_L'} f G_m(s)\right] / i_t$

$= \frac{G_m(s) R_O f}{1 + SR_O C_L'} = \frac{g_{m1} R_O f}{(1 + SR_O C_L')(1 - S/P_2)}$

To locate ω_{unity}, $\omega_{unity} \gg |P_1| = \frac{1}{R_O C_L'}$ and

$|R| \approx \frac{g_{m1} R_O f}{|SR_O C_L'(1 - S/P_2)|}$

$= \frac{g_{m1} f}{C_L'} \frac{1}{|S||1 - S/P_2|}$

$= \frac{0.1\times10^{-3}\times0.89}{1.9\times10^{-12}} \frac{1}{|j\omega||1 - j\omega/P_2|}$

$= \frac{4.7\times10^{7}}{\omega\sqrt{1 + \omega^2/P_2^2}}$

$= 1$

$\omega_{unity} = 4.7\times10^{7}$ rad/s $\ll |P_2|$

The phase shift from P_1 is $90°$.

The phase shift from P_2 is

$\tan^{-1}\left(\frac{\omega_{unity}}{|P_2|}\right) = \tan^{-1}\left(\frac{4.7\times10^{7}}{2\times10^{8}}\right) = 13°$

The phase margin is

$180° - (90° + 13°) = 77°$

9.40

$V_X = -\frac{Z_1}{Z_1 + Z_2} V_t$

$V_r = a_v V_X$

$R = -\frac{V_r}{V_t} = a_v \frac{Z_1}{Z_1 + Z_2}$

There are 4 possibilities:

(1) $R = a_v \frac{R_1}{R_1 + R_2}$, and the phase shift is $0°$;

(2) $R = a_v \frac{R_1}{R_1 + 1/j\omega C_2} = a_v \frac{j\omega R_1 C_2}{1 + j\omega R_1 C_2}$, and the phase shift is between $0°$ and $90°$;

(3) $R = a_v \frac{1/j\omega C_1}{1/j\omega C_1 + R_2} = a_v \frac{1}{1 + j\omega R_2 C_1}$, and the phase shift is between $-90°$ and $0°$;

(4) $R = a_v \frac{1/j\omega C_1}{1/j\omega C_1 + 1/j\omega C_2} = a_v \frac{C_2}{C_1 + C_2}$, and the phase shift is $0°$.

The phase shift never reaches $-180°$, so the circuit is stable.

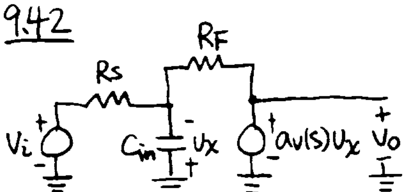
9.41

$$\mathcal{R} = a_v(s)\frac{j\omega RC}{1+j\omega RC}$$

$$= \frac{a_v}{(1+\frac{j\omega}{|P_1|})(1+\frac{j\omega}{|P_2|})}\frac{j\omega RC}{1+j\omega RC}$$

The $a_v \cdot j\omega RC$ term contributes a $90°$ phase shift. Each of the 3 LHP poles contributes a $-90°$ phase shift when $\omega \to \infty$. The total phase shift never reaches $-180°$ for $0<\omega<\infty$, so the circuit is stable.

9.42



$$\mathcal{R} = \frac{R_s // \frac{1}{sC_{in}}}{R_F + R_s // \frac{1}{sC_{in}}} a_v(s)$$

$$= \frac{\frac{R_s}{R_s+R_F}}{1+s(R_s//R_F)C_{in}} \frac{1000}{(1+\frac{s}{100})(1+\frac{s}{10^6})}$$

$$= \frac{\frac{1}{2}}{1+s \cdot 50k \cdot C_{in}} \frac{1000}{(1+\frac{s}{100})(1+\frac{s}{10^6})}$$

$$= \frac{500}{(1+s \cdot 50k \cdot C_{in})(1+\frac{s}{100})(1+\frac{s}{10^6})}$$

(a) $C_{in}=0$

$$\mathcal{R} = \frac{500}{(1+\frac{s}{100})(1+\frac{s}{10^6})}$$

When $s=j\omega=j5\times10^4$, $|\mathcal{R}(j\omega)|=1$.

When $s=j\omega=j10^5$, $|a_v(j\omega)|=1$.

The latter frequency is twice the former.

(b)

C_{in} (pF)	ω_u (rad/s)	poles (rad/s)	phase shift	phase margin
0		100 10^6	$-90°$ $-3°$	$87°$
4	5×10^4	100 10^6 5×10^6	$-90°$ $-3°$ $-1°$	$86°$
20		100 10^6 (double)	$-90°$ $-6°$	$84°$

Even with the addition of the third pole from C_{in}, the phase shift never reaches $-180°$ at ω_u.

9.43

(a) See next page.

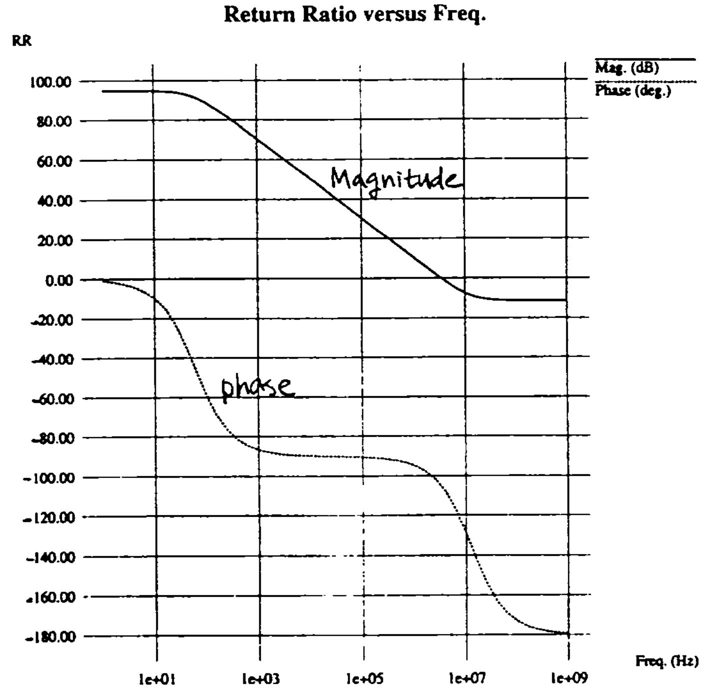
(b) The unity-gain frequency is ~4MHz.

The phase margin is ~70°.

The gain margin is ~10dB.

```
RETURN RATIO
VDD 1 0 5
VSS 2 0 -5
.GLOBAL 1 2
.SUBCKT AMP (6 5 9)
IBIAS 3 2 20U
M1 7 5 4 4 CMOSP W=100U L=6.4U
M2 8 6 4 4 CMOSP W=100U L=6.4U
M3 7 7 2 2 CMOSN W=50U  L=6.4U
M4 8 7 2 2 CMOSN W=50U  L=6.4U
M5 4 3 1 1 CMOSP W=100U L=6.4U
M6 9 8 2 2 CMOSN W=100U L=6.4U
M7 9 3 1 1 CMOSP W=100U L=6.4U
M8 3 3 1 1 CMOSP W=100U L=6.4U
M9 10 1 8 2 CMOSN W=6.1U L=6.4U
CCOMP 10 9 5P
.MODEL CMOSN NMOS LEVEL=1 LAMBDA=0.0313 VTO=0.7  KP=60.4U LD=0.12U
.MODEL CMOSP PMOS LEVEL=1 LAMBDA=0.0156 VTO=-0.7 KP=30.2U LD=0.18U
.ENDS AMP
.OPTIONS NOMOD
XRRV (0 11 12) AMP
VT 11 12 AC 1
R1 12 0 1G
XRRI (0 21 22) AMP
IT 0 31 AC 1
VDUMMY1 31 21 0
VDUMMY2 22 31 0
R2 31 0 1G
.AC DEC 5 1 1G
.PRINT AC RRVR=PAR('-VM(12)/VM(11)*COS(3.14*(VP(12)-VP(11))/180)')\
RRVI=PAR('-VM(12)/VM(11)*SIN(3.14*(VP(12)-VP(11))/180)')\
RRIR=PAR('-IM(VDUMMY2)/IM(VDUMMY1)*COS(3.14*(IP(VDUMMY2)-IP(VDUMMY1))/180)')\
RRII=PAR('-IM(VDUMMY2)/IM(VDUMMY1)*SIN(3.14*(IP(VDUMMY2)-IP(VDUMMY1))/180)')\
.OPTIONS SPICE
.WIDTH OUT=80
.END
****** OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
+0:1      = 5.000E+00 0:2      =-5.000E+00 0:11      =-4.599E-05
+0:12     =-4.599E-05 0:21     =-4.599E-05 0:22      =-4.599E-05
+0:31     =-4.599E-05 1:3      = 4.019E+00 1:4       = 8.972E-01
+1:7      =-4.096E+00 1:8      =-4.106E+00 1:10      =-4.106E+00
+2:3      = 4.019E+00 2:4      = 8.972E-01 2:7       =-4.096E+00
+2:8      =-4.106E+00 2:10     =-4.106E+00
**** MOSFETS
SUBCKT   XRRV       XRRV       XRRV       XRRV       XRRV       XRRV
ELEMENT  1:M1       1:M2       1:M3       1:M4       1:M5       1:M6
MODEL    1:CMOSP    1:CMOSP    1:CMOSN    1:CMOSN    1:CMOSP    1:CMOSN
 ID      -1.048E-05 -1.048E-05  1.048E-05  1.048E-05 -2.096E-05  2.124E-05
 IBS       0.         0.         0.         0.         0.         0.
 IBD      4.993E-14  5.004E-14 -9.039E-15 -8.935E-15  4.103E-14 -5.000E-14
 VGS     -8.972E-01 -8.972E-01  9.039E-01  9.039E-01 -9.807E-01  8.935E-01
 VDS     -4.993E+00 -5.003E+00  9.039E-01  8.935E-01 -4.102E+00  5.000E+00
 VBS       0.         0.         0.         0.         0.         0.
 VTH     -7.000E-01 -7.000E-01  7.000E-01  7.000E-01 -7.000E-01  7.000E-01
 VDSAT   -1.972E-01 -1.972E-01  2.039E-01  2.039E-01 -2.807E-01  1.935E-01
 BETA     5.389E-04  5.390E-04  5.041E-04  5.040E-04  5.320E-04  1.134E-03
 GAM EFF   0.         0.         0.         0.         0.         0.
 GM       1.063E-04  1.063E-04  1.028E-04  1.028E-04  1.493E-04  2.195E-04
 GDS      1.517E-07  1.516E-07  3.190E-07  3.190E-07  3.073E-07  5.747E-07
 GMB       0.         0.         0.         0.         0.         0.
 CDTOT     0.         0.         0.         0.         0.         0.
 CGTOT     0.         0.         0.         0.         0.         0.
 CSTOT     0.         0.         0.         0.         0.         0.
 CBTOT     0.         0.         0.         0.         0.         0.
 CGS       0.         0.         0.         0.         0.         0.
 CGD       0.         0.         0.         0.         0.         0.
SUBCKT   XRRV       XRRV       XRRV       XRRI       XRRI       XRRI
ELEMENT  1:M7       1:M8       1:M9       2:M1       2:M2       2:M3
MODEL    1:CMOSP    1:CMOSP    1:CMOSN    2:CMOSP    2:CMOSP    2:CMOSN
 ID      -2.124E-05 -2.000E-05 -9.025E-13 -1.048E-05 -1.048E-05  1.048E-05
 IBS       0.         0.        -8.935E-15   0.         0.         0.
 IBD      5.000E-14  9.807E-15 -8.935E-15  4.993E-14  5.004E-14 -9.039E-15
 VGS     -9.807E-01 -9.807E-01  9.106E+00 -8.972E-01 -8.972E-01  9.039E-01
 VDS     -5.000E+00 -9.807E-01 -1.795E-09 -4.993E+00 -5.003E+00  9.039E-01
 VBS       0.         0.        -8.935E-01   0.         0.         0.
 VTH     -7.000E-01 -7.000E-01  7.000E-01 -7.000E-01 -7.000E-01  7.000E-01
 VDSAT   -2.807E-01 -2.807E-01  1.795E-09 -1.972E-01 -1.972E-01  2.039E-01
 BETA     5.390E-04  5.076E-04  5.981E-05  5.389E-04  5.390E-04  5.041E-04
 GAM EFF   0.         0.         0.         0.         0.         0.
 GM       1.513E-04  1.425E-04  1.074E-13  1.063E-04  1.063E-04  1.028E-04
 GDS      3.073E-07  3.073E-07  5.028E-04  1.517E-07  1.516E-07  3.190E-07
 GMB       0.         0.         0.         0.         0.         0.
 CDTOT     0.         0.         0.         0.         0.         0.
 CGTOT     0.         0.         0.         0.         0.         0.
 CSTOT     0.         0.         0.         0.         0.         0.
 CBTOT     0.         0.         0.         0.         0.         0.
 CGS       0.         0.         0.         0.         0.         0.
 CGD       0.         0.         0.         0.         0.         0.
SUBCKT   XRRI       XRRI       XRRI       XRRI       XRRI       XRRI
ELEMENT  2:M4       2:M5       2:M6       2:M7       2:M8       2:M9
MODEL    2:CMOSN    2:CMOSP    2:CMOSN    2:CMOSP    2:CMOSP    2:CMOSN
 ID       1.048E-05 -2.096E-05  2.124E-05 -2.124E-05 -2.000E-05 -9.025E-13
 IBS       0.         0.         0.         0.         0.        -8.935E-15
 IBD     -8.935E-15  4.103E-14 -5.000E-14  5.000E-14  9.807E-15 -8.935E-15
 VGS      9.039E-01 -9.807E-01  8.935E-01 -9.807E-01 -9.807E-01  9.106E+00
 VDS      8.935E-01 -4.102E+00  5.000E+00 -5.000E+00 -9.807E-01 -1.795E-09
 VBS       0.         0.         0.         0.         0.        -8.935E-01
 VTH      7.000E-01 -7.000E-01  7.000E-01 -7.000E-01 -7.000E-01  7.000E-01
 VDSAT    2.039E-01 -2.807E-01  1.935E-01 -2.807E-01 -2.807E-01  1.795E-09
 BETA     5.040E-04  5.320E-04  1.134E-03  5.390E-04  5.076E-04  5.981E-05
 GAM EFF   0.         0.         0.         0.         0.         0.
 GM       1.028E-04  1.493E-04  2.195E-04  1.513E-04  1.425E-04  1.074E-13
 GDS      3.190E-07  3.073E-07  5.747E-07  3.073E-07  3.073E-07  5.028E-04
 GMB       0.         0.         0.         0.         0.         0.
 CDTOT     0.         0.         0.         0.         0.         0.
 CGTOT     0.         0.         0.         0.         0.         0.
 CSTOT     0.         0.         0.         0.         0.         0.
 CBTOT     0.         0.         0.         0.         0.         0.
 CGS       0.         0.         0.         0.         0.         0.
 CGD       0.         0.         0.         0.         0.         0.

****** AC ANALYSIS                          TNOM=  27.000 TEMP=  27.000
      FREQ        RRVR        RRVI        RRIR        RRII
 1.0000E+00    5.601E+04  -1.024E+03   9.999E+27  -1.592E+25
 1.5848E+00    5.598E+04  -1.570E+03   9.999E+27  -1.592E+25
 2.5118E+00    5.592E+04  -2.434E+03   9.999E+27  -1.592E+25
 3.9810E+00    5.577E+04  -3.796E+03   9.999E+27  -1.592E+25
 6.3095E+00    5.540E+04  -5.925E+03   9.999E+27  -1.592E+25
 1.0000E+01    5.449E+04  -9.187E+03   9.999E+27  -1.592E+25
 1.5848E+01    5.233E+04  -1.393E+04   9.999E+27  -1.592E+25
 2.5118E+01    4.761E+04  -2.005E+04   9.999E+27  -1.592E+25
 3.9810E+01    3.881E+04  -2.588E+04   9.999E+27  -1.592E+25
 6.3095E+01    2.651E+04  -2.800E+04   9.999E+27  -1.592E+25
 1.0000E+02    1.475E+04  -2.470E+04   9.999E+27  -1.592E+25
 1.5848E+02    6.977E+03  -1.852E+04   9.999E+27  -1.592E+25
 2.5118E+02    2.999E+03  -1.263E+04   9.999E+27  -1.592E+25
 3.9810E+02    1.231E+03  -8.240E+03   9.999E+27  -1.592E+25
 6.3095E+02    4.951E+02  -5.269E+03   9.999E+27  -1.592E+25
 1.0000E+03    1.970E+02  -3.342E+03   9.999E+27  -1.592E+25
 1.5848E+03    7.783E+01  -2.113E+03   9.999E+27  -1.592E+25
 2.5118E+03    3.045E+01  -1.334E+03   9.999E+27  -1.592E+25
 3.9810E+03    1.171E+01  -8.423E+02   9.999E+27  -1.592E+25
 6.3095E+03    4.347E+00  -5.315E+02   9.999E+27  -1.592E+25
 1.0000E+04    1.469E+00  -3.354E+02   9.999E+27  -1.592E+25
 1.5848E+04    3.600E-01  -2.116E+02   9.999E+27  -1.592E+25
 2.5118E+04   -5.870E-02  -1.335E+02   9.999E+27  -1.592E+25
 3.9810E+04   -2.109E-01  -8.425E+01   9.999E+27  -1.592E+25
 6.3095E+04   -2.624E-01  -5.316E+01   9.999E+27  -1.592E+25
 1.0000E+05   -2.771E-01  -3.354E+01   9.999E+27  -1.592E+25
 1.5848E+05   -2.793E-01  -2.116E+01   9.999E+27  -1.592E+25
 2.5118E+05   -2.779E-01  -1.335E+01   9.999E+27  -1.592E+25
 3.9810E+05   -2.759E-01  -8.425E+00   9.999E+27  -1.593E+25
 6.3095E+05   -2.742E-01  -5.315E+00   9.999E+27  -1.593E+25
 1.0000E+06   -2.729E-01  -3.354E+00   9.999E+27  -1.593E+25
 1.5848E+06   -2.721E-01  -2.116E+00   9.999E+27  -1.594E+25
 2.5118E+06   -2.715E-01  -1.335E+00   9.999E+27  -1.595E+25
 3.9810E+06   -2.711E-01  -8.424E-01   9.999E+27  -1.595E+25
 6.3095E+06   -2.709E-01  -5.315E-01   9.999E+27  -1.595E+25
 1.0000E+07   -2.707E-01  -3.353E-01   9.999E+27  -1.594E+25
 1.5848E+07   -2.707E-01  -2.115E-01   9.999E+27  -1.594E+25
 2.5118E+07   -2.706E-01  -1.335E-01   9.999E+27  -1.593E+25
 3.9810E+07   -2.706E-01  -8.421E-02   9.999E+27  -1.593E+25
 6.3095E+07   -2.706E-01  -5.313E-02   9.999E+27  -1.593E+25
 1.0000E+08   -2.706E-01  -3.353E-02   9.999E+27  -1.592E+25
 1.5848E+08   -2.706E-01  -2.115E-02   9.999E+27  -1.592E+25
 2.5118E+08   -2.706E-01  -1.335E-02   9.999E+27  -1.592E+25
 3.9810E+08   -2.706E-01  -8.421E-03   9.999E+27  -1.592E+25
 6.3095E+08   -2.706E-01  -5.313E-03   9.999E+27  -1.592E+25
 1.0000E+09   -2.706E-01  -3.353E-03   9.999E+27  -1.592E+25
```

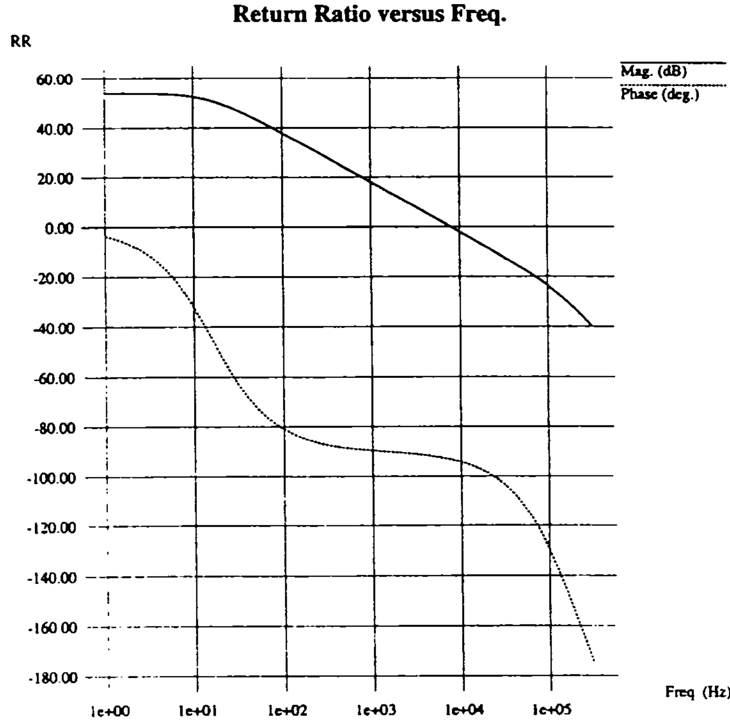
Return Ratio versus Freq.



```
RETURN RATIO
.SUBCKT AMP (1 2)
EAMP 3 0 LAPLACE 0 1 1000 / 1 10.001M 0.01U
R1 1 0 100K
R2 2 3 100K
CIN 1 0 4P
.ENDS AMP
.OPTIONS NOMOD
XRRV (11 12) AMP
VT 12 11 AC 1

XRRI (21 22) AMP
IT 0 31 AC 1
VDUMMY1 31 21 0
VDUMMY2 22 31 0

.AC DEC 10 1 300K
.PRINT AC RRVR=PAR('-VM(12)/VM(11)*COS(3.14*(VP(12)-VP(11))/180)')\
RRVI=PAR('-VM(12)/VM(11)*SIN(3.14*(VP(12)-VP(11))/180)')\
RRIR=PAR('-IM(VDUMMY2)/IM(VDUMMY1)*COS(3.14*(IP(VDUMMY2)-IP(VDUMMY1))/180)')\
RRII=PAR('-IM(VDUMMY2)/IM(VDUMMY1)*SIN(3.14*(IP(VDUMMY2)-IP(VDUMMY1))/180)')\
.OPTIONS SPICE
.WIDTH OUT=80
.END
```

****** AC ANALYSIS TNOM= 27.000 TEMP= 27.000

FREQ	RRVR	RRVI	RRIR	RRII
1.0000E+00	9.969E+02	-6.414E+01	9.969E+02	-6.415E+01
1.2589E+00	9.946E+02	-8.016E+01	9.946E+02	-8.016E+01
1.5848E+00	9.910E+02	-1.001E+02	9.910E+02	-1.001E+02
1.9952E+00	9.853E+02	-1.249E+02	9.853E+02	-1.249E+02
2.5118E+00	9.764E+02	-1.554E+02	9.764E+02	-1.554E+02
3.1622E+00	9.627E+02	-1.926E+02	9.627E+02	-1.926E+02
3.9810E+00	9.417E+02	-2.368E+02	9.417E+02	-2.368E+02
5.0118E+00	9.103E+02	-2.878E+02	9.103E+02	-2.878E+02
6.3095E+00	8.646E+02	-3.438E+02	8.646E+02	-3.438E+02
7.9432E+00	8.010E+02	-4.006E+02	8.010E+02	-4.007E+02
1.0000E+01	7.173E+02	-4.514E+02	7.173E+02	-4.514E+02
1.2589E+01	6.154E+02	-4.873E+02	6.154E+02	-4.874E+02
1.5848E+01	5.024E+02	-5.006E+02	5.024E+02	-5.006E+02
1.9952E+01	3.892E+02	-4.879E+02	3.892E+02	-4.880E+02
2.5118E+01	2.869E+02	-4.524E+02	2.868E+02	-4.524E+02
3.1622E+01	2.026E+02	-4.018E+02	2.025E+02	-4.018E+02
3.9810E+01	1.383E+02	-3.448E+02	1.383E+02	-3.448E+02
5.0118E+01	9.223E+01	-2.885E+02	9.220E+01	-2.885E+02
6.3095E+01	6.050E+01	-2.372E+02	6.047E+01	-2.372E+02
7.9432E+01	3.932E+01	-1.926E+02	3.928E+01	-1.926E+02
1.0000E+02	2.547E+01	-1.552E+02	2.543E+01	-1.552E+02
1.2589E+02	1.652E+01	-1.244E+02	1.648E+01	-1.244E+02
1.5848E+02	1.080E+01	-9.943E+01	1.076E+01	-9.944E+01
1.9952E+02	7.156E+00	-7.927E+01	7.116E+00	-7.928E+01
2.5118E+02	4.846E+00	-6.311E+01	4.806E+00	-6.312E+01
3.1622E+02	3.385E+00	-5.020E+01	3.345E+00	-5.021E+01
3.9810E+02	2.462E+00	-3.991E+01	2.422E+00	-3.992E+01
5.0118E+02	1.881E+00	-3.172E+01	1.841E+00	-3.173E+01
6.3095E+02	1.515E+00	-2.521E+01	1.475E+00	-2.521E+01
7.9432E+02	1.284E+00	-2.002E+01	1.244E+00	-2.003E+01
1.0000E+03	1.140E+00	-1.591E+01	1.100E+00	-1.591E+01
1.2589E+03	1.049E+00	-1.263E+01	1.009E+00	-1.264E+01
1.5848E+03	9.923E-01	-1.003E+01	9.523E-01	-1.004E+01
1.9952E+03	9.568E-01	-7.971E+00	9.168E-01	-7.981E+00
2.5118E+03	9.347E-01	-6.329E+00	8.946E-01	-6.341E+00
3.1622E+03	9.209E-01	-5.024E+00	8.809E-01	-5.039E+00
3.9810E+03	9.124E-01	-3.986E+00	8.723E-01	-4.005E+00
5.0118E+03	9.072E-01	-3.161E+00	8.671E-01	-3.184E+00
6.3095E+03	9.041E-01	-2.503E+00	8.639E-01	-2.533E+00
7.9432E+03	9.022E-01	-1.979E+00	8.620E-01	-2.017E+00
1.0000E+04	9.013E-01	-1.561E+00	8.608E-01	-1.608E+00
1.2589E+04	9.008E-01	-1.225E+00	8.602E-01	-1.284E+00
1.5848E+04	9.009E-01	-9.557E-01	8.598E-01	-1.029E+00
1.9952E+04	9.013E-01	-7.364E-01	8.596E-01	-8.296E-01
2.5118E+04	9.021E-01	-5.563E-01	8.595E-01	-6.737E-01
3.1622E+04	9.035E-01	-4.060E-01	8.594E-01	-5.537E-01
3.9810E+04	9.056E-01	-2.775E-01	8.592E-01	-4.635E-01
5.0118E+04	9.089E-01	-1.643E-01	8.585E-01	-3.983E-01
6.3095E+04	9.135E-01	-6.085E-02	8.570E-01	-3.552E-01
7.9432E+04	9.199E-01	4.066E-02	8.534E-01	-3.321E-01
1.0000E+05	9.281E-01	1.386E-01	8.457E-01	-3.280E-01
1.2589E+05	9.381E-01	2.400E-01	8.302E-01	-3.418E-01
1.5848E+05	9.493E-01	3.492E-01	8.019E-01	-3.711E-01
1.9952E+05	9.605E-01	4.718E-01	7.550E-01	-4.109E-01
2.5118E+05	9.706E-01	6.144E-01	6.858E-01	-4.523E-01
3.1622E+05	9.788E-01	7.858E-01	5.949E-01	-4.842E-01

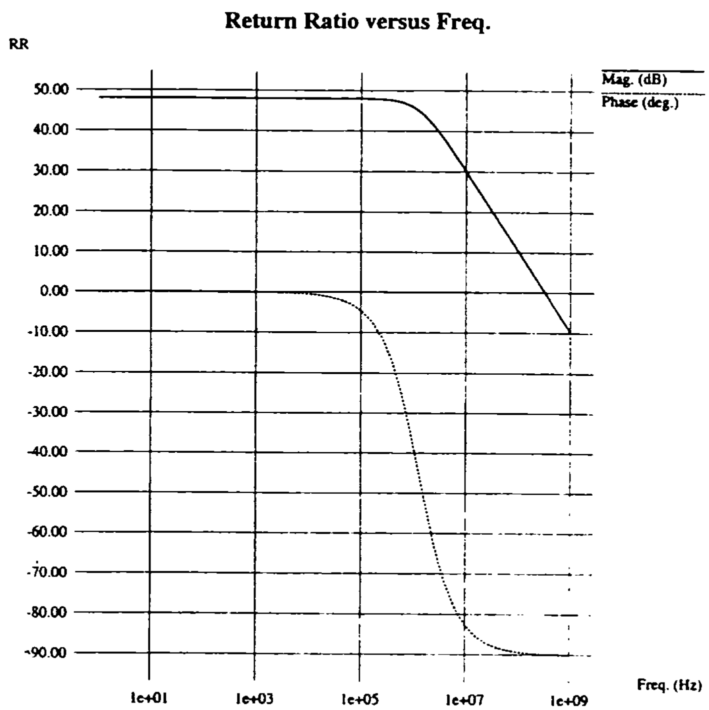


9.44 (a) See above.
(b) The unity-gain frequency is ~8kHz.
The phase margin is ~90°.
The gain margin is ~40dB.

```
RETURN RATIO
.SUBCKT AMP (3 4)
VDD 1 0 5
IB 1 2 0.5M
M1 2 3 0 0 CMOSN W=50U L=0.6U
R1 2 4 20K
C1 2 0 2P
.MODEL CMOSN NMOS LEVEL=1 LAMBDA=0.0333 VTO=0.6 KP=194U
.ENDS AMP
.OPTIONS NOMOD
XRRV (11 12) AMP
VT 11 12 AC 1

XRRI (21 22) AMP
IT 0 31 AC 1
VDUMMY1 31 21 0
VDUMMY2 22 31 0

.AC DEC 5 1 1G
.PRINT AC RRVR=PAR('-VM(12)/VM(11)*COS(3.14*(VP(12)-VP(11))/180)')\
RRVI=PAR('-VM(12)/VM(11)*SIN(3.14*(VP(12)-VP(11))/180)')\
RRIR=PAR('-IM(VDUMMY2)/IM(VDUMMY1)*COS(3.14*(IP(VDUMMY2)-IP(VDUMMY1))/180)')\
RRII=PAR('-IM(VDUMMY2)/IM(VDUMMY1)*SIN(3.14*(IP(VDUMMY2)-IP(VDUMMY1))/180)')\
.OPTIONS SPICE
.WIDTH OUT=80
.END

****** OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000

+0:11      = 8.453E-01 0:12      = 8.453E-01 0:21      = 8.453E-01
+0:22      = 8.453E-01 0:31      = 8.453E-01 1:1       = 5.000E+00
+1:2       = 8.453E-01 2:1       = 5.000E+00 2:2       = 8.453E-01

**** MOSFETS

SUBCKT   XRRV        XRRI
ELEMENT  1:M1        2:M1
MODEL    1:CMOSN     2:CMOSN
 ID       5.000E-04  5.000E-04
 IBS      0.         0.
 IBD     -8.453E-15 -8.453E-15
 VGS      8.453E-01  8.453E-01
 VDS      8.453E-01  8.453E-01
 VBS      0.         0.
 VTH      6.000E-01  6.000E-01
 VDSAT    2.453E-01  2.453E-01
 BETA     1.662E-02  1.662E-02
 GAM EFF  0.         0.
 GM       4.077E-03  4.077E-03
 GDS      1.619E-05  1.619E-05
 GMB      0.         0.
 CDTOT    0.         0.
 CGTOT    0.         0.
 CSTOT    0.         0.
 CBTOT    0.         0.
 CGS      0.         0.
 CGD      0.         0.
```

****** AC ANALYSIS   TNOM= 27.000 TEMP= 27.000

FREQ	RRVR	RRVI	RRIR	RRII
1.0000E+00	2.517E+02	-4.011E-01	9.999E+27	1.592E+25
1.5848E+00	2.517E+02	-4.012E-01	9.999E+27	1.592E+25
2.5118E+00	2.517E+02	-4.014E-01	9.999E+27	1.592E+25
3.9810E+00	2.517E+02	-4.017E-01	9.999E+27	1.592E+25
6.3095E+00	2.517E+02	-4.022E-01	9.999E+27	1.592E+25
1.0000E+01	2.517E+02	-4.029E-01	9.999E+27	1.592E+25
1.5848E+01	2.517E+02	-4.040E-01	9.999E+27	1.592E+25
2.5118E+01	2.517E+02	-4.058E-01	9.999E+27	-1.592E+25
3.9810E+01	2.517E+02	-4.087E-01	9.999E+27	-1.592E+25
6.3095E+01	2.517E+02	-4.133E-01	9.999E+27	-1.592E+25
1.0000E+02	2.517E+02	-4.204E-01	9.999E+27	1.592E+25
1.5848E+02	2.517E+02	-4.319E-01	9.999E+27	1.592E+25
2.5118E+02	2.517E+02	-4.500E-01	9.999E+27	1.592E+25
3.9810E+02	2.517E+02	-4.787E-01	9.999E+27	-1.592E+25
6.3095E+02	2.517E+02	-5.241E-01	9.999E+27	1.592E+25
1.0000E+03	2.517E+02	-5.962E-01	9.999E+27	-1.592E+25
1.5848E+03	2.517E+02	-7.104E-01	9.999E+27	1.592E+25
2.5118E+03	2.517E+02	-8.914E-01	9.999E+27	-1.592E+25
3.9810E+03	2.517E+02	-1.178E+00	9.999E+27	1.592E+25
6.3095E+03	2.517E+02	-1.632E+00	9.999E+27	-1.592E+25
1.0000E+04	2.517E+02	-2.353E+00	9.999E+27	1.592E+25
1.5848E+04	2.517E+02	-3.495E+00	9.999E+27	1.592E+25
2.5118E+04	2.516E+02	-5.303E+00	9.999E+27	1.592E+25
3.9810E+04	2.515E+02	-8.166E+00	9.999E+27	1.592E+25
6.3095E+04	2.511E+02	-1.269E+01	9.999E+27	-1.592E+25
1.0000E+05	2.502E+02	-1.980E+01	9.999E+27	-1.592E+25
1.5848E+05	2.479E+02	-3.088E+01	9.999E+27	1.592E+25
2.5118E+05	2.424E+02	-4.763E+01	9.999E+27	1.592E+25
3.9810E+05	2.297E+02	-7.132E+01	9.999E+27	-1.592E+25
6.3095E+05	2.029E+02	-9.970E+01	9.999E+27	-1.592E+25
1.0000E+06	1.569E+02	-1.221E+02	9.999E+27	1.592E+25
1.5848E+06	1.000E+02	-1.233E+02	9.999E+27	-1.592E+25
2.5118E+06	5.235E+01	-1.023E+02	9.999E+27	-1.592E+25
3.9810E+06	2.380E+01	-7.378E+01	9.999E+27	1.592E+25
6.3095E+06	1.003E+01	-4.936E+01	9.999E+27	1.592E+25
1.0000E+07	4.085E+00	-3.191E+01	9.999E+27	-1.592E+25
1.5848E+07	1.636E+00	-2.033E+01	9.999E+27	1.592E+25
2.5118E+07	6.503E-01	-1.288E+01	9.999E+27	1.592E+25
3.9810E+07	2.569E-01	-8.141E+00	9.999E+27	-1.592E+25
6.3095E+07	1.008E-01	-5.139E+00	9.999E+27	1.592E+25
1.0000E+08	3.920E-02	-3.243E+00	9.999E+27	-1.592E+25
1.5848E+08	1.501E-02	-2.046E+00	9.999E+27	-1.592E+25
2.5118E+08	5.594E-03	-1.291E+00	9.999E+27	1.592E+25
3.9810E+08	1.988E-03	-8.149E-01	9.999E+27	-1.592E+25
6.3095E+08	6.402E-04	-5.142E-01	9.999E+27	1.592E+25
1.0000E+09	1.596E-04	-3.244E-01	9.999E+27	-1.592E+25



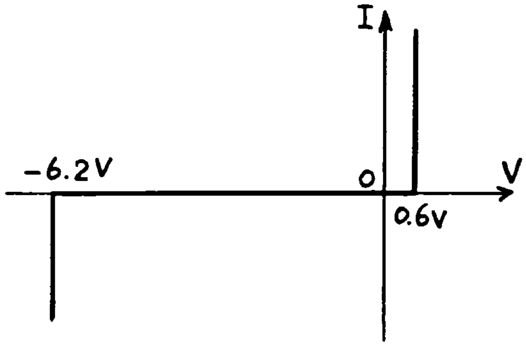
9.45 (a) See above.

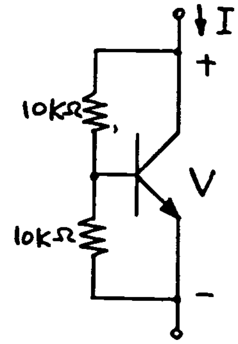
(b) The unity-gain frequency is ~400MHz.
The phase margin is ~90°.
The gain margin is ∞ (the phase never reaches -180°).

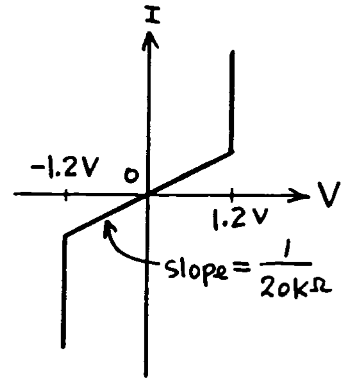
CHAPTER 10

10.1

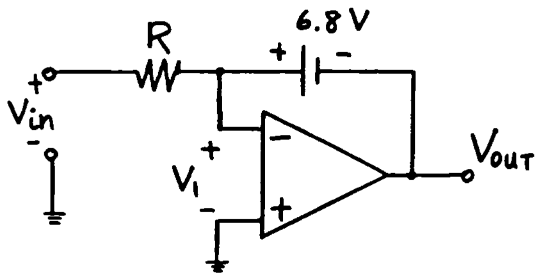
Zener diode characteristic





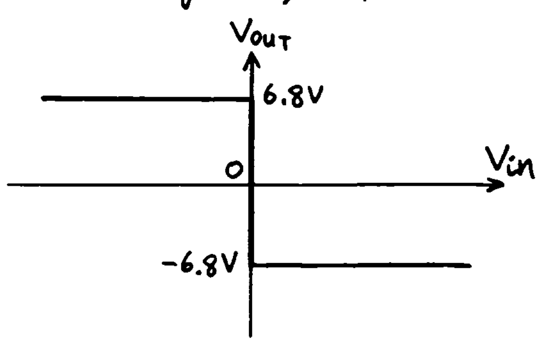


For Vin positive, V_{OUT} is negative and we have



Since $V_1 = 0$, $V_{OUT} = -6.8V$

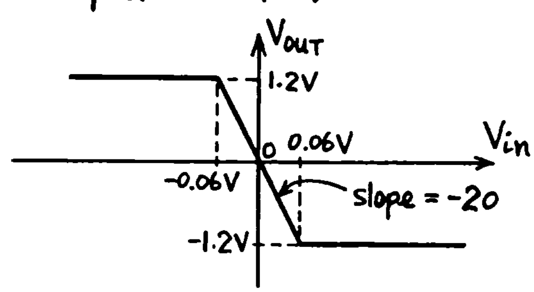
For Vin negative, $V_{OUT} = +6.8V$



For V_{OUT} between ±1.2V, the transistor is off and

$$\frac{\Delta V_{OUT}}{\Delta V_{in}} = -\frac{20k\Omega}{1k\Omega} = -20$$

Outside this range, V_{OUT} is clamped to ±1.2V



10.2

Consider the V_{BE}-multiplier.

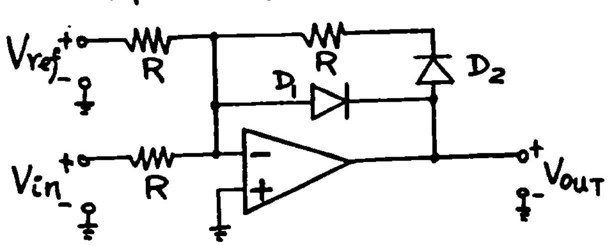
∵ Symmetrical transistor, ∴

```
CKT FOR PROBLEM 10.2
RIN 1 2 1K
Q1 4 3 2 N
R1 4 3 10K
R2 3 2 10K
EOP_AMP 4 0 2 0 -10000
VIN 1 0 0V
.MODEL N NPN BF=99 BR=99 IS=1E-16
.PLOT DC V(4)
.DC VIN -0.1 0.1 0.01
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

****** DC TRANSFER CURVES                    TNOM=  27.000 TEMP=  27.000

    VOLT       V(4)
(A       )  -2.000E+00  -1.000E-00      0.         1.000E-00   2.000E+00
                +           +           +           +           +
-1.000E-01  1.37E+00-+-----+-----+-----+-----+-----+-----+---A-+-----+-
-9.000E-02  1.35E+00 +     +     +     +     +     +     +   A +     +
-8.000E-02  1.32E+00 +     +     +     +     +     +     +   A +     +
-7.000E-02  1.28E+00 +     +     +     +     +     +     +  A  +     +
-6.000E-02  1.18E+00 +     +     +     +     +     +     + A   +     +
-5.000E-02  9.97E-01 +     +     +     +     +     +     A     +     +
-4.000E-02  7.98E-01 +     +     +     +     +     +   A +     +     +
-3.000E-02  5.99E-01 +     +     +     +     +     +A    +     +     +
-2.000E-02  3.99E-01 +     +     +     +     +    A+     +     +     +
-1.000E-02  2.00E-01 +     +     +     +     +  A  +     +     +     +
 0.         0.      -+-----+-----+-----+-----A-----+-----+-----+-----+-
 1.000E-02 -2.00E-01 +     +     +     +  A  +     +     +     +     +
 2.000E-02 -3.99E-01 +     +     +     +A    +     +     +     +     +
 3.000E-02 -5.99E-01 +     +     +    A+     +     +     +     +     +
 4.000E-02 -7.98E-01 +     +     + A   +     +     +     +     +     +
 5.000E-02 -9.97E-01 +     +     A     +     +     +     +     +     +
 6.000E-02 -1.18E+00 +     +  A  +     +     +     +     +     +     +
 7.000E-02 -1.28E+00 +     + A   +     +     +     +     +     +     +
 8.000E-02 -1.32E+00 +     +A    +     +     +     +     +     +     +
 9.000E-02 -1.35E+00 +     +A    +     +     +     +     +     +     +
 1.000E-01 -1.37E+00-+-----+A----+-----+-----+-----+-----+-----+-----+-
                +           +           +           +           +

****** OPERATING POINT INFORMATION           TNOM=  27.000 TEMP=  27.000

+0:1      =  0.       0:2      =  0.       0:3      =  0.
+0:4      =  0.

**** BIPOLAR JUNCTION TRANSISTORS

ELEMENT  0:Q1
MODEL    0:N
 IB        0.
 IC        0.
 VBE       0.
 VCE       0.
 VBC       0.
 VS        0.
 POWER     0.
 BETAD     0.
 GM        0.
 RPI      2.560E+16
 RX        0.
 RO       2.586E+14
 CPI       0.
 CMU       0.
 CBX       0.
 CCS       0.
 BETAAC    0.
 FT       6.216E-03
```

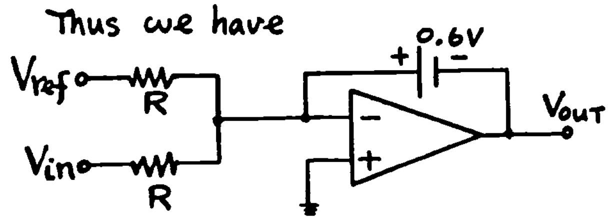
10.3

For $V_{in} > -V_{ref}$, the input to the op amp is positive, and V_{OUT} is negative.

$\therefore$ D_1 is on, D_2 is off.

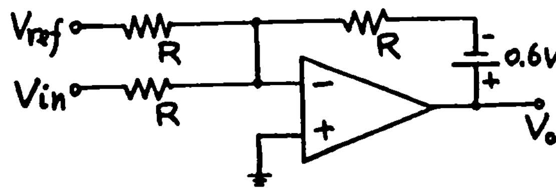


Thus we have

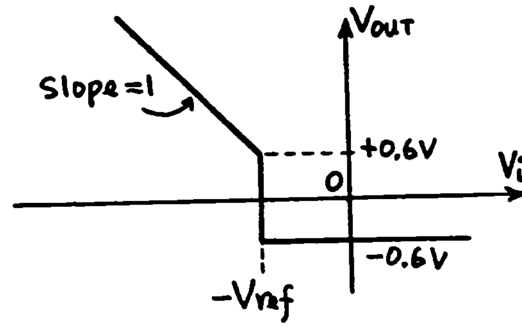


$$V_{OUT} = -0.6V$$

For $V_{in} < -V_{ref}$, V_{OUT} is positive and D_2 is on, D_1 is off.



$$V_{OUT} = 0.6 + V_{in} + V_{ref}$$



10.4

The multiplier transfer function is

$$I_{OUT} = I_{c_{3-5}} - I_{c_{4-6}}$$

$$= I_{EE} \tanh\frac{V_1}{2V_T} \tanh\frac{V_2}{2V_T}$$

For $V_1 = 0.1\,V_T$

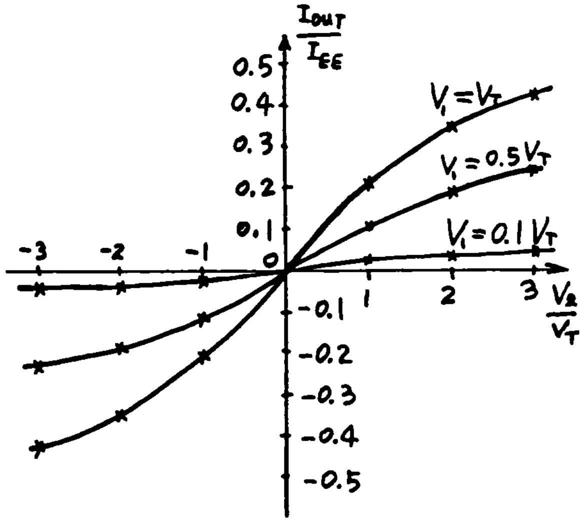
$$I_{OUT} = I_{EE} \times 0.050 \tanh\frac{V_2}{2V_T}$$

$V_1 = 0.5\,V_T$

$$I_{OUT} = I_{EE} \times 0.245 \tanh\frac{V_2}{2V_T}$$

$V_1 = V_T$

$$I_{OUT} = I_{EE} \times 0.462 \tanh\frac{V_2}{2V_T}$$



10.5

For the emitter coupled pair

$$\Delta I_C = I_{C1} - I_{C2} = I_{EE}\tanh\left(\frac{V_{id}}{2V_T}\right)$$

$$= I_{EE}\frac{e^{\frac{V_{id}}{V_T}} - 1}{e^{\frac{V_{id}}{V_T}} + 1}$$

The slope of the characteristic is

$$\frac{d(\Delta I_c)}{dV_{id}} = \frac{I_{EE}}{V_T}\frac{(e^{\frac{V_{id}}{V_T}}+1)e^{\frac{V_{id}}{V_T}} - (e^{\frac{V_{id}}{V_T}}-1)e^{\frac{V_{id}}{V_T}}}{(e^{\frac{V_{id}}{V_T}}+1)^2}$$

$$= \frac{I_{EE}}{V_T}\frac{2e^{\frac{V_{id}}{V_T}}}{(e^{\frac{V_{id}}{V_T}}+1)^2} \quad \text{------(1)}$$

For $V_{id} = 0$

$$\frac{d(\Delta I_c)}{dV_{id}} = \frac{1}{2}\frac{I_{EE}}{V_T}$$

In (1) put $\frac{d(\Delta I_c)}{dV_{id}} = 0.99 \times \frac{1}{2} \times \frac{I_{EE}}{V_T}$

$\therefore\ 0.99 = 4\frac{a}{(a+1)^2}$ where $a = e^{\frac{V_{id}}{V_T}}$

$\therefore\ a^2 + 2a + 1 = \frac{4}{0.99}a$

$\therefore\ a^2 - 2.0404a + 1 = 0$

$$\therefore\ a = \frac{2.0404 \pm \sqrt{4.1632 - 4}}{2}$$

$= 1.222$ or 0.8182

$\therefore\ V_{id} = \pm 0.2V_T = \pm 5\,mV$

10.6

$$\Delta I_C = I_{EE}\tanh\left(\frac{V_{id}}{2V_T}\right)$$

$$\simeq I_{EE}\left[\frac{V_{id}}{2V_T} - \frac{1}{3}\left(\frac{V_{id}}{2V_T}\right)^3\right]$$

Put $V_{id} = V\sin\omega_0 t$

Then

$$\Delta I_C = \frac{I_{EE}}{2V_T}\left[V\sin\omega_0 t - \frac{1}{12}\frac{V^3}{V_T^2}\sin^3\omega_0 t\right]$$

$$= \frac{I_{EE}V}{2V_T}\left[\sin\omega_0 t - \frac{V^3}{48V_T^2}(3\sin\omega_0 t - \sin 3\omega_0 t)\right]$$

$$\therefore\ I_{OUT}(t) = I_0\left[\sin\omega_0 t + \frac{\frac{V^2}{48V_T^2}}{1 - 3\frac{V^2}{48V_T^2}}\sin 3\omega_0 t\right]$$

put $$\frac{\frac{V^2}{48V_T^2}}{1 - 3\frac{V_T^2}{48V_T^2}} = 0.01$$

$\therefore\ V = 17.7\,mV$

This is the maximum allowable input amplitude.

10-4

```
EMITTER-COUPLED PAIR
VCC 1 0 5V
VDUMMY 1 11 0V
Q1 11 3 2 N
Q2 1 4 2 N
IEE 2 0 1MA
VIN 3 0 SIN 0 17.7MV 10K
VIN2 4 0 0V
.MODEL N NPN
.PLOT TRAN I(VDUMMY)
.TRAN 0.005MS 0.2MS
.FOUR 10K I(VDUMMY)
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END
```

```
 ******  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000

+0:1       = 5.000E+00 0:2       =-7.560E-01 0:3       =   0.
+0:4       =   0.      0:11      = 5.000E+00
```

**** BIPOLAR JUNCTION TRANSISTORS

ELEMENT	0:Q1	0:Q2
MODEL	0:N	0:N
IB	4.950E-06	4.950E-06
IC	4.950E-04	4.950E-04
VBE	7.560E-01	7.560E-01
VCE	5.756E+00	5.756E+00
VBC	-5.000E+00	-5.000E+00
VS	-5.000E+00	-5.000E+00
POWER	2.853E-03	2.853E-03
BETAD	1.000E+02	1.000E+02
GM	1.914E-02	1.914E-02
RPI	5.224E+03	5.224E+03
RX	0.	0.
RO	5.000E+16	5.000E+16
CPI	0.	0.
CMU	0.	0.
CBX	0.	0.
CCS	0.	0.
BETAAC	9.999E+01	9.999E+01
FT	3.046E+12	3.046E+12

```
 ******  TRANSIENT ANALYSIS                 TNOM=  27.000 TEMP=  27.000

   TIME       I(VDUMMY)
(A      )           3.000E-04   4.000E-04   5.000E-04   6.000E-04   7.000E-04
                        +           +           +           +           +

   0.     4.95E-04-+-----+-----+-----+----A+-----+-----+-----+-----+-
5.000E-06 5.47E-04 +     +     +     +     +     A     +     +     +
1.000E-05 5.93E-04 +     +     +     +     +     +    A+     +     +
1.500E-05 6.29E-04 +     +     +     +     +     +     +   A +     +
2.000E-05 6.50E-04 +     +     +     +     +     +     +     A     +
2.500E-05 6.58E-04 +     +     +     +     +     +     +     +A    +
3.000E-05 6.50E-04 +     +     +     +     +     +     +     A     +
3.500E-05 6.29E-04 +     +     +     +     +     +     +   A +     +
4.000E-05 5.92E-04 +     +     +     +     +     +    A+     +     +
4.500E-05 5.47E-04 +     +     +     +     +     A     +     +     +
5.000E-05 4.95E-04-+-----+-----+-----+----A+-----+-----+-----+-----+-
5.500E-05 4.43E-04 +     +     +    A+     +     +     +     +     +
6.000E-05 3.97E-04 +     +     A     +     +     +     +     +     +
6.500E-05 3.61E-04 +     + A   +     +     +     +     +     +     +
7.000E-05 3.41E-04 +    A+     +     +     +     +     +     +     +
7.500E-05 3.32E-04 +  A  +     +     +     +     +     +     +     +
8.000E-05 3.41E-04 +    A+     +     +     +     +     +     +     +
8.500E-05 3.61E-04 +     + A   +     +     +     +     +     +     +
9.000E-05 3.98E-04 +     +     A     +     +     +     +     +     +
9.500E-05 4.43E-04 +     +     +    A+     +     +     +     +     +
1.000E-04 4.95E-04-+-----+-----+-----+----A+-----+-----+-----+-----+-
1.050E-04 5.47E-04 +     +     +     +     +     A     +     +     +
1.100E-04 5.93E-04 +     +     +     +     +     +    A+     +     +
1.150E-04 6.29E-04 +     +     +     +     +     +     +   A +     +
1.200E-04 6.50E-04 +     +     +     +     +     +     +     A     +
1.250E-04 6.58E-04 +     +     +     +     +     +     +     +A    +
1.300E-04 6.50E-04 +     +     +     +     +     +     +     A     +
1.350E-04 6.29E-04 +     +     +     +     +     +     +   A +     +
1.400E-04 5.92E-04 +     +     +     +     +     +    A+     +     +
1.450E-04 5.47E-04 +     +     +     +     +     A     +     +     +
1.500E-04 4.95E-04-+-----+-----+-----+----A+-----+-----+-----+-----+-
1.550E-04 4.43E-04 +     +     +    A+     +     +     +     +     +
1.600E-04 3.97E-04 +     +     A     +     +     +     +     +     +
1.650E-04 3.61E-04 +     + A   +     +     +     +     +     +     +
1.700E-04 3.41E-04 +    A+     +     +     +     +     +     +     +
1.750E-04 3.32E-04 +  A  +     +     +     +     +     +     +     +
1.800E-04 3.41E-04 +    A+     +     +     +     +     +     +     +
1.850E-04 3.61E-04 +     + A   +     +     +     +     +     +     +
1.900E-04 3.98E-04 +     +     A     +     +     +     +     +     +
1.950E-04 4.43E-04 +     +     +    A+     +     +     +     +     +
2.000E-04 4.95E-04-+-----+-----+-----+----A+-----+-----+-----+-----+-
                   +           +           +           +           +
```

******

FOURIER COMPONENTS OF TRANSIENT RESPONSE I(VDUMMY)

DC COMPONENT =   4.950D-04

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	9.999E+03	1.640E-04	1.000E+00	-7.158E-03	0.
2	2.000E+04	1.607E-08	9.800E-05	1.195E-01	1.267E-01
3	3.000E+04	1.421E-06	8.664E-03	1.655E+00	1.662E+00
4	4.000E+04	2.449E-09	1.493E-05	2.509E+00	2.516E+00
5	5.000E+04	5.072E-08	3.093E-04	1.324E+02	1.324E+02
6	6.000E+04	3.553E-10	2.166E-06	3.370E+00	3.378E+00
7	7.000E+04	2.602E-08	1.586E-04	-1.432E+02	-1.432E+02
8	8.000E+04	1.085E-09	6.615E-06	-1.973E+01	-1.973E+01
9	9.000E+04	1.752E-07	1.068E-03	-1.926E+01	-1.925E+01

TOTAL HARMONIC DISTORTION =   8.737E-01 PERCENT

```
EMITTER-COUPLED PAIR WITH EMITTER DEGENERATION
VCC 1 0 5V
VDUMMY 1 7 0V
Q1 7 3 5 N
Q2 1 4 6 N
RE1 5 2 200
RE2 6 2 200
IEE 2 0 1MA
VIN 3 0 SIN 0 17.7MV 10K
VIN2 4 0 0V
.MODEL N NPN
.PLOT TRAN I(VDUMMY)
.TRAN 0.005MS 0.2MS
.FOUR 10K I(VDUMMY)
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END
```

```
 ******  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000

+0:1       = 5.000E+00 0:2       =-8.560E-01 0:3       =   0.
+0:4       =   0.      0:5       =-7.560E-01 0:6       =-7.560E-01
+0:7       = 5.000E+00
```

**** BIPOLAR JUNCTION TRANSISTORS

ELEMENT	0:Q1	0:Q2
MODEL	0:N	0:N
IB	4.950E-06	4.950E-06
IC	4.950E-04	4.950E-04
VBE	7.560E-01	7.560E-01
VCE	5.756E+00	5.756E+00
VBC	-5.000E+00	-5.000E+00
VS	-5.000E+00	-5.000E+00
POWER	2.853E-03	2.853E-03
BETAD	1.000E+02	1.000E+02
GM	1.914E-02	1.914E-02
RPI	5.224E+03	5.224E+03
RX	0.	0.
RO	5.000E+16	5.000E+16
CPI	0.	0.
CMU	0.	0.
CBX	0.	0.
CCS	0.	0.
BETAAC	9.999E+01	9.999E+01
FT	3.046E+12	3.046E+12

```
******  TRANSIENT ANALYSIS                 TNOM=  27.000 TEMP=  27.000

   TIME        I(VDUMMY)
(A       )      4.600E-04     4.800E-04     5.000E-04     5.200E-04     5.400E-04
                    +             +             +             +             +
 0.        4.95E-04-+------+------+------+---A--+------+------+------+------+-
 5.000E-06 5.06E-04 +      +      +      +      +   A  +      +      +      +
 1.000E-05 5.15E-04 +      +      +      +      +      +  A   +      +      +
 1.500E-05 5.23E-04 +      +      +      +      +      +      + A    +      +
 2.000E-05 5.28E-04 +      +      +      +      +      +      +     A+      +
 2.500E-05 5.30E-04 +      +      +      +      +      +      +      A      +
 3.000E-05 5.28E-04 +      +      +      +      +      +      +     A+      +
 3.500E-05 5.23E-04 +      +      +      +      +      +      + A    +      +
 4.000E-05 5.15E-04 +      +      +      +      +      +  A   +      +      +
 4.500E-05 5.06E-04 +      +      +      +      +   A  +      +      +      +
 5.000E-05 4.95E-04-+------+------+------+---A--+------+------+------+------+-
 5.500E-05 4.84E-04 +      +      +  A   +      +      +      +      +      +
 6.000E-05 4.75E-04 +      +  A   +      +      +      +      +      +      +
 6.500E-05 4.67E-04 +    A +      +      +      +      +      +      +      +
 7.000E-05 4.62E-04 + A    +      +      +      +      +      +      +      +
 7.500E-05 4.60E-04 A      +      +      +      +      +      +      +      +
 8.000E-05 4.62E-04 + A    +      +      +      +      +      +      +      +
 8.500E-05 4.67E-04 +    A +      +      +      +      +      +      +      +
 9.000E-05 4.75E-04 +      +  A   +      +      +      +      +      +      +
 9.500E-05 4.84E-04 +      +      +  A   +      +      +      +      +      +
 1.000E-04 4.95E-04-+------+------+------+---A--+------+------+------+------+-
 1.050E-04 5.06E-04 +      +      +      +      +   A  +      +      +      +
 1.100E-04 5.15E-04 +      +      +      +      +      +  A   +      +      +
 1.150E-04 5.23E-04 +      +      +      +      +      +      + A    +      +
 1.200E-04 5.28E-04 +      +      +      +      +      +      +     A+      +
 1.250E-04 5.30E-04 +      +      +      +      +      +      +      A      +
 1.300E-04 5.28E-04 +      +      +      +      +      +      +     A+      +
 1.350E-04 5.23E-04 +      +      +      +      +      +      + A    +      +
 1.400E-04 5.15E-04 +      +      +      +      +      +  A   +      +      +
 1.450E-04 5.06E-04 +      +      +      +      +   A  +      +      +      +
 1.500E-04 4.95E-04-+------+------+------+---A--+------+------+------+------+-
 1.550E-04 4.84E-04 +      +      +  A   +      +      +      +      +      +
 1.600E-04 4.75E-04 +      +  A   +      +      +      +      +      +      +
 1.650E-04 4.67E-04 +    A +      +      +      +      +      +      +      +
 1.700E-04 4.62E-04 + A    +      +      +      +      +      +      +      +
 1.750E-04 4.60E-04 A      +      +      +      +      +      +      +      +
 1.800E-04 4.62E-04 + A    +      +      +      +      +      +      +      +
 1.850E-04 4.67E-04 +    A +      +      +      +      +      +      +      +
 1.900E-04 4.75E-04 +      +  A   +      +      +      +      +      +      +
 1.950E-04 4.84E-04 +      +      +  A   +      +      +      +      +      +
 2.000E-04 4.95E-04-+------+------+------+---A--+------+------+------+------+-
                    +             +             +             +             +
```

******

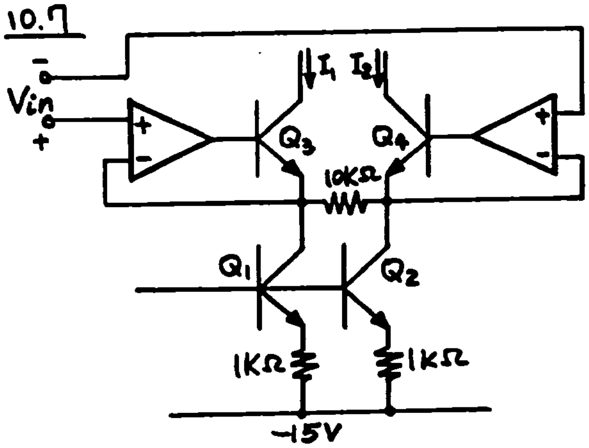
FOURIER COMPONENTS OF TRANSIENT RESPONSE I(VDUMMY)

DC COMPONENT = 4.950D-04

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	9.999E+03	3.467E-05	1.000E+00	-7.119E-03	0.
2	2.000E+04	3.142E-09	9.063E-05	1.159E-01	1.230E-01
3	3.000E+04	1.601E-08	4.616E-04	1.509E+02	1.509E+02
4	4.000E+04	2.206E-10	6.361E-06	5.205E+00	5.213E+00
5	5.000E+04	1.067E-08	3.078E-04	1.394E+02	1.394E+02
6	6.000E+04	3.660E-11	1.055E-06	6.605E+00	6.612E+00
7	7.000E+04	6.790E-09	1.958E-04	-1.576E+02	-1.576E+02
8	8.000E+04	2.139E-10	6.168E-06	-2.165E+01	-2.165E+01
9	9.000E+04	3.783E-08	1.091E-03	-1.996E+01	-1.995E+01

TOTAL HARMONIC DISTORTION = 1.243E-01 PERCENT

10.7



The nominal bias currents are

$I_{c1} = I_{c2} = I_{c3} = I_{c4} = 1mA$

Given $\frac{\Delta R}{R} = \pm 0.3\%$, $\frac{\Delta I_s}{I_s} = \pm 2\%$

From (4.154) the worst-case mismatch in I_{c1} and I_{c2} is

$$\left|\frac{\Delta I_c}{I_c}\right| = \frac{1}{1+g_m R}\frac{\Delta I_s}{I_s} + \frac{g_m R}{1+g_m R}\frac{\Delta R}{R}$$

$$= \frac{1}{1+\frac{1000}{26}}0.02 + \frac{\frac{1000}{26}}{1+\frac{1000}{26}}0.003$$

$$= 3.43\times10^{-3}$$

$$\therefore \Delta I_c = 3.43\times10^{-3}\times10^{-3}A$$

$$= 3.43\,\mu A$$

This gives an input offset (when $I_1 = I_2$) of

$$V_{os} = \frac{\Delta I_c}{2G_m} = 3.43\mu A \times 10K\Omega \times \frac{1}{2}$$

$$= 17.1\ mV$$

Offset due to Q_3 and Q_4 is negligible because of the ideal op amps.

```
VOLTAGE-CURRENT CONVERTER
VCC 1 0 15V
VDUMMY 1 14 0V
VSS 2 0 -15V
Q1 14 7 5 N
Q2 1 8 6 N
REE 5 6 10K
Q3 5 11 9 N
Q4 6 11 10 N
R1 9 2 1K
R2 10 2 1K
R3 12 2 1K
IBIAS 1 13 1MA
Q5 13 11 12 N
Q6 1 13 11 N
EAMP1 7 0 4 5 10000
EAMP2 8 0 3 6 10000
VS 3 0 SIN 0 5V 10K
EVS 4 0 3 0 -1
RX1 3 0 100MEG
RX2 4 0 100MEG
.MODEL N NPN IS=1E-16
.PLOT TRAN I(VDUMMY)
.TRAN 0.005MS 0.2MS
.FOUR 10K I(VDUMMY)
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END
```

```
******  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000

+0:1      = 1.500E+01 0:2     =-1.500E+01 0:3     =   0.
+0:4      =   0.      0:5     =-7.739E-05 0:6     =-7.739E-05
+0:7      = 7.739E-01 0:8     = 7.739E-01 0:9     =-1.399E+01
+0:10     =-1.399E+01 0:11    =-1.321E+01 0:12    =-1.399E+01
+0:13     =-1.253E+01 0:14    = 1.500E+01
```

**** BIPOLAR JUNCTION TRANSISTORS

ELEMENT	0:Q1	0:Q2	0:Q3	0:Q4	0:Q5	0:Q6
MODEL	0:N	0:N	0:N	0:N	0:N	0:N
IB	9.898E-06	9.898E-06	9.997E-06	9.997E-06	9.997E-06	2.969E-07
IC	9.898E-04	9.898E-04	9.997E-04	9.997E-04	9.997E-04	2.969E-05
VBE	7.739E-01	7.739E-01	7.742E-01	7.742E-01	7.742E-01	6.832E-01
VCE	1.500E+01	1.500E+01	1.399E+01	1.399E+01	1.457E+00	2.821E+01
VBC	-1.422E+01	-1.422E+01	-1.321E+01	-1.321E+01	-6.832E-01	-2.753E+01
VS	-1.500E+01	-1.500E+01	7.739E-05	7.739E-05	1.253E+01	-1.500E+01
POWER	1.485E-02	1.485E-02	1.399E-02	1.399E-02	1.465E-03	8.381E-04
BETAD	1.000E+02	1.000E+02	1.000E+02	1.000E+02	1.000E+02	1.000E+02
GM	3.827E-02	3.827E-02	3.865E-02	3.865E-02	3.865E-02	1.148E-03
RPI	2.613E+03	2.613E+03	2.587E+03	2.587E+03	2.587E+03	8.710E+04
RX	0.	0.	0.	0.	0.	0.
RO	1.422E+17	1.422E+17	1.321E+17	1.321E+17	6.832E+15	2.753E+17
CPI	0.	0.	0.	0.	0.	0.
CMU	0.	0.	0.	0.	0.	0.
CBX	0.	0.	0.	0.	0.	0.
CCS	0.	0.	0.	0.	0.	0.
BETAAC	9.999E+01	9.999E+01	9.999E+01	9.999E+01	9.999E+01	9.999E+01
FT	6.090E+12	6.090E+12	6.151E+12	6.151E+12	6.151E+12	1.827E+11

```
******  TRANSIENT ANALYSIS                    TNOM=  27.000 TEMP=  27.000

   TIME        I(VDUMMY)
(A        )    0.           5.000E-04     1.000E-03     1.500E-03     2.000E-03
                     +             +             +             +             +
 0.        9.90E-04-+------+------+------+------A------+------+------+------+-
 5.000E-06 6.84E-04 +      +      +    A +      +      +      +      +      +
 1.000E-05 4.12E-04 +      +    A +      +      +      +      +      +      +
 1.500E-05 1.89E-04 +    A +      +      +      +      +      +      +      +
 2.000E-05 5.57E-05 + A    +      +      +      +      +      +      +      +
 2.500E-05 3.89E-11 A      +      +      +      +      +      +      +      +
 3.000E-05 4.85E-05 +A     +      +      +      +      +      +      +      +
 3.500E-05 1.89E-04 +    A +      +      +      +      +      +      +      +
 4.000E-05 4.12E-04 +      +    A +      +      +      +      +      +      +
 4.500E-05 6.86E-04 +      +      +    A +      +      +      +      +      +
 5.000E-05 9.90E-04-+------+------+------+------A------+------+------+------+-
 5.500E-05 1.29E-03 +      +      +      +      +      +A     +      +      +
 6.000E-05 1.57E-03 +      +      +      +      +      +      + A    +      +
 6.500E-05 1.79E-03 +      +      +      +      +      +      +      +A     +
 7.000E-05 1.92E-03 +      +      +      +      +      +      +      +    A +
 7.500E-05 1.98E-03 +      +      +      +      +      +      +      +     A+
 8.000E-05 1.93E-03 +      +      +      +      +      +      +      +    A +
 8.500E-05 1.79E-03 +      +      +      +      +      +      +      +A     +
 9.000E-05 1.57E-03 +      +      +      +      +      +      + A    +      +
 9.500E-05 1.29E-03 +      +      +      +      +      +A     +      +      +
 1.000E-04 9.90E-04-+------+------+------+------A------+------+------+------+-
 1.050E-04 6.86E-04 +      +      +    A +      +      +      +      +      +
 1.100E-04 4.11E-04 +      +    A +      +      +      +      +      +      +
 1.150E-04 1.89E-04 +    A +      +      +      +      +      +      +      +
 1.200E-04 5.57E-05 + A    +      +      +      +      +      +      +      +
 1.250E-04 3.89E-11 A      +      +      +      +      +      +      +      +
 1.300E-04 4.85E-05 +A     +      +      +      +      +      +      +      +
 1.350E-04 1.89E-04 +    A +      +      +      +      +      +      +      +
 1.400E-04 4.12E-04 +      +    A +      +      +      +      +      +      +
 1.450E-04 6.86E-04 +      +      +    A +      +      +      +      +      +
 1.500E-04 9.90E-04-+------+------+------+------A------+------+------+------+-
 1.550E-04 1.29E-03 +      +      +      +      +      +A     +      +      +
 1.600E-04 1.57E-03 +      +      +      +      +      +      + A    +      +
 1.650E-04 1.79E-03 +      +      +      +      +      +      +      +A     +
 1.700E-04 1.92E-03 +      +      +      +      +      +      +      +    A +
 1.750E-04 1.98E-03 +      +      +      +      +      +      +      +     A+
 1.800E-04 1.93E-03 +      +      +      +      +      +      +      +    A +
 1.850E-04 1.79E-03 +      +      +      +      +      +      +      +A     +
 1.900E-04 1.57E-03 +      +      +      +      +      +      + A    +      +
 1.950E-04 1.29E-03 +      +      +      +      +      +A     +      +      +
 2.000E-04 9.90E-04-+------+------+------+------A------+------+------+------+-
                     +             +             +             +             +
```

```
******
FOURIER COMPONENTS OF TRANSIENT RESPONSE I(VDUMMY)
DC COMPONENT =   9.898D-04
```

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	9.999E+03	9.870E-04	1.000E+00	1.799E+02	0.
2	2.000E+04	8.858E-08	8.974E-05	1.735E+02	-6.391E+00
3	3.000E+04	1.121E-06	1.135E-03	-4.055E+01	-2.205E+02
4	4.000E+04	1.752E-08	1.775E-05	-1.310E+02	-3.110E+02
5	5.000E+04	4.472E-07	4.531E-04	6.031E+01	-1.196E+02
6	6.000E+04	1.803E-08	1.827E-05	4.726E+01	-1.327E+02
7	7.000E+04	3.780E-07	3.830E-04	-1.080E+02	-2.880E+02
8	8.000E+04	2.962E-08	3.001E-05	-1.678E+02	-3.478E+02
9	9.000E+04	7.880E-07	7.983E-04	1.381E+02	-4.179E+01

TOTAL HARMONIC DISTORTION =   1.513E-01 PERCENT

10.8

Assuming an ideal op amp.

$$\frac{V_{in}}{R} = -\frac{V_Z}{R} \quad \therefore \; V_Z = -V_{in}$$

But $V_Z = K V_X V_Y = K V_{OUT} V_{REF}$

Thus $V_{OUT} = \dfrac{-V_{in}}{K V_{REF}}$

and this circuit produces an output proportional to the quotient of two voltages.

10.9

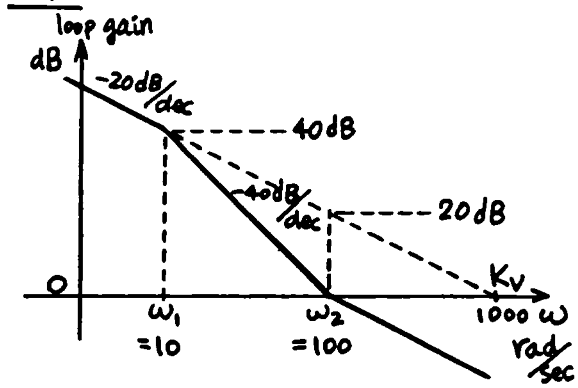
Loop bandwidth $= K_v = K_o K_D$

$= 10^3\ 1/s$

In order to produce poles at 45° to the axis, we add a loop filter pole at ω_1 where

$\omega_1 = 2K_v = 2000$ rad/s

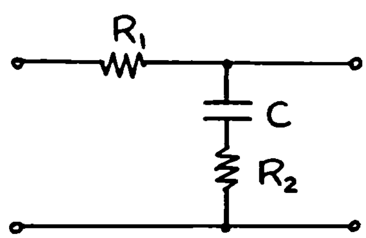
10.10



If ω_2 (the zero frequency) is at the unity gain point, then then the loop phase shift will be −135° at this point, ∴ we require $\omega_2 = 100$ rad/sec

If $\omega_1 = 10$ rad/sec, the requirements will be satisfied (see diagram)

The filter becomes



$\omega_2 = \dfrac{1}{R_2 C} \qquad \omega_1 = \dfrac{1}{(R_1+R_2)C}$

$\therefore \dfrac{\omega_2}{\omega_1} = 1 + \dfrac{R_1}{R_2} = 10$

$\therefore R_1 = 9R_2$

Appropriate values of R_1, R_2 and C can now be chosen.

10.11

For capture we need

$$|(\omega_i - \omega_o)| < \frac{\pi}{2} K_v \left|F[j(\omega_i - \omega_o)]\right|$$

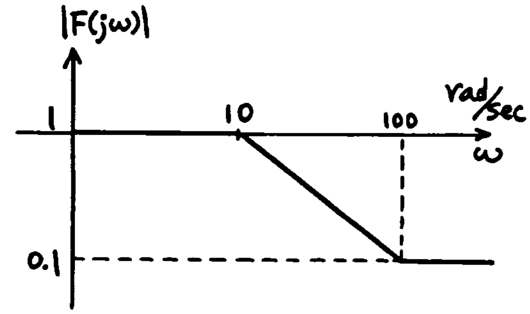
Put $|(\omega_i - \omega_o)| = \frac{\pi}{2} K_v \left|F[j(\omega_i - \omega_o)]\right|$

$\omega_o = 10^5$ rad/sec

$K_v = 1000$ rad/sec

$$\therefore |(\omega_i - \omega_o)| = 1570 \left|F[j(\omega_i - \omega_o)]\right| \quad \text{---- (1)}$$

From problem 10.10



From the figure we can solve (1) to find

$(\omega_i - \omega_o) = 157$ rad/sec

and this is the capture range.

10.12

For the 560B

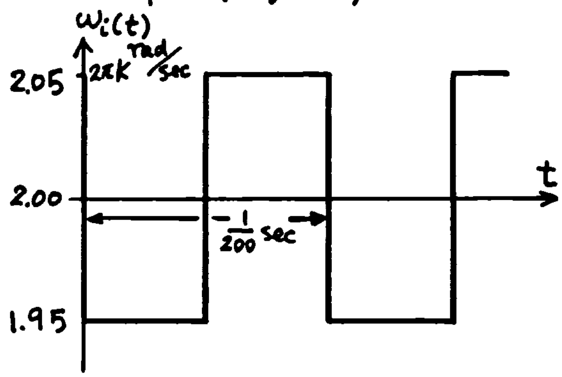
$K_o = 0.93\,\omega_o = 0.93(2\pi)(2000)$

$= 11687$ rad/V·s

$K_v = 2.36\,\omega_o = 2.36(2\pi)(2000)$

$= 29657$ rad/s

The input frequency is

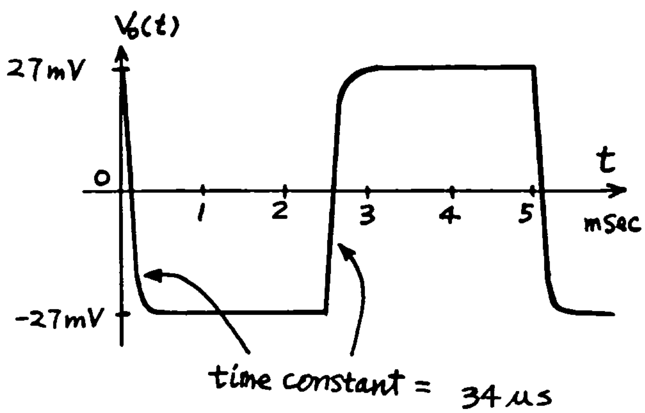


$$\frac{V_o}{\omega_i}(s) = \frac{1}{K_o}\frac{K_v}{S+K_v} \quad \text{-----} \quad (1)$$

The peak-to-peak amplitude of the output is

$$\Delta V_o = \frac{\Delta W_i}{K_o} = \frac{2\pi\,(100)}{11687} = 54\,mV$$

Since $w_i(t)$ is a square wave, (1) predicts that $V_o(t)$ has a time constant $\frac{1}{K_v} = 34\,\mu s$ and the waveform shown below.



10.13

$$f = \frac{I_1}{4C\,V_{BE(ON)}}$$

$I_1 = (10\,kHz)(4)(0.01\mu F)(0.7V)$ ← guess (0.7 V)

$= 280\mu A$

$$V_{BE} = V_T \ln \frac{2(280\mu A)}{10^{-16}}$$

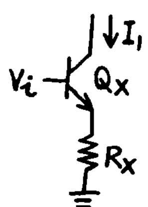
$= 0.763\,V$

$I_1 = 305\,\mu A$ at center freq

for 2:1 variation of freq,

vary $I_1 = 203$ to $407\mu A$

$\Delta I_1 = 204\mu A$



$$I_1 = \frac{V_i - V_{BEX}}{R_X}$$

dc bias :

$$I_1 = 305\mu = \frac{V_i - 0.763}{R_X}$$

$$\Delta I_1 \simeq \frac{\Delta V_i}{R_X}$$

$$204\mu = \frac{200mV}{R_X}$$

$R_X = 1k$

dc bias $I_1 = 305\mu = \dfrac{V_i - 0.763}{1k}$

bias $V_i = 1.07V$

make current in R small compared to 2I

$$\frac{V_{BE}}{R} = 60\mu A$$

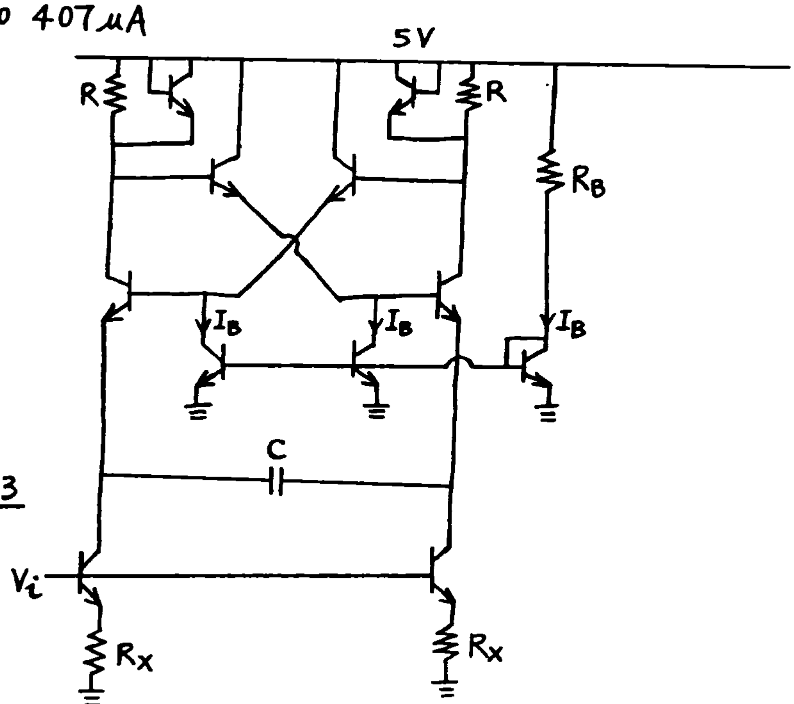
$$R = \frac{0.763V}{60\mu A} = 12.7\,k$$

I_B is bias only.

$I_B = 200\mu A$ is adequate .

$$I_B = \frac{5 - V_T \ln \frac{200\mu}{10^{-16}}}{R_B} = 200\mu$$

$R_B = 21.3\,k$



```
******
* SUMMARY
* VI (V)      OSCILLATION FREQ (KHZ)
* 0.97        10
* 1.07        14.3
* 1.17        18.2
******
* OSCILLATION FREQ VARIATION = 18.2:10 = 1.82:1
******
* VI = BIAS = 1.07V
* EXPECTED OSCILLATION FREQUENCY = 10 KHZ
*               PERIOD = 100 US
* ACTUAL OSCILLATION FREQUENCY = 14.3 KHZ
*               PERIOD = 70 US
* THIS DIFFERENCE IS DUE TO THE ERROR IN HAND-CALCULATING
* THE VBE AND INPUT CURRENT I1 WHICH IS DIRECTLY
* PROPORTIONAL TO THE OSCILLATION FREQUENCY.
******
* VOLTAGE CONTROLLED OSCILLATOR
VCC 1 0 5V
Q1 7 10 5 N
Q2 8 9 6 N
Q3 1 7 9 N
Q4 1 8 10 N
Q5 1 1 7 N
Q6 1 1 8 N
Q7 5 2 3 N
Q8 6 2 4 N
R1 1 7 12.7K
R2 1 8 12.7K
R3 3 0 1K
R4 4 0 1K
Q9 10 13 0 N
Q10 9 13 0 N
Q11 13 13 0 N
R5 1 13 21.3K
* ADDED A SMALL CAPACITOR BETWEEN NODES 7,8
CAP 5 61 0.01UF
VI 2 0 1.07V
* ADDED A SERIES PWL VOLTAGE TO LOAD CAP TO SET IC
VKICK 61 6 PWL 0 100M 1US 100M 1.01US 0
CX1 7 8 0.01NF
.MODEL N NPN BF=100 IS=1E-16
.PLOT V(6,5)
.TRAN 5US 500US
.OPTIONS NOPAGE NOMOD LIMPTS=700
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

***** OPERATING POINT STATUS IS ALL       SIMULATION TIME IS      0.
+0:1       = 5.000E+00 0:2        = 1.070E+00 0:3        = 3.251E-01
+0:4       = 3.251E-01 0:5        = 2.784E+00 0:6        = 2.784E+00
+0:7       = 4.260E+00 0:8        = 4.260E+00 0:9        = 3.528E+00
+0:10      = 3.528E+00 0:13       = 7.319E-01 0:61       = 2.884E+00
**** BIPOLAR JUNCTION TRANSISTORS
ELEMENT  0:Q1       0:Q2       0:Q3       0:Q4       0:Q5       0:Q6
MODEL    0:N        0:N        0:N        0:N        0:N        0:N
 IB      3.187E-06  3.187E-06  1.958E-06  1.958E-06  2.598E-06  2.598E-06
 IC      3.187E-04  3.187E-04  1.958E-04  1.958E-04  2.598E-04  2.598E-04
 VBE     7.446E-01  7.446E-01  7.320E-01  7.320E-01  7.394E-01  7.394E-01
 VCE     1.476E+00  1.476E+00  1.471E+00  1.471E+00  7.394E-01  7.394E-01
 VBC    -7.320E-01 -7.320E-01 -7.394E-01 -7.394E-01   0.         0.
 VS     -4.260E+00 -4.260E+00 -5.000E+00 -5.000E+00 -5.000E+00 -5.000E+00
 POWER   4.730E-04  4.730E-04  2.895E-04  2.895E-04  1.940E-04  1.940E-04
 BETAD   1.000E+02  1.000E+02  1.000E+02  1.000E+02  1.000E+02  1.000E+02
 GM      1.232E-02  1.232E-02  7.569E-03  7.569E-03  1.005E-02  1.005E-02
 RPI     8.115E+03  8.115E+03  1.321E+04  1.321E+04  9.953E+03  9.953E+03
 RX       0.         0.         0.         0.         0.         0.
 RO      7.320E+15  7.320E+15  7.393E+15  7.393E+15  2.586E+14  2.586E+14
 BETAAC  9.999E+01  9.999E+01  9.999E+01  9.999E+01  9.999E+01  9.999E+01
 FT      1.961E+12  1.961E+12  1.204E+12  1.204E+12  1.599E+12  1.599E+12
ELEMENT  0:Q7       0:Q8       0:Q9       0:Q10      0:Q11
MODEL    0:N        0:N        0:N        0:N        0:N
 IB      3.219E-06  3.219E-06  1.945E-06  1.945E-06  1.945E-06
 IC      3.219E-04  3.219E-04  1.945E-04  1.945E-04  1.945E-04
 VBE     7.449E-01  7.449E-01  7.319E-01  7.319E-01  7.319E-01
 VCE     2.458E+00  2.458E+00  3.528E+00  3.528E+00  7.319E-01
 VBC    -1.714E+00 -1.714E+00 -2.796E+00 -2.796E+00   0.
 VS     -2.784E+00 -2.784E+00 -3.528E+00 -3.528E+00 -7.319E-01
 POWER   7.939E-04  7.939E-04  6.879E-04  6.879E-04  1.438E-04
 BETAD   1.000E+02  1.000E+02  1.000E+02  1.000E+02  1.000E+02
 GM      1.245E-02  1.245E-02  7.522E-03  7.522E-03  7.522E-03
 RPI     8.035E+03  8.035E+03  1.329E+04  1.329E+04  1.329E+04
 RX       0.         0.         0.         0.         0.
 RO      1.714E+16  1.714E+16  2.796E+16  2.796E+16  2.586E+14
 BETAAC  9.999E+01  9.999E+01  9.999E+01  9.999E+01  9.999E+01
 FT      1.980E+12  1.980E+12  1.197E+12  1.197E+12  1.197E+12
******  TRANSIENT ANALYSIS                  TNOM=  27.000 TEMP=  27.000
   TIME       V(6,5)
(A        )   -1.000E-00   -5.000E-01    0.          5.000E-01   1.000E-00
                   +            +          +             +           +
  0.          0.
 5.000E-06 -2.79E-02
 1.000E-05 -1.81E-01
 1.500E-05 -3.34E-01
 2.000E-05 -4.88E-01
 2.500E-05 -4.68E-01
 3.000E-05 -3.07E-01
 3.500E-05 -1.46E-01
 4.000E-05  1.50E-02
 4.500E-05  1.76E-01
 5.000E-05  3.37E-01
 5.500E-05  4.99E-01
 6.000E-05  4.85E-01
 6.500E-05  3.24E-01
 7.000E-05  1.63E-01
 7.500E-05  2.04E-03
 8.000E-05 -1.59E-01
 8.500E-05 -3.20E-01
 9.000E-05 -4.81E-01
 9.500E-05 -5.05E-01
 1.000E-04 -3.44E-01
 1.050E-04 -1.83E-01
 1.100E-04 -2.22E-02
 1.150E-04  1.39E-01
 1.200E-04  3.00E-01
 1.250E-04  4.61E-01
 1.300E-04  5.25E-01
 1.350E-04  3.64E-01
 1.400E-04  2.04E-01
 1.450E-04  4.26E-02
 1.500E-04 -1.18E-01
 1.550E-04 -2.79E-01
 1.600E-04 -4.40E-01
 1.650E-04 -5.46E-01
 1.700E-04 -3.85E-01
 1.750E-04 -2.24E-01
 1.800E-04 -6.33E-02
 1.850E-04  9.77E-02
 1.900E-04  2.59E-01
 1.950E-04  4.20E-01
 2.000E-04  5.67E-01
 2.050E-04  4.06E-01
 2.100E-04  2.45E-01
 2.150E-04  8.37E-02
 2.200E-04 -7.72E-02
 2.250E-04 -2.38E-01
 2.300E-04 -3.99E-01
 2.350E-04 -5.60E-01
 2.400E-04 -4.26E-01
 2.450E-04 -2.65E-01
 2.500E-04 -1.04E-01
 2.550E-04  5.65E-02
 2.600E-04  2.17E-01
 2.650E-04  3.74E-01
 2.700E-04  5.32E-01
 2.750E-04  4.06E-01
 2.800E-04  2.45E-01
 2.850E-04  8.43E-02
 2.900E-04 -7.66E-02
 2.950E-04 -2.38E-01
 3.000E-04 -3.99E-01
 3.050E-04 -5.59E-01
 3.100E-04 -4.27E-01
 3.150E-04 -2 66E-01
 3.200E-04 -1.05E-01
 3.250E-04  5.63E-02
 3.300E-04  2.17E-01
 3.350E-04  3.78E-01
 3.400E-04  5.39E-01
 3.450E-04  4.47E-01
 3.500E-04  2.86E-01
 3.550E-04  1.25E-01
 3.600E-04 -3.57E-02
 3.650E-04 -1.96E-01
 3.700E-04 -3.54E-01
 3.750E-04 -5.11E-01
 3.800E-04 -4.28E-01
 3.850E-04 -2.67E-01
 3.900E-04 -1.06E-01
 3.950E-04  5.47E-02
 4.000E-04  2.16E-01
 4.050E-04  3.77E-01
 4.100E-04  5.37E-01
 4.150E-04  4.49E-01
 4.200E-04  2.88E-01
 4.250E-04  1.27E-01
 4.300E-04 -3.38E-02
 4.350E-04 -1.95E-01
 4.400E-04 -3.56E-01
 4.450E-04 -5.17E-01
 4.500E-04 -4.70E-01
 4.550E-04 -3.09E-01
 4.600E-04 -1.48E-01
 4.650E-04  1.32E-02
 4.700E-04  1.74E-01
 4.750E-04  3.32E-01
 4.800E-04  4.89E-01
 4.850E-04  4.50E-01
 4.900E-04  2.99E-01
 4.950E-04  1.28E-01
 5.000E-04 -3.30E-02
```

```
******
* VI = BIAS + 100MV = 1.17V
* EXPECTED OSCILLATION FREQUENCY = 13.3 KHZ
*             PERIOD = 75 US
* ACTUAL OSCILLATION FREQUENCY = 18.2 KHZ
*             PERIOD = 55 US
******
* VOLTAGE CONTROLLED OSCILLATOR
VCC 1 0 5V
Q1 7 10 5 N
Q2 8 9 6 N
Q3 1 7 9 N
Q4 1 8 10 N
Q5 1 1 7 N
Q6 1 1 8 N
Q7 5 2 3 N
Q8 6 2 4 N
R1 1 7 12.7K
R2 1 8 12.7K
R3 3 0 1K
R4 4 0 1K
Q9 10 13 0 N
Q10 9 13 0 N
Q11 13 13 0 N
R5 1 13 21.3K
* ADDED A SMALL CAPACITOR BETWEEN NODES 7,8
CAP 5 61 0.01UF
VI 2 0 1.17V
* ADDED A SERIES PWL VOLTAGE TO LOAD CAP TO SET IC
VKICK 61 6 PWL 0 100M 1US 100M 1.01US 0
CX1 7 8 0.01NF
.MODEL N NPN BF=100 IS=1E-16
.PLOT V(6,5)
.TRAN 5US 500US
.OPTIONS NOPAGE NOMOD LIMPTS=700
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END
```

****** OPERATING POINT INFORMATION   TNOM= 27.000 TEMP= 27.000

```
+0:1    = 5.000E+00 0:2    = 1.170E+00 0:3    = 4.186E-01
+0:4    = 4.186E-01 0:5    = 2.769E+00 0:6    = 2.769E+00
+0:7    = 4.252E+00 0:8    = 4.252E+00 0:9    = 3.520E+00
+0:10   = 3.520E+00 0:13   = 7.319E-01 0:61   = 2.869E+00
```

**** BIPOLAR JUNCTION TRANSISTORS

ELEMENT	0:Q1	0:Q2	0:Q3	0:Q4	0:Q5	0:Q6
MODEL	0:N	0:N	0:N	0:N	0:N	0:N
IB	4.103E-06	4.103E-06	1.967E-06	1.967E-06	3.500E-06	3.500E-06
IC	4.103E-04	4.103E-04	1.967E-04	1.967E-04	3.500E-04	3.500E-04
VBE	7.512E-01	7.512E-01	7.321E-01	7.321E-01	7.471E-01	7.471E-01
VCE	1.483E+00	1.483E+00	1.479E+00	1.479E+00	7.471E-01	7.471E-01
VBC	-7.321E-01	-7.321E-01	-7.471E-01	-7.471E-01	0.	0.
VS	-4.252E+00	-4.252E+00	-5.000E+00	-5.000E+00	-5.000E+00	-5.000E+00
POWER	6.117E-04	6.117E-04	2.924E-04	2.924E-04	2.641E-04	2.641E-04
BETAD	1.000E+02	1.000E+02	1.000E+02	1.000E+02	1.000E+02	1.000E+02
GM	1.586E-02	1.586E-02	7.604E-03	7.604E-03	1.353E-02	1.353E-02
RPI	6.303E+03	6.303E+03	1.315E+04	1.315E+04	7.390E+03	7.390E+03
RX	0.	0.	0.	0.	0.	0.
RO	7.321E+15	7.321E+15	7.470E+15	7.470E+15	2.586E+14	2.586E+14
BETAAC	9.999E+01	9.999E+01	9.999E+01	9.999E+01	9.999E+01	9.999E+01
FT	2.524E+12	2.524E+12	1.210E+12	1.210E+12	2.153E+12	2.153E+12

ELEMENT	0:Q7	0:Q8	0:Q9	0:Q10	0:Q11
MODEL	0:N	0:N	0:N	0:N	0:N
IB	4.144E-06	4.144E-06	1.945E-06	1.945E-06	1.945E-06
IC	4.144E-04	4.144E-04	1.945E-04	1.945E-04	1.945E-04
VBE	7.514E-01	7.514E-01	7.319E-01	7.319E-01	7.319E-01
VCE	2.351E+00	2.351E+00	3.520E+00	3.520E+00	7.319E-01
VBC	-1.599E+00	-1.599E+00	-2.788E+00	-2.788E+00	0.
VS	-2.769E+00	-2.769E+00	-3.520E+00	-3.520E+00	-7.319E-01
POWER	9.775E-04	9.775E-04	6.864E-04	6.864E-04	1.438E-04
BETAD	1.000E+02	1.000E+02	1.000E+02	1.000E+02	1.000E+02
GM	1.602E-02	1.602E-02	7.522E-03	7.522E-03	7.522E-03
RPI	6.240E+03	6.240E+03	1.329E+04	1.329E+04	1.329E+04
RX	0.	0.	0.	0.	0.
RO	1.599E+16	1.599E+16	2.788E+16	2.788E+16	2.586E+14
BETAAC	9.999E+01	9.999E+01	9.999E+01	9.999E+01	9.999E+01
FT	2.550E+12	2.550E+12	1.197E+12	1.197E+12	1.197E+12

****** TRANSIENT ANALYSIS   TNOM= 27.000 TEMP= 27.000

```
   TIME       V(6,5)
A              -1.000E+00  -5.000E-01    0.     5.000E-01   1.000E+00
                 +           +           +           +           +

0.          0      +-----+-----+-----+-----A-----+-----+-----+-----+
5.000E-06 -6.52E-02 +     +     +     +   A +     +     +     +     +
1.000E-05 -2.68E-01 +     +     +     A     +     +     +     +     +
1.500E-05 -4.70E-01 +     +     +A    +     +     +     +     +     +
2.000E-05 -4.55E-01 +     +     +A    +     +     +     +     +     +
2.500E-05 -2.48E-01 +     +     +     A     +     +     +     +     +
3.000E-05 -4.10E-02 +     +     +     +    A+     +     +     +     +
3.500E-05  1.66E-01 +     +     +     +     +   A +     +     +     +
4.000E-05  3.73E-01 +     +     +     +     +     +  A  +     +     +
4.500E-05  5.66E-01 +     +     +     +     +     +     + A   +     +
5.000E-05  3.59E-01-+-----+-----+-----+-----+-----+--A--+-----+-----+
5.500E-05  1.52E-01 +     +     +     +     +   A +     +     +     +
6.000E-05 -5.56E-02 +     +     +     +    A+     +     +     +     +
6.500E-05 -2.63E-01 +     +     +     A     +     +     +     +     +
7.000E-05 -4.70E-01 +     +     +A    +     +     +     +     +     +
7.500E-05 -4.71E-01 +     +     +A    +     +     +     +     +     +
8.000E-05 -2.63E-01 +     +     +     A     +     +     +     +     +
8.500E-05 -5.61E-02 +     +     +     +    A+     +     +     +     +
9.000E-05  1.51E-01 +     +     +     +     +   A +     +     +     +
9.500E-05  3.58E-01 +     +     +     +     +     +  A  +     +     +
1.000E-04  5.65E-01-+-----+-----+-----+-----+-----+-----+-A---+-----+
1.050E-04  3.76E-01 +     +     +     +     +     +  A  +     +     +
1.100E-04  1.69E-01 +     +     +     +     +   A +     +     +     +
1.150E-04 -3.83E-02 +     +     +     +    A+     +     +     +     +
1.200E-04 -2.45E-01 +     +     +     A     +     +     +     +     +
1.250E-04 -4.53E-01 +     +     +A    +     +     +     +     +     +
1.300E-04 -4.90E-01 +     +     A     +     +     +     +     +     +
1.350E-04 -2.83E-01 +     +     +    A+     +     +     +     +     +
1.400E-04 -7.54E-02 +     +     +     +   A +     +     +     +     +
1.450E-04  1.32E-01 +     +     +     +     +  A  +     +     +     +
1.500E-04  3.39E-01-+-----+-----+-----+-----+-----+-A---+-----+-----+
1.550E-04  5.46E-01 +     +     +     +     +     +     +A    +     +
1.600E-04  3.96E-01 +     +     +     +     +     +   A +     +     +
1.650E-04  1.89E-01 +     +     +     +     +    A+     +     +     +
1.700E-04 -1.81E-02 +     +     +     +     A     +     +     +     +
1.750E-04 -2.25E-01 +     +     +     +A    +     +     +     +     +
1.800E-04 -4.32E-01 +     +     + A   +     +     +     +     +     +
1.850E-04 -5.10E-01 +     +     A     +     +     +     +     +     +
1.900E-04 -3.03E-01 +     +     +    A+     +     +     +     +     +
1.950E-04 -9.57E-02 +     +     +     +   A +     +     +     +     +
2.000E-04  1.12E-01-+-----+-----+-----+-----+--A--+-----+-----+-----+
2.050E-04  3.19E-01 +     +     +     +     +     + A   +     +     +
2.100E-04  5.26E-01 +     +     +     +     +     +     +A    +     +
2.150E-04  4.17E-01 +     +     +     +     +     +   A +     +     +
2.200E-04  2.09E-01 +     +     +     +     +    A+     +     +     +
2.250E-04  2.25E-03 +     +     +     +     A     +     +     +     +
2.300E-04 -2.05E-01 +     +     +     +A    +     +     +     +     +
2.350E-04 -4.12E-01 +     +     + A   +     +     +     +     +     +
2.400E-04 -5.30E-01 +     +    A+     +     +     +     +     +     +
2.450E-04 -3.23E-01 +     +     +   A +     +     +     +     +     +
2.500E-04 -1.16E-01-+-----+-----+-----+--A--+-----+-----+-----+-----+
2.550E-04  9.13E-02 +     +     +     +     + A   +     +     +     +
2.600E-04  2.99E-01 +     +     +     +     +     +A    +     +     +
2.650E-04  5.06E-01 +     +     +     +     +     +     A     +     +
2.700E-04  4.37E-01 +     +     +     +     +     +   A +     +     +
2.750E-04  2.30E-01 +     +     +     +     +     A     +     +     +
2.800E-04  2.24E-02 +     +     +     +     +A    +     +     +     +
2.850E-04 -1.85E-01 +     +     +     + A   +     +     +     +     +
2.900E-04 -3.92E-01 +     +     +  A  +     +     +     +     +     +
2.950E-04 -5.51E-01 +     +    A+     +     +     +     +     +     +
3.000E-04 -3.43E-01-+-----+-----+---A-+-----+-----+-----+-----+-----+
3.050E-04 -1.36E-01 +     +     +     +  A  +     +     +     +     +
3.100E-04  7.11E-02 +     +     +     +     + A   +     +     +     +
3.150E-04  2.78E-01 +     +     +     +     +     +A    +     +     +
3.200E-04  4.85E-01 +     +     +     +     +     +     A     +     +
3.250E-04  4.57E-01 +     +     +     +     +     +    A+     +     +
3.300E-04  2.50E-01 +     +     +     +     +     A     +     +     +
3.350E-04  4.27E-02 +     +     +     +     +A    +     +     +     +
3.400E-04 -1.65E-01 +     +     +     + A   +     +     +     +     +
3.450E-04 -3.72E-01 +     +     +  A  +     +     +     +     +     +
3.500E-04 -5.73E-01-+-----+---A-+-----+-----+-----+-----+-----+-----+
3.550E-04 -3.66E-01 +     +     +  A  +     +     +     +     +     +
3.600E-04 -1.58E-01 +     +     +     + A   +     +     +     +     +
3.650E-04  4.89E-02 +     +     +     +     +A    +     +     +     +
3.700E-04  2.56E-01 +     +     +     +     +     A     +     +     +
3.750E-04  4.63E-01 +     +     +     +     +     +    A+     +     +
3.800E-04  4.79E-01 +     +     +     +     +     +    A+     +     +
3.850E-04  2.72E-01 +     +     +     +     +     +A    +     +     +
3.900E-04  6.44E-02 +     +     +     +     + A   +     +     +     +
3.950E-04 -1.43E-01 +     +     +     +  A  +     +     +     +     +
4.000E-04 -3.50E-01-+-----+-----+---A-+-----+-----+-----+-----+-----+
4.050E-04 -5.57E-01 +     +    A+     +     +     +     +     +     +
4.100E-04 -3.85E-01 +     +     +  A  +     +     +     +     +     +
4.150E-04 -1.78E-01 +     +     +     + A   +     +     +     +     +
4.200E-04  2.94E-02 +     +     +     +     +A    +     +     +     +
4.250E-04  2.37E-01 +     +     +     +     +     A     +     +     +
4.300E-04  4.44E-01 +     +     +     +     +     +    A+     +     +
4.350E-04  4.99E-01 +     +     +     +     +     +     A     +     +
4.400E-04  2.91E-01 +     +     +     +     +     +A    +     +     +
4.450E-04  8.41E-02 +     +     +     +     + A   +     +     +     +
4.500E-04 -1.23E-01-+-----+-----+-----+--A--+-----+-----+-----+-----+
4.550E-04 -3.30E-01 +     +     +   A +     +     +     +     +     +
4.600E-04 -5.37E-01 +     +    A+     +     +     +     +     +     +
4.650E-04 -4.05E-01 +     +     + A   +     +     +     +     +     +
4.700E-04 -1.98E-01 +     +     +     +A    +     +     +     +     +
4.750E-04  9.58E-03 +     +     +     +     A     +     +     +     +
4.800E-04  2.17E-01 +     +     +     +     +    A+     +     +     +
4.850E-04  4.24E-01 +     +     +     +     +     +   A +     +     +
4.900E-04  5.19E-01 +     +     +     +     +     +     A     +     +
4.950E-04  3.11E-01 +     +     +     +     +     +A    +     +     +
5.000E-04  1.04E-01-+-----+-----+-----+-----+-A---+-----+-----+-----+
                 +           +           +           +           +
```

```
******
* VI = BIAS -100MV = 0.97V
* EXPECTED OSCILLATION FREQUENCY = 6.65 KHZ
*              PERIOD = 150 US
* ACTUAL OSCILLATION FREQUENCY = 10 KHZ
*              PERIOD = 100 US
******
* VOLTAGE CONTROLLED OSCILLATOR
VCC 1 0 5V
Q1 7 10 5 N
Q2 8 9 6 N
Q3 1 7 9 N
Q4 1 8 10 N
Q5 1 1 7 N
Q6 1 1 8 N
Q7 5 2 3 N
Q8 6 2 4 N
R1 1 7 12.7K
R2 1 8 12.7K
R3 3 0 1K
R4 4 0 1K
Q9 10 13 0 N
Q10 9 13 0 N
Q11 13 13 0 N
R5 1 13 21.3K
* ADDED A SMALL CAPACITOR BETWEEN NODES 7,8
CAP 5 61 0.01UF
VI 2 0 0.97V
* ADDED A SERIES PWL VOLTAGE TO LOAD CAP TO SET IC
VKICK 61 6 PWL 0 100M 1US 100M 1.01US 0
CX1 7 8 0.01NF
.MODEL N NPN BF=100 IS=1E-16
.PLOT V(6,5)
.TRAN 5US 500US
.OPTIONS NOPAGE NOMOD LIMPTS=700
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END
```

****** OPERATING POINT INFORMATION   TNOM= 27.000 TEMP= 27.000

```
+0:1    = 5.000E+00 0:2    = 9.700E-01 0:3    = 2.337E-01
+0:4    = 2.337E-01 0:5    = 2.803E+00 0:6    = 2.803E+00
+0:7    = 4.271E+00 0:8    = 4.271E+00 0:9    = 3.539E+00
+0:10   = 3.539E+00 0:13   = 7.319E-01 0:61   = 2.903E+00
```

**** BIPOLAR JUNCTION TRANSISTORS

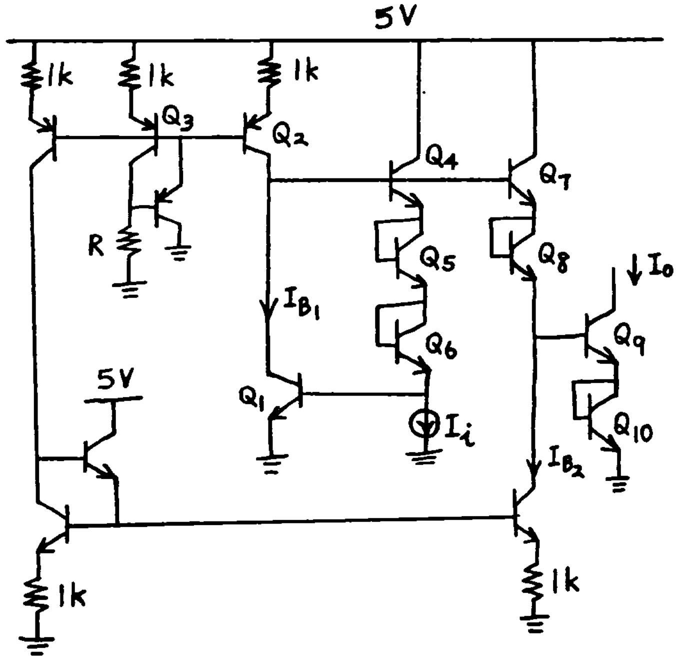
ELEMENT	0:Q1	0:Q2	0:Q3	0:Q4	0:Q5	0:Q6
MODEL	0:N	0:N	0:N	0:N	0:N	0:N
IB	2.290E-06	2.290E-06	1.949E-06	1.949E-06	1.719E-06	1.719E-06
IC	2.290E-04	2.290E-04	1.949E-04	1.949E-04	1.719E-04	1.719E-04
VBE	7.361E-01	7.361E-01	7.319E-01	7.319E-01	7.287E-01	7.287E-01
VCE	1.468E+00	1.468E+00	1.460E+00	1.460E+00	7.287E-01	7.287E-01
VBC	-7.319E-01	-7.319E-01	-7.287E-01	-7.287E-01	0.	0.
VS	-4.271E+00	-4.271E+00	-5.000E+00	-5.000E+00	-5.000E+00	-5.000E+00
POWER	3.379E-04	3.379E-04	2.861E-04	2.861E-04	1.265E-04	1.265E-04
BETAD	1.000E+02	1.000E+02	1.000E+02	1.000E+02	1.000E+02	1.000E+02
GM	8.856E-03	8.856E-03	7.535E-03	7.535E-03	6.646E-03	6.646E-03
RPI	1.129E+04	1.129E+04	1.327E+04	1.327E+04	1.504E+04	1.504E+04
RX	0.	0.	0.	0.	0.	0.
RO	7.319E+15	7.319E+15	7.286E+15	7.286E+15	2.586E+14	2.586E+14
BETAAC	9.999E+01	9.999E+01	9.999E+01	9.999E+01	9.999E+01	9.999E+01
FT	1.409E+12	1.409E+12	1.199E+12	1.199E+12	1.057E+12	1.057E+12

ELEMENT	0:Q7	0:Q8	0:Q9	0:Q10	0:Q11
MODEL	0:N	0:N	0:N	0:N	0:N
IB	2.313E-06	2.313E-06	1.945E-06	1.945E-06	1.945E-06
IC	2.313E-04	2.313E-04	1.945E-04	1.945E-04	1.945E-04
VBE	7.363E-01	7.363E-01	7.319E-01	7.319E-01	7.319E-01
VCE	2.569E+00	2.569E+00	3.539E+00	3.539E+00	7.319E-01
VBC	-1.833E+00	-1.833E+00	-2.807E+00	-2.807E+00	0.
VS	-2.803E+00	-2.803E+00	-3.539E+00	-3.539E+00	-7.319E-01
POWER	5.962E-04	5.962E-04	6.900E-04	6.900E-04	1.438E-04
BETAD	1.000E+02	1.000E+02	1.000E+02	1.000E+02	1.000E+02
GM	8.944E-03	8.944E-03	7.522E-03	7.522E-03	7.522E-03
RPI	1.118E+04	1.118E+04	1.329E+04	1.329E+04	1.329E+04
RX	0.	0.	0.	0.	0.
RO	1.833E+16	1.833E+16	2.807E+16	2.807E+16	2.586E+14
BETAAC	9.999E+01	9.999E+01	9.999E+01	9.999E+01	9.999E+01
FT	1.423E+12	1.423E+12	1.197E+12	1.197E+12	1.197E+12

****** TRANSIENT ANALYSIS   TNOM= 27.000 TEMP= 27.000

```
   TIME       V(6,5)
+A     )    -1.000E-00  -5.000E-01   0.         5.000E-01   1.000E-00
                 +           +           +           +           +
 0.          0       -+-----+-----+-----+-----A-----+-----+-----+-----+-
 5.000E-06  7.47E-03 +     +     +     +     A     +     +     +     +
 1.000E-05 -1.08E-01 +     +     +     +   A +     +     +     +     +
 1.500E-05 -2.24E-01 +     +     +     +A    +     +     +     +     +
 2.000E-05 -3.40E-01 +     +     +  A  +     +     +     +     +     +
 2.500E-05 -4.55E-01 +     +     +A    +     +     +     +     +     +
 3.000E-05 -5.69E-01 +     +   A +     +     +     +     +     +     +
 3.500E-05 -4.54E-01 +     +     +A    +     +     +     +     +     +
 4.000E-05 -3.38E-01 +     +     +   A +     +     +     +     +     +
 4.500E-05 -2.22E-01 +     +     +     +A    +     +     +     +     +
 5.000E-05 -1.07E-01-+-----+-----+-----+---A-+-----+-----+-----+-----+-
 5.500E-05  9.07E-03 +     +     +     +     A     +     +     +     +
 6.000E-05  1.25E-01 +     +     +     +     + A   +     +     +     +
 6.500E-05  2.40E-01 +     +     +     +     +     A     +     +     +
 7.000E-05  3.56E-01 +     +     +     +     +     + A   +     +     +
 7.500E-05  4.72E-01 +     +     +     +     +     +    A+     +     +
 8.000E-05  5.54E-01 +     +     +     +     +     +     + A   +     +
 8.500E-05  4.38E-01 +     +     +     +     +     +   A +     +     +
 9.000E-05  3.22E-01 +     +     +     +     +     + A   +     +     +
 9.500E-05  2.07E-01 +     +     +     +     +    A+     +     +     +
 1.000E-04  9.11E-02-+-----+-----+-----+-----+-A---+-----+-----+-----+-
 1.050E-04 -2.46E-02 +     +     +     +    A+     +     +     +     +
 1.100E-04 -1.40E-01 +     +     +     + A   +     +     +     +     +
 1.150E-04 -2.56E-01 +     +     +     A     +     +     +     +     +
 1.200E-04 -3.72E-01 +     +     + A   +     +     +     +     +     +
 1.250E-04 -4.87E-01 +     +     A     +     +     +     +     +     +
 1.300E-04 -5.37E-01 +     +    A+     +     +     +     +     +     +
 1.350E-04 -4.22E-01 +     +     + A   +     +     +     +     +     +
 1.400E-04 -3.06E-01 +     +     +   A +     +     +     +     +     +
 1.450E-04 -1.90E-01 +     +     +     + A   +     +     +     +     +
 1.500E-04 -7.47E-02-+-----+-----+-----+----A+-----+-----+-----+-----+-
 1.550E-04  4.10E-02 +     +     +     +     +A    +     +     +     +
 1.600E-04  1.57E-01 +     +     +     +     +   A +     +     +     +
 1.650E-04  2.72E-01 +     +     +     +     +     +A    +     +     +
 1.700E-04  3.88E-01 +     +     +     +     +     +   A +     +     +
 1.750E-04  5.04E-01 +     +     +     +     +     +     A     +     +
 1.800E-04  5.21E-01 +     +     +     +     +     +     +A    +     +
 1.850E-04  4.05E-01 +     +     +     +     +     +   A +     +     +
 1.900E-04  2.89E-01 +     +     +     +     +     +A    +     +     +
 1.950E-04  1.74E-01 +     +     +     +     +    A+     +     +     +
 2.000E-04  5.80E-02-+-----+-----+-----+-----+-A---+-----+-----+-----+-
 2.050E-04 -5.77E-02 +     +     +     +   A +     +     +     +     +
 2.100E-04 -1.73E-01 +     +     +     + A   +     +     +     +     +
 2.150E-04 -2.89E-01 +     +     +    A+     +     +     +     +     +
 2.200E-04 -4.05E-01 +     +     + A   +     +     +     +     +     +
 2.250E-04 -5.20E-01 +     +    A+     +     +     +     +     +     +
 2.300E-04 -5.05E-01 +     +     A     +     +     +     +     +     +
 2.350E-04 -3.89E-01 +     +     + A   +     +     +     +     +     +
 2.400E-04 -2.74E-01 +     +     +    A+     +     +     +     +     +
 2.450E-04 -1.58E-01 +     +     +     + A   +     +     +     +     +
 2.500E-04 -4.24E-02-+-----+-----+-----+----A+-----+-----+-----+-----+-
 2.550E-04  7.33E-02 +     +     +     +     + A   +     +     +     +
 2.600E-04  1.89E-01 +     +     +     +     +   A +     +     +     +
 2.650E-04  3.05E-01 +     +     +     +     +     + A   +     +     +
 2.700E-04  4.20E-01 +     +     +     +     +     +   A +     +     +
 2.750E-04  5.36E-01 +     +     +     +     +     +     +A    +     +
 2.800E-04  4.90E-01 +     +     +     +     +     +     A     +     +
 2.850E-04  3.74E-01 +     +     +     +     +     + A   +     +     +
 2.900E-04  2.59E-01 +     +     +     +     +     A     +     +     +
 2.950E-04  1.43E-01 +     +     +     +     +   A +     +     +     +
 3.000E-04  2.73E-02-+-----+-----+-----+-----+A----+-----+-----+-----+-
 3.050E-04 -8.84E-02 +     +     +     +   A +     +     +     +     +
 3.100E-04 -2.04E-01 +     +     +     +A    +     +     +     +     +
 3.150E-04 -3.20E-01 +     +     +   A +     +     +     +     +     +
 3.200E-04 -4.35E-01 +     +     + A   +     +     +     +     +     +
 3.250E-04 -5.51E-01 +     +    A+     +     +     +     +     +     +
 3.300E-04 -4.71E-01 +     +     +A    +     +     +     +     +     +
 3.350E-04 -3.55E-01 +     +     +   A +     +     +     +     +     +
 3.400E-04 -2.40E-01 +     +     +     A     +     +     +     +     +
 3.450E-04 -1.24E-01 +     +     +     +   A +     +     +     +     +
 3.500E-04 -8.17E-03-+-----+-----+-----+-----A-----+-----+-----+-----+-
 3.550E-04  1.07E-01 +     +     +     +     + A   +     +     +     +
 3.600E-04  2.23E-01 +     +     +     +     +    A+     +     +     +
 3.650E-04  3.39E-01 +     +     +     +     +     + A   +     +     +
 3.700E-04  4.54E-01 +     +     +     +     +     +    A+     +     +
 3.750E-04  5.70E-01 +     +     +     +     +     +     + A   +     +
 3.800E-04  4.55E-01 +     +     +     +     +     +    A+     +     +
 3.850E-04  3.40E-01 +     +     +     +     +     + A   +     +     +
 3.900E-04  2.24E-01 +     +     +     +     +    A+     +     +     +
 3.950E-04  1.08E-01 +     +     +     +     + A   +     +     +     +
 4.000E-04 -7.50E-03-+-----+-----+-----+-----A-----+-----+-----+-----+-
 4.050E-04 -1.23E-01 +     +     +     +   A +     +     +     +     +
 4.100E-04 -2.39E-01 +     +     +     A     +     +     +     +     +
 4.150E-04 -3.55E-01 +     +     +   A +     +     +     +     +     +
 4.200E-04 -4.70E-01 +     +     +A    +     +     +     +     +     +
 4.250E-04 -5.54E-01 +     +   A +     +     +     +     +     +     +
 4.300E-04 -4.38E-01 +     +     + A   +     +     +     +     +     +
 4.350E-04 -3.22E-01 +     +     +   A +     +     +     +     +     +
 4.400E-04 -2.07E-01 +     +     +     +A    +     +     +     +     +
 4.450E-04 -9.11E-02 +     +     +     +   A +     +     +     +     +
 4.500E-04  2.46E-02-+-----+-----+-----+-----+A----+-----+-----+-----+-
 4.550E-04  1.40E-01 +     +     +     +     +  A  +     +     +     +
 4.600E-04  2.56E-01 +     +     +     +     +     A     +     +     +
 4.650E-04  3.72E-01 +     +     +     +     +     + A   +     +     +
 4.700E-04  4.87E-01 +     +     +     +     +     +     A     +     +
 4.750E-04  5.38E-01 +     +     +     +     +     +     +A    +     +
 4.800E-04  4.22E-01 +     +     +     +     +     +   A +     +     +
 4.850E-04  3.07E-01 +     +     +     +     +     + A   +     +     +
 4.900E-04  1.91E-01 +     +     +     +     +   A +     +     +     +
 4.950E-04  7.53E-02 +     +     +     +     + A   +     +     +     +
 5.000E-04 -4.03E-02-+-----+-----+-----+----A+-----+-----+-----+-----+-
                     +           +           +           +           +
```

10.14



$$V_{BE_1} + V_{BE_6} + V_{BE_5} + V_{BE_4} = V_{BE_7} + V_{BE_8} + V_{BE_9} + V_{BE_{10}}$$

$$\frac{I_{B_1} I_i^3}{I_S^4} = \frac{I_{B_2}^2 I_o^2}{I_S^4}$$

$$I_o = \frac{\sqrt{I_{B_1}}}{I_{B_2}} I_i^{3/2}$$

$$100\mu = \frac{\sqrt{I_{B_1}}}{I_{B_2}} 100\mu^{3/2}$$

$$100 = \frac{\sqrt{I_{B_1}}}{I_{B_2}}$$

set $I_{B_2} = 100\mu$

then $I_{B_1} = 100\mu$

$$R = \frac{5 - 2V_{BE} - 100m}{100\mu} = 33.4k$$

$$V_{BE} = V_T \ln \frac{I_C}{I_S} = V_T \ln \frac{100\mu}{10^{-17}} = 0.778V$$

$$I_o = K I_i^{3/2} = 100 \; I_i^{3/2}$$

```
NONLINEAR FUNCTION SYNTHESIS
VCC 1 0 5V
Q1 5 2 0 N
Q2 5 14 18 P
RQ2 18 1 1K
Q3 15 14 17 P
RQ3 17 1 1K
Q12 13 14 16 P
RQ12 16 1 1K
Q11 0 15 14 P
RBIAS 15 0 33.4K
Q4 1 5 4 N
Q5 4 4 3 N
Q6 3 3 2 N
II 2 0 100UA
Q7 1 5 6 N
Q8 6 6 7 N
Q15 7 10 11 N
RQ15 11 0 1K
Q9 8 7 9 N
Q10 9 9 0 N
Q13 13 10 12 N
RQ13 12 0 1K
Q14 1 13 10 N
V2VBE 20 0 1.56V
VDUMMY 20 8 0V
.MODEL N NPN BF=100 IS=1E-17
.MODEL P PNP BF=100 IS=1E-17
.DC II 0 500U 10U
.PLOT DC I(VDUMMY)
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END
```

```
******  DC TRANSFER CURVES                        TNOM=  27.000 TEMP=  27.000

   AMPS      I(VDUMMY)
(A       )      -5.000E-04    0.           5.000E-04     1.000E-03     1.500E-03
                    +             +             +             +             +

   0.       1.00E-07-+------+------A------+------+------+------+------+------+-
1.000E-05  3.57E-06 +      +      A      +      +      +      +      +      +
2.000E-05  9.39E-06 +      +      A      +      +      +      +      +      +
3.000E-05  1.68E-05 +      +      A      +      +      +      +      +      +
4.000E-05  2.55E-05 +      +      +A     +      +      +      +      +      +
5.000E-05  3.54E-05 +      +      +A     +      +      +      +      +      +
6.000E-05  4.62E-05 +      +      +A     +      +      +      +      +      +
7.000E-05  5.79E-05 +      +      + A    +      +      +      +      +      +
8.000E-05  7.04E-05 +      +      + A    +      +      +      +      +      +
9.000E-05  8.37E-05 +      +      + A    +      +      +      +      +      +
1.000E-04  9.77E-05-+------+------+--A---+------+------+------+------+------+-
1.100E-04  1.12E-04 +      +      +  A   +      +      +      +      +      +
1.200E-04  1.28E-04 +      +      +   A  +      +      +      +      +      +
1.300E-04  1.43E-04 +      +      +   A  +      +      +      +      +      +
1.400E-04  1.60E-04 +      +      +   A  +      +      +      +      +      +
1.500E-04  1.77E-04 +      +      +    A +      +      +      +      +      +
1.600E-04  1.94E-04 +      +      +    A +      +      +      +      +      +
1.700E-04  2.12E-04 +      +      +     A+      +      +      +      +      +
1.800E-04  2.30E-04 +      +      +     A+      +      +      +      +      +
1.900E-04  2.49E-04 +      +      +      A      +      +      +      +      +
2.000E-04  2.68E-04-+------+------+------+A-----+------+------+------+------+-
2.100E-04  2.88E-04 +      +      +      +A     +      +      +      +      +
2.200E-04  3.08E-04 +      +      +      + A    +      +      +      +      +
2.300E-04  3.28E-04 +      +      +      + A    +      +      +      +      +
2.400E-04  3.49E-04 +      +      +      +  A   +      +      +      +      +
2.500E-04  3.70E-04 +      +      +      +  A   +      +      +      +      +
2.600E-04  3.91E-04 +      +      +      +   A  +      +      +      +      +
2.700E-04  4.13E-04 +      +      +      +    A +      +      +      +      +
2.800E-04  4.35E-04 +      +      +      +    A +      +      +      +      +
2.900E-04  4.57E-04 +      +      +      +     A+      +      +      +      +
3.000E-04  4.80E-04-+------+------+------+-----A+------+------+------+------+-
3.100E-04  5.03E-04 +      +      +      +      A      +      +      +      +
3.200E-04  5.26E-04 +      +      +      +      +A     +      +      +      +
3.300E-04  5.49E-04 +      +      +      +      +A     +      +      +      +
3.400E-04  5.72E-04 +      +      +      +      + A    +      +      +      +
3.500E-04  5.96E-04 +      +      +      +      +  A   +      +      +      +
3.600E-04  6.20E-04 +      +      +      +      +  A   +      +      +      +
3.700E-04  6.44E-04 +      +      +      +      +   A  +      +      +      +
3.800E-04  6.69E-04 +      +      +      +      +    A +      +      +      +
3.900E-04  6.93E-04 +      +      +      +      +    A +      +      +      +
4.000E-04  7.18E-04-+------+------+------+------+-----A+------+------+------+-
4.100E-04  7.43E-04 +      +      +      +      +      A      +      +      +
4.200E-04  7.68E-04 +      +      +      +      +      +A     +      +      +
4.300E-04  7.93E-04 +      +      +      +      +      +A     +      +      +
4.400E-04  8.19E-04 +      +      +      +      +      + A    +      +      +
4.500E-04  8.44E-04 +      +      +      +      +      +  A   +      +      +
4.600E-04  8.70E-04 +      +      +      +      +      +  A   +      +      +
4.700E-04  8.96E-04 +      +      +      +      +      +   A  +      +      +
4.800E-04  9.22E-04 +      +      +      +      +      +    A +      +      +
4.900E-04  9.48E-04 +      +      +      +      +      +     A+      +      +
5.000E-04  9.75E-04-+------+------+------+------+------+-----A+------+------+-
                    +             +             +             +             +
```

```
******  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000

+0:1      = 5.000E+00 0:2      = 7.744E-01 0:3      = 1.548E+00
+0:4      = 2.322E+00 0:5      = 3.097E+00 0:6      = 2.322E+00
+0:7      = 1.547E+00 0:8      = 1.560E+00 0:9      = 7.736E-01
+0:10     = 8.788E-01 0:11     = 1.039E-01 0:12     = 1.039E-01
+0:13     = 1.552E+00 0:14     = 4.121E+00 0:15     = 3.437E+00
+0:16     = 4.896E+00 0:17     = 4.896E+00 0:18     = 4.896E+00
+0:20     = 1.560E+00
```

**** BIPOLAR JUNCTION TRANSISTORS

ELEMENT	0:Q1	0:Q2	0:Q3	0:Q12	0:Q11	0:Q4
MODEL	0:N	0:P	0:P	0:P	0:P	0:N
IB	1.009E-06	-1.029E-06	-1.029E-06	-1.029E-06	-3.056E-08	1.000E-06
IC	1.009E-04	-1.029E-04	-1.029E-04	-1.029E-04	-3.056E-06	1.000E-04
VBE	7.744E-01	-7.749E-01	-7.749E-01	-7.749E-01	-6.840E-01	7.742E-01
VCE	3.097E+00	-1.799E+00	-1.458E+00	-3.343E+00	-4.121E+00	2.677E+00
VBC	-2.322E+00	1.024E+00	6.840E-01	2.568E+00	3.437E+00	-1.902E+00
VS	-3.097E+00	-4.121E+00	-4.121E+00	-4.121E+00	-3.437E+00	-5.000E+00
POWER	3.131E-04	1.859E-04	1.509E-04	3.448E-04	1.261E-05	2.685E-04
BETAD	1.000E+02	1.000E+02	1.000E+02	1.000E+02	1.000E+02	1.000E+02
GM	3.899E-03	3.978E-03	3.978E-03	3.978E-03	1.181E-04	3.867E-03
RPI	2.564E+04	2.514E+04	2.514E+04	2.514E+04	8.464E+05	2.586E+04
RX	0.	0.	0.	0.	0.	0.
RO	2.322E+17	1.024E+17	6.839E+16	2.568E+17	3.437E+17	1.902E+17
CPI	0.	0.	0.	0.	0.	0.
CMU	0.	0.	0.	0.	0.	0.
CBX	0.	0.	0.	0.	0.	0.
CCS	0.	0.	0.	0.	0.	0.
BETAAC	9.999E+01	9.999E+01	9.999E+01	9.999E+01	9.999E+01	9.999E+01
FT	6.205E+11	6.330E+11	6.330E+11	6.330E+11	1.880E+10	6.154E+11

ELEMENT	0:Q5	0:Q6	0:Q7	0:Q8	0:Q15	0:Q9
MODEL	0:N	0:N	0:N	0:N	0:N	0:N
IB	1.000E-06	1.000E-06	1.028E-06	1.028E-06	1.029E-06	9.769E-07
IC	1.000E-04	1.000E-04	1.028E-04	1.028E-04	1.029E-04	9.769E-05
VBE	7.742E-01	7.742E-01	7.749E-01	7.749E-01	7.749E-01	7.736E-01
VCE	7.742E-01	7.742E-01	2.677E+00	7.749E-01	1.443E+00	7.864E-01
VBC	0.	0.	-1.902E+00	0.	-6.684E-01	-1.279E-02
VS	-2.322E+00	-1.548E+00	-5.000E+00	-2.322E+00	-1.547E+00	-1.560E+00
POWER	7.820E-05	7.820E-05	2.761E-04	8.046E-05	1.493E-04	7.758E-05
BETAD	1.000E+02	9.999E+01	1.000E+02	1.000E+02	1.000E+02	1.000E+02
GM	3.867E-03	3.867E-03	3.975E-03	3.975E-03	3.977E-03	3.777E-03
RPI	2.586E+04	2.586E+04	2.515E+04	2.515E+04	2.514E+04	2.647E+04
RX	0.	0.	0.	0.	0.	0.
RO	2.586E+15	2.586E+15	1.902E+17	2.586E+15	6.683E+16	4.240E+15
CPI	0.	0.	0.	0.	0.	0.
CMU	0.	0.	0.	0.	0.	0.
CBX	0.	0.	0.	0.	0.	0.
CCS	0.	0.	0.	0.	0.	0.
BETAAC	9.999E+01	9.999E+01	9.999E+01	9.999E+01	9.999E+01	9.999E+01
FT	6.154E+11	6.154E+11	6.326E+11	6.326E+11	6.329E+11	6.011E+11

ELEMENT	0:Q10	0:Q13	0:Q14
MODEL	0:N	0:N	0:N
IB	9.769E-07	1.029E-06	2.037E-08
IC	9.769E-05	1.029E-04	2.037E-06
VBE	7.736E-01	7.749E-01	6.735E-01
VCE	7.736E-01	1.448E+00	4.121E+00
VBC	0.	-6.735E-01	-3.447E+00
VS	-7.736E-01	-1.552E+00	-5.000E+00
POWER	7.633E-05	1.498E-04	8.408E-06
BETAD	1.000E+02	1.000E+02	1.000E+02
GM	3.777E-03	3.977E-03	7.875E-05
RPI	2.647E+04	2.514E+04	1.269E+06
RX	0.	0.	0.
RO	2.586E+15	6.735E+16	3.447E+17
CPI	0.	0.	0.
CMU	0.	0.	0.
CBX	0.	0.	0.
CCS	0.	0.	0.
BETAAC	9.999E+01	9.999E+01	9.999E+01
FT	6.011E+11	6.329E+11	1.253E+10

II (UA)	100*II^1.5 (UA)	IO (UA)	ERROR (%)
100	100	97.7	2.3
200	283	268	5.1
300	520	480	7.7
400	800	718	10.2

```
NONLINEAR FUNCTION SYNTHESIS, ADD RB AND RE
VCC 1 0 5V
Q1 5 2 0 N
Q2 5 14 18 P
RQ2 18 1 1K
Q3 15 14 17 P
RQ3 17 1 1K
Q12 13 14 16 P
RQ12 16 1 1K
Q11 0 15 14 P
RBIAS 15 0 33.4K
Q4 1 5 4 N
Q5 4 4 3 N
Q6 3 3 2 N
II 2 0 100UA
Q7 1 5 6 N
Q8 6 6 7 N
Q15 7 10 11 N
RQ15 11 0 1K
Q9 8 7 9 N
Q10 9 9 0 N
Q13 13 10 12 N
RQ13 12 0 1K
Q14 1 13 10 N
V2VBE 20 0 1.56V
VDUMMY 20 8 0V
.MODEL N NPN BF=100 IS=1E-17 RB=200 RE=2
.MODEL P PNP BF=100 IS=1E-17 RB=200 RE=2
.DC II 0 500U 10U
.PLOT DC I(VDUMMY)
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END
```

```
******  DC TRANSFER CURVES                       TNOM=  27.000 TEMP=  27.000

  AMPS       I(VDUMMY)
(A       )  -5.000E-04    0.          5.000E-04     1.000E-03     1.500E-03
                    +             +             +             +             +

0.         9.96E-08-+------+------A------+------+------+------+------+------+-
1.000E-05  3.55E-06 +      +      A      +      +      +      +      +      +
2.000E-05  9.35E-06 +      +      A      +      +      +      +      +      +
3.000E-05  1.68E-05 +      +      A      +      +      +      +      +      +
4.000E-05  2.55E-05 +      +      +A     +      +      +      +      +      +
5.000E-05  3.53E-05 +      +      +A     +      +      +      +      +      +
6.000E-05  4.61E-05 +      +      +A     +      +      +      +      +      +
7.000E-05  5.79E-05 +      +      + A    +      +      +      +      +      +
8.000E-05  7.04E-05 +      +      + A    +      +      +      +      +      +
9.000E-05  8.37E-05 +      +      + A    +      +      +      +      +      +
1.000E-04  9.77E-05-+------+------+--A---+------+------+------+------+------+-
1.100E-04  1.12E-04 +      +      +  A   +      +      +      +      +      +
1.200E-04  1.28E-04 +      +      +   A  +      +      +      +      +      +
1.300E-04  1.43E-04 +      +      +   A  +      +      +      +      +      +
1.400E-04  1.60E-04 +      +      +   A  +      +      +      +      +      +
1.500E-04  1.77E-04 +      +      +    A +      +      +      +      +      +
1.600E-04  1.94E-04 +      +      +    A +      +      +      +      +      +
1.700E-04  2.12E-04 +      +      +     A+      +      +      +      +      +
1.800E-04  2.30E-04 +      +      +     A+      +      +      +      +      +
1.900E-04  2.49E-04 +      +      +      A      +      +      +      +      +
2.000E-04  2.68E-04-+------+------+------A------+------+------+------+------+-
2.100E-04  2.87E-04 +      +      +      +A     +      +      +      +      +
2.200E-04  3.06E-04 +      +      +      + A    +      +      +      +      +
2.300E-04  3.26E-04 +      +      +      + A    +      +      +      +      +
2.400E-04  3.47E-04 +      +      +      +  A   +      +      +      +      +
2.500E-04  3.67E-04 +      +      +      +  A   +      +      +      +      +
2.600E-04  3.88E-04 +      +      +      +   A  +      +      +      +      +
2.700E-04  4.09E-04 +      +      +      +   A  +      +      +      +      +
2.800E-04  4.31E-04 +      +      +      +    A +      +      +      +      +
2.900E-04  4.52E-04 +      +      +      +     A+      +      +      +      +
3.000E-04  4.74E-04-+------+------+------+-----A+------+------+------+------+-
3.100E-04  4.96E-04 +      +      +      +      A      +      +      +      +
3.200E-04  5.18E-04 +      +      +      +      +A     +      +      +      +
3.300E-04  5.40E-04 +      +      +      +      +A     +      +      +      +
3.400E-04  5.63E-04 +      +      +      +      + A    +      +      +      +
3.500E-04  5.86E-04 +      +      +      +      + A    +      +      +      +
3.600E-04  6.08E-04 +      +      +      +      +  A   +      +      +      +
3.700E-04  6.31E-04 +      +      +      +      +   A  +      +      +      +
3.800E-04  6.54E-04 +      +      +      +      +   A  +      +      +      +
3.900E-04  6.78E-04 +      +      +      +      +    A +      +      +      +
4.000E-04  7.01E-04-+------+------+------+------+-----A+------+------+------+-
4.100E-04  7.24E-04 +      +      +      +      +     A+      +      +      +
4.200E-04  7.48E-04 +      +      +      +      +      A      +      +      +
4.300E-04  7.72E-04 +      +      +      +      +      +A     +      +      +
4.400E-04  7.95E-04 +      +      +      +      +      +A     +      +      +
4.500E-04  8.19E-04 +      +      +      +      +      + A    +      +      +
4.600E-04  8.43E-04 +      +      +      +      +      +  A   +      +      +
4.700E-04  8.67E-04 +      +      +      +      +      +  A   +      +      +
4.800E-04  8.91E-04 +      +      +      +      +      +   A  +      +      +
4.900E-04  9.15E-04 +      +      +      +      +      +    A +      +      +
5.000E-04  9.40E-04-+------+------+------+------+------+----A-+------+------+-
                    +             +             +             +             +
```

**** BIPOLAR JUNCTION TRANSISTORS

ELEMENT	0:Q1	0:Q2	0:Q3	0:Q12	0:Q11	0:Q4
MODEL	0:N	0:P	0:P	0:P	0:P	0:N
IB	1.008E-06	-1.029E-06	-1.029E-06	-1.029E-06	-3.055E-08	1.000E-06
IC	1.008E-04	-1.029E-04	-1.029E-04	-1.029E-04	-3.055E-06	1.000E-04
VBE	7.748E-01	-7.754E-01	-7.754E-01	-7.754E-01	-6.840E-01	7.746E-01
VCE	3.098E+00	-1.797E+00	-1.459E+00	-3.343E+00	-4.120E+00	2.675E+00
VBC	-2.323E+00	1.022E+00	6.840E-01	2.568E+00	3.436E+00	-1.901E+00
VS	-3.098E+00	-4.121E+00	-4.121E+00	-4.121E+00	-3.436E+00	-5.000E+00
POWER	3.132E-04	1.857E-04	1.509E-04	3.447E-04	1.261E-05	2.684E-04
BETAD	1.000E+02	1.000E+02	1.000E+02	1.000E+02	1.000E+02	1.000E+02
GM	3.899E-03	3.977E-03	3.977E-03	3.977E-03	1.181E-04	3.867E-03
RPI	2.564E+04	2.514E+04	2.514E+04	2.514E+04	8.465E+05	2.586E+04
RX	2.000E+02	2.000E+02	2.000E+02	2.000E+02	2.000E+02	2.000E+02
RO	2.324E+17	1.022E+17	6.842E+16	2.568E+17	3.436E+17	1.901E+17
CPI	0.	0.	0.	0.	0.	0.
CMU	0.	0.	0.	0.	0.	0.
CBX	0.	0.	0.	0.	0.	0.
CCS	0.	0.	0.	0.	0.	0.
BETAAC	9.999E+01	9.999E+01	9.999E+01	9.999E+01	9.999E+01	9.999E+01
FT	6.205E+11	6.329E+11	6.329E+11	6.329E+11	1.880E+10	6.154E+11

ELEMENT	0:Q5	0:Q6	0:Q7	0:Q8	0:Q15	0:Q9
MODEL	0:N	0:N	0:N	0:N	0:N	0:N
IB	1.000E-06	1.000E-06	1.028E-06	1.028E-06	1.028E-06	9.770E-07
IC	1.000E-04	1.000E-04	1.028E-04	1.028E-04	1.028E-04	9.770E-05
VBE	7.746E-01	7.746E-01	7.753E-01	7.753E-01	7.753E-01	7.740E-01
VCE	7.746E-01	7.746E-01	2.676E+00	7.753E-01	1.444E+00	7.860E-01
VBC	0.	0.	-1.901E+00	0.	-6.688E-01	-1.200E-02
VS	-2.324E+00	-1.549E+00	-5.000E+00	-2.323E+00	-1.548E+00	-1.560E+00
POWER	7.824E-05	7.824E-05	2.759E-04	8.050E-05	1.493E-04	7.755E-05
BETAD	1.000E+02	1.000E+02	1.000E+02	1.000E+02	1.000E+02	1.000E+02
GM	3.867E-03	3.867E-03	3.974E-03	3.974E-03	3.976E-03	3.777E-03
RPI	2.586E+04	2.586E+04	2.516E+04	2.516E+04	2.514E+04	2.647E+04
RX	2.000E+02	2.000E+02	2.000E+02	2.000E+02	2.000E+02	2.000E+02
RO	2.606E+15	2.606E+15	1.901E+17	2.607E+15	6.689E+16	4.144E+15
CPI	0.	0.	0.	0.	0.	0.
CMU	0.	0.	0.	0.	0.	0.
CBX	0.	0.	0.	0.	0.	0.
CCS	0.	0.	0.	0.	0.	0.
BETAAC	9.999E+01	9.999E+01	9.999E+01	9.999E+01	9.999E+01	9.999E+01
FT	6.154E+11	6.154E+11	6.325E+11	6.325E+11	6.328E+11	6.011E+11

ELEMENT	0:Q10	0:Q13	0:Q14
MODEL	0:N	0:N	0:N
IB	9.770E-07	1.028E-06	2.037E-08
IC	9.770E-05	1.028E-04	2.037E-06
VBE	7.740E-01	7.753E-01	6.735E-01
VCE	7.740E-01	1.448E+00	4.120E+00
VBC	0.	-6.735E-01	-3.447E+00
VS	-7.740E-01	-1.552E+00	-5.000E+00
POWER	7.638E-05	1.498E-04	8.406E-06
BETAD	1.000E+02	1.000E+02	1.000E+02
GM	3.777E-03	3.976E-03	7.874E-05
RPI	2.647E+04	2.514E+04	1.270E+06
RX	2.000E+02	2.000E+02	2.000E+02
RO	2.606E+15	6.737E+16	3.447E+17
CPI	0.	0.	0.
CMU	0.	0.	0.
CBX	0.	0.	0.
CCS	0.	0.	0.
BETAAC	9.999E+01	9.999E+01	9.999E+01
FT	6.011E+11	6.328E+11	1.253E+10

II (UA)	100*II^1.5 (UA)	IO (UA)	ERROR (%)
100	100	97.7	2.3
200	283	268	5.1
300	520	474	8.9
400	800	701	12.4

10.15

$I_{D_1} = I_{D_2} = I_{D_3} = I_{D_4} = 50\mu A$

$I_{D_5} = I_{D_6} = I_{D_7} = I_{D_8} = 50\mu A$

$I_{D_9} = I_{D_{10}} = 100\mu A$

$$I_D = \frac{\mu C_{ox}}{2}\frac{W}{L}(V_{GS} - V_t)^2$$

for m_1 thru m_8

$$50\mu = \frac{60(20)}{2}(V_{GS} - V_t)^2 \mu$$

$$V_{GS} - V_t = 0.29V$$

for m_9, m_{10}

$$100\mu = \frac{60(20)}{2}(V_{GS} - V_t)^2 \mu$$

$$V_{GS} - V_t = 0.41V$$

$I_{D_2} = |I_{D_7}|$

$$\frac{\mu_n C_{ox}}{2}\left(\frac{W}{L}\right)_2 (V_{GS_2} - V_{t_2})^2 = \frac{\mu_p C_{ox}}{2}\left(\frac{W}{L}\right)_7 (V_{GS_7} - V_{t_7})^2$$

$V_{GS_2} - V_{t_2} = |V_{GS_7}| - |V_{t_7}|$

$\gamma = 0 \therefore V_{t_2} = |V_{t_7}|$

$V_{GS_2} = |V_{GS_7}|$

$\therefore$ m_2 and m_7 share V_i equally

$$I_{D_2} = \frac{\mu_n C_{ox}}{2}\left(\frac{W}{L}\right)_2 \left(V_{GS_{bias}} + \frac{V_i}{2} - V_t\right)^2$$

$$I_{D_3} = \frac{\mu_n C_{ox}}{2}\left(\frac{W}{L}\right)_3 \left(V_{GS\,bias} - \frac{V_i}{2} - V_t\right)^2$$

$$I_o = |I_{D10}| - 2I_1 = |I_{D9}| - 2I_1$$

$$= I_{D_2} + I_{D_3} - 2I_1$$

$$= \frac{\mu_n C_{ox}}{2}\frac{W}{L}\left[2(V_{GS_{bias}} - V_t)^2 + 2\left(\frac{V_i}{2}\right)^2\right] - 2I_1$$

$$I_1 = \frac{\mu_n C_{ox}}{2}\frac{W}{L}(V_{GS\,bias} - V_t)^2$$

$$\therefore I_o = \mu_n C_{ox}\frac{W}{L}\left(\frac{V_i^2}{4}\right)$$

$$= 300\mu\ V_i^2$$

The above is true for m_2, m_3, m_6, m_7 all on.

$$|V_i| < 2(V_{GS} - V_t)$$

$$|V_i| < 2(0.29V) = 0.58V$$

10-18

```
CROSS-COUPLED MOS QUAD
VDD 1 0 5V
M1 14 3 5 0 N W=20U L=1U
M2 13 3 7 0 N W=20U L=1U
M3 13 4 8 0 N W=20U L=1U
M4 14 4 6 0 N W=20U L=1U
M5 9 9 5 1 P W=60U L=1U
M6 0 9 8 1 P W=60U L=1U
M7 0 12 7 1 P W=60U L=1U
M8 12 12 6 1 P W=60U L=1U
M9 13 13 1 1 P W=60U L=1U
M10 14 13 1 1 P W=60U L=1U
VOUT 14 0 3.5V
IBIAS1 9 0 50UA
IBIAS2 12 0 50UA
.MODEL N NMOS KP=60U VTO=0.7
.MODEL P PMOS KP=20U VTO=-0.7
VS 3 21 SIN 0 0.1V 10K
EVS 4 22 3 21 -1
VBIAS1 21 0 3V
VBIAS2 22 0 3V
.PLOT TRAN I(VOUT)
.TRAN 0.0025MS 0.2MS
.FOUR 10K I(VOUT)
.DC VS 0V 0.3V 0.02V
.PLOT DC I(VOUT)
.OPTIONS NOPAGE NOMOD
.OPTIONS VNTOL=1N ABSTOL=1F RELTOL=1U
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END
```

```
 ******  DC TRANSFER CURVES                  TNOM=  27.000 TEMP=  27.000
    VOLT      I(VOUT)
(A        )         0.        5.000E-05     1.000E-04     1.500E-04     2.000E-04
                    +             +             +             +             +
    0.    2.99E-12-A------+------+------+------+------+------+------+------+-
 2.000E-02 4.80E-07 A      +      +      +      +      +      +      +      +
 4.000E-02 1.92E-06 +A     +      +      +      +      +      +      +      +
 6.000E-02 4.32E-06 +A     +      +      +      +      +      +      +      +
 8.000E-02 7.68E-06 + A    +      +      +      +      +      +      +      +
 1.000E-01 1.20E-05 +  A   +      +      +      +      +      +      +      +
 1.200E-01 1.73E-05 +    A +      +      +      +      +      +      +      +
 1.400E-01 2.35E-05 +      A      +      +      +      +      +      +      +
 1.600E-01 3.07E-05 +      + A    +      +      +      +      +      +      +
 1.800E-01 3.89E-05 +      +   A  +      +      +      +      +      +      +
 2.000E-01 4.80E-05-+------+-----A+------+------+------+------+------+------+-
 2.200E-01 5.81E-05 +      +      + A    +      +      +      +      +      +
 2.400E-01 6.91E-05 +      +      +    A +      +      +      +      +      +
 2.600E-01 8.11E-05 +      +      +      + A    +      +      +      +      +
 2.800E-01 9.41E-05 +      +      +      +    A +      +      +      +      +
 3.000E-01 1.08E-04 +      +      +      +      + A    +      +      +      +
                    +             +             +             +             +
 *****
```

	DESIRED	ACTUAL
VI=2*VS (V)	300U*VI^2 (UA)	IO (UA)
0.08	1.92	1.92
0.2	12	12
0.4	48	48

```
 ******  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000

+0:1        = 5.000E+00 0:3         = 3.000E+00 0:4        = 3.000E+00
+0:5        = 2.011E+00 0:6         = 2.011E+00 0:7        = 2.011E+00
+0:8        = 2.011E+00 0:9         = 1.022E+00 0:12       = 1.022E+00
+0:13       = 3.891E+00 0:14        = 3.500E+00 0:21       = 3.000E+00
+0:22       = 3.000E+00
```

**** MOSFETS

ELEMENT	0:M1	0:M2	0:M3	0:M4	0:M5	0:M6
MODEL	0:N	0:N	0:N	0:N	0:P	0:P
ID	5.000E-05	5.000E-05	5.000E-05	5.000E-05	-5.000E-05	-5.000E-05
IBS	-2.011E-14	-2.011E-14	-2.011E-14	-2.011E-14	2.989E-14	2.989E-14
IBD	-3.500E-14	-3.892E-14	-3.892E-14	-3.500E-14	3.977E-14	5.000E-14
VGS	9.887E-01	9.887E-01	9.887E-01	9.887E-01	-9.887E-01	-9.887E-01
VDS	1.488E+00	1.880E+00	1.880E+00	1.488E+00	-9.887E-01	-2.011E+00
VBS	-2.011E+00	-2.011E+00	-2.011E+00	-2.011E+00	2.988E+00	2.988E+00
VTH	7.000E-01	7.000E-01	7.000E-01	7.000E-01	-7.000E-01	-7.000E-01
VDSAT	2.887E-01	2.887E-01	2.887E-01	2.887E-01	-2.887E-01	-2.887E-01
BETA	1.200E-03	1.200E-03	1.200E-03	1.200E-03	1.200E-03	1.200E-03
GAM EFF	0.	0.	0.	0.	0.	0.
GM	3.464E-04	3.464E-04	3.464E-04	3.464E-04	3.464E-04	3.464E-04

ELEMENT	0:M7	0:M8	0:M9	0:M10
MODEL	0:P	0:P	0:P	0:P
ID	-5.000E-05	-5.000E-05	-1.000E-04	-1.000E-04
IBS	2.989E-14	2.989E-14	0.	0.
IBD	5.000E-14	3.977E-14	1.108E-14	1.500E-14
VGS	-9.887E-01	-9.887E-01	-1.108E+00	-1.108E+00
VDS	-2.011E+00	-9.887E-01	-1.108E+00	-1.500E+00
VBS	2.988E+00	2.988E+00	0.	0.
VTH	-7.000E-01	-7.000E-01	-7.000E-01	-7.000E-01
VDSAT	-2.887E-01	-2.887E-01	-4.082E-01	-4.082E-01
BETA	1.200E-03	1.200E-03	1.200E-03	1.200E-03
GAM EFF	0.	0.	0.	0.
GM	3.464E-04	3.464E-04	4.899E-04	4.899E-04

```
 ******  TRANSIENT ANALYSIS                  TNOM=  27.000 TEMP=  27.000
    TIME      I(VOUT)
(A        )         0.        5.000E-06     1.000E-05     1.500E-05     2.000E-05
                    +             +             +             +             +
    0.    2.99E-12-A------+------+------+------+------+------+------+------+-
 2.500E-06 2.94E-07 +A     +      +      +      +      +      +      +      +
 5.000E-06 1.15E-06 +  A   +      +      +      +      +      +      +      +
 7.500E-06 2.58E-06 +      A      +      +      +      +      +      +      +
 1.000E-05 4.18E-06 +      +    A +      +      +      +      +      +      +
 1.250E-05 6.01E-06 +      +      + A    +      +      +      +      +      +
 1.500E-05 7.85E-06 +      +      +      +A     +      +      +      +      +
 1.750E-05 9.47E-06 +      +      +      +     A+      +      +      +      +
 2.000E-05 1.07E-05 +      +      +      +      + A    +      +      +      +
 2.250E-05 1.15E-05 +      +      +      +      +   A  +      +      +      +
 2.500E-05 1.20E-05-+------+------+------+------+-----A+------+------+------+-
 2.750E-05 1.16E-05 +      +      +      +      +    A +      +      +      +
 3.000E-05 1.07E-05 +      +      +      +      + A    +      +      +      +
 3.250E-05 9.43E-06 +      +      +      +    A +      +      +      +      +
 3.500E-05 7.85E-06 +      +      +      +A     +      +      +      +      +
 3.750E-05 6.00E-06 +      +      + A    +      +      +      +      +      +
 4.000E-05 4.20E-06 +      +    A +      +      +      +      +      +      +
 4.250E-05 2.53E-06 +      A      +      +      +      +      +      +      +
 4.500E-05 1.25E-06 +  A   +      +      +      +      +      +      +      +
 4.750E-05 4.64E-07 +A     +      +      +      +      +      +      +      +
 5.000E-05 2.99E-12-A------+------+------+------+------+------+------+------+-
 5.250E-05 3.28E-07 +A     +      +      +      +      +      +      +      +
 5.500E-05 1.30E-06 +  A   +      +      +      +      +      +      +      +
 5.750E-05 2.51E-06 +      A      +      +      +      +      +      +      +
 6.000E-05 4.20E-06 +      +    A +      +      +      +      +      +      +
 6.250E-05 5.99E-06 +      +      + A    +      +      +      +      +      +
 6.500E-05 7.85E-06 +      +      +      +A     +      +      +      +      +
 6.750E-05 9.42E-06 +      +      +      +    A +      +      +      +      +
 7.000E-05 1.09E-05 +      +      +      +      + A    +      +      +      +
 7.250E-05 1.15E-05 +      +      +      +      +   A  +      +      +      +
 7.500E-05 1.20E-05-+------+------+------+------+-----A+------+------+------+-
 7.750E-05 1.16E-05 +      +      +      +      +    A +      +      +      +
 8.000E-05 1.07E-05 +      +      +      +      + A    +      +      +      +
 8.250E-05 9.43E-06 +      +      +      +    A +      +      +      +      +
 8.500E-05 7.85E-06 +      +      +      +A     +      +      +      +      +
 8.750E-05 6.00E-06 +      +      + A    +      +      +      +      +      +
 9.000E-05 4.20E-06 +      +    A +      +      +      +      +      +      +
 9.250E-05 2.53E-06 +      A      +      +      +      +      +      +      +
 9.500E-05 1.25E-06 +  A   +      +      +      +      +      +      +      +
 9.750E-05 4.64E-07 +A     +      +      +      +      +      +      +      +
 1.000E-04 2.99E-12-A------+------+------+------+------+------+------+------+-
 1.025E-04 3.28E-07 +A     +      +      +      +      +      +      +      +
 1.050E-04 1.30E-06 +  A   +      +      +      +      +      +      +      +
 1.075E-04 2.51E-06 +      A      +      +      +      +      +      +      +
 1.100E-04 4.20E-06 +      +    A +      +      +      +      +      +      +
 1.125E-04 5.99E-06 +      +      + A    +      +      +      +      +      +
 1.150E-04 7.85E-06 +      +      +      +A     +      +      +      +      +
 1.175E-04 9.42E-06 +      +      +      +    A +      +      +      +      +
 1.200E-04 1.09E-05 +      +      +      +      + A    +      +      +      +
 1.225E-04 1.15E-05 +      +      +      +      +   A  +      +      +      +
 1.250E-04 1.20E-05-+------+------+------+------+-----A+------+------+------+-
 1.275E-04 1.16E-05 +      +      +      +      +    A +      +      +      +
 1.300E-04 1.07E-05 +      +      +      +      + A    +      +      +      +
 1.325E-04 9.43E-06 +      +      +      +    A +      +      +      +      +
 1.350E-04 7.85E-06 +      +      +      +A     +      +      +      +      +
 1.375E-04 6.00E-06 +      +      + A    +      +      +      +      +      +
 1.400E-04 4.20E-06 +      +    A +      +      +      +      +      +      +
 1.425E-04 2.53E-06 +      A      +      +      +      +      +      +      +
 1.450E-04 1.25E-06 +  A   +      +      +      +      +      +      +      +
 1.475E-04 4.64E-07 +A     +      +      +      +      +      +      +      +
 1.500E-04 2.99E-12-A------+------+------+------+------+------+------+------+-
 1.525E-04 3.28E-07 +A     +      +      +      +      +      +      +      +
 1.550E-04 1.30E-06 +  A   +      +      +      +      +      +      +      +
 1.575E-04 2.51E-06 +      A      +      +      +      +      +      +      +
 1.600E-04 4.20E-06 +      +    A +      +      +      +      +      +      +
 1.625E-04 5.99E-06 +      +      + A    +      +      +      +      +      +
 1.650E-04 7.85E-06 +      +      +      +A     +      +      +      +      +
 1.675E-04 9.42E-06 +      +      +      +    A +      +      +      +      +
 1.700E-04 1.09E-05 +      +      +      +      + A    +      +      +      +
 1.725E-04 1.15E-05 +      +      +      +      +   A  +      +      +      +
 1.750E-04 1.20E-05-+------+------+------+------+-----A+------+------+------+-
 1.775E-04 1.16E-05 +      +      +      +      +    A +      +      +      +
 1.800E-04 1.07E-05 +      +      +      +      + A    +      +      +      +
 1.825E-04 9.43E-06 +      +      +      +    A +      +      +      +      +
 1.850E-04 7.85E-06 +      +      +      +A     +      +      +      +      +
 1.875E-04 6.00E-06 +      +      + A    +      +      +      +      +      +
 1.900E-04 4.20E-06 +      +    A +      +      +      +      +      +      +
 1.925E-04 2.53E-06 +      A      +      +      +      +      +      +      +
 1.950E-04 1.25E-06 +  A   +      +      +      +      +      +      +      +
 1.975E-04 4.64E-07 +A     +      +      +      +      +      +      +      +
 2.000E-04 2.99E-12-A------+------+------+------+------+------+------+------+-
                    +             +             +             +             +
```

******

FOURIER COMPONENTS OF TRANSIENT RESPONSE I(VOUT)

DC COMPONENT = 6.001D-06

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	9.999E+03	2.547E-09	1.000E+00	-9.009E+01	0.
2	2.000E+04	5.900E-06	2.315E+03	-9.002E+01	6.485E-02
3	3.000E+04	2.579E-09	1.012E+00	-9.036E+01	-2.750E-01
4	4.000E+04	4.602E-09	1.806E+00	-1.443E+02	-5.427E+01
5	5.000E+04	4.049E-10	1.590E-01	-9.669E+01	-6.604E+00
6	6.000E+04	2.205E-08	8.654E+00	-1.104E+02	-2.033E+01
7	7.000E+04	2.342E-10	9.193E-02	-1.111E+02	-2.101E+01
8	8.000E+04	6.213E-09	2.439E+00	1.308E+02	2.209E+02
9	9.000E+04	2.968E-10	1.165E-01	-1.284E+02	-3.836E+01

TOTAL HARMONIC DISTORTION = 2.315E+05 PERCENT

THE SECOND HARMONIC COMPONENT IN IO IS MUCH LARGER THAN THE FIRST HARMONIC COMPONENT. BECAUSE THE TRANSFER FUNCTION IS IO=K*VI^2, WE EXPECT, IDEALLY, TO SEE ONLY A SECOND HARMONIC COMPONENT AND NO FIRST HARMONIC COMPONENT.

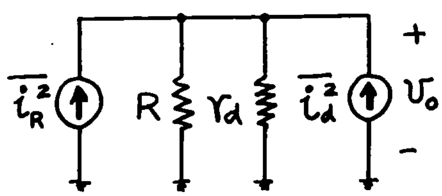
11.1

Diode current

$$I_D = \frac{10-0.6}{20K} = 470\,\mu A$$

where $\underline{K}$ is kilo $= 10^3$

Equivalent circuit



$$r_d = \frac{kT}{qI_D} = \frac{26}{470}\,k\Omega = 55.3\,\Omega$$

where $\underline{k}$ is the Boltzmann's const.

$R = 20\,k\Omega$

$r_d \| R = 55.3\,\Omega$

$$\therefore \overline{v_o^2} = (\overline{i_R^2} + \overline{i_d^2})\, r_d^2$$

$$= 55.3^2 \left(4kT\frac{1}{R} + 2qI_D\right)\Delta f$$

$$= 3060\left(\frac{1.66\times10^{-20}}{2\times10^4} + 3.2\times10^{-19}\times470\times10^{-6}\right) \times \Delta f$$

$$= 3060 \times 1.51\times10^{-22}\,\Delta f$$

$$\therefore \frac{\overline{v_o^2}}{\Delta f} = 4.63\times10^{-19}\ V^2/HZ$$

If $\Delta f = 10^5$ HZ

$$\overline{v_{oT}^2} = 4.63\times10^{-19}\times10^5$$

$$= 4.63\times10^{-14}\ V^2$$

$\therefore v_{oT} = 0.215\ \mu V$ rms

11.2

$$\overline{i_d^2} = 2qI_D\Delta f + 3\times10^{-16}\frac{I_D}{f}\Delta f$$

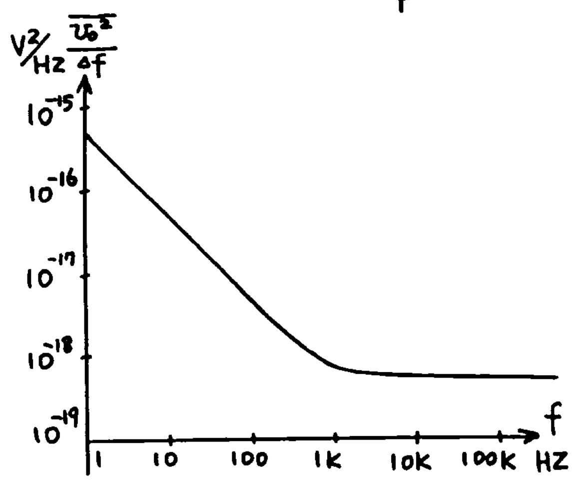
$$\therefore \frac{\overline{i_d^2}}{\Delta f} = 3.2\times10^{-19}\times470\times10^{-6} + 3\times10^{-16}\times\frac{470\times10^{-6}}{f}$$

$$= 1.5\times10^{-22} + \frac{1.41\times10^{-19}}{f}$$

$$\therefore \overline{v_o^2} = 55.3^2\times(\overline{i_d^2} + \overline{i_R^2})$$

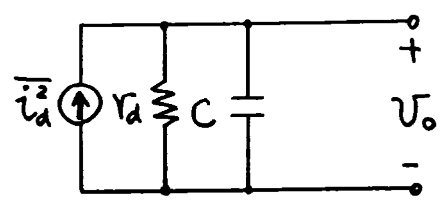
$$\therefore \frac{\overline{v_o^2}}{\Delta f} = 3060\left(1.51\times10^{-22} + \frac{1.41\times10^{-19}}{f}\right)$$

$$= 4.62\times10^{-19} + \frac{4.32\times10^{-16}}{f}$$



11.3

Neglect R and noise in R.



$$v_o = i_d\,\frac{r_d}{1 + j\omega C r_d}$$

$$\overline{v_o^2} = \overline{i_d^2}\,\frac{r_d^2}{1 + (\omega r_d C)^2}$$

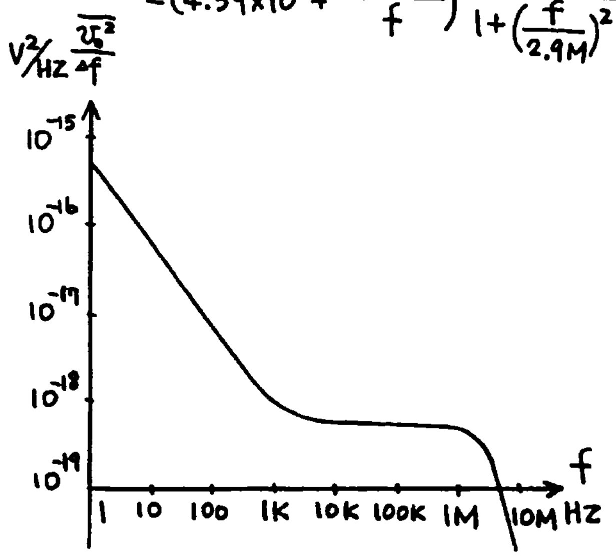
$r_d = 55.3\,\Omega$, $C = 1000\,pF$

$$\therefore \frac{1}{r_d C} = 18.1\times10^{6}\ \text{rad/sec}$$

$$\therefore \frac{1}{2\pi r_d C} = 2.9\ \text{MHz}$$

$$\therefore \frac{\overline{v_o^2}}{\Delta f} = \left(1.5\times10^{-22} + \frac{1.41\times10^{-19}}{f}\right)\frac{3060}{1+\left(\frac{f}{2.9M}\right)^2}$$

$$= \left(4.59\times10^{-19} + \frac{4.32\times10^{-16}}{f}\right)\frac{1}{1+\left(\frac{f}{2.9M}\right)^2}$$




```
NOISE ANALYSIS
VCC 1 0 10V AC 1
RL 1 2 20K
DIODE 2 0 D
CAP 2 0 1NF
.NOISE V(2) VCC 10
.AC DEC 10 1 10MEG
.MODEL D D KF=3E-16 AF=1
.OPTIONS NOMOD SPICE
.WIDTH OUT=80
.END

 ******  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
+0:1        = 1.000E+01 0:2        = 6.355E-01
**** DIODES
ELEMENT  0:DIODE
MODEL    0:D
 ID        4.682E-04
 VD        6.355E-01
 REQ       5.523E+01
 CAP         0.

NOISE ANALYSIS

    FREQUENCY = 1.000E+00  HZ
**** RESISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT       0:RL
   TOTAL  2.515E-21
**** DIODE SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT       0:DIODE
      ID  4.553E-19
      FN  4.263E-16
   TOTAL  4.267E-16
**** TOTAL OUTPUT NOISE VOLTAGE          = 4.267E-16 SQ V/HZ

    FREQUENCY = 9.999E+00  HZ
**** RESISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT       0:RL
   TOTAL  2.515E-21
**** DIODE SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT       0:DIODE
      ID  4.553E-19
      FN  4.263E-17
   TOTAL  4.308E-17
**** TOTAL OUTPUT NOISE VOLTAGE          = 4.308E-17 SQ V/HZ

    FREQUENCY = 1.000E+02  HZ
**** RESISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT       0:RL
   TOTAL  2.515E-21
**** DIODE SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT       0:DIODE
      ID  4.553E-19
      FN  4.263E-18
   TOTAL  4.718E-18
**** TOTAL OUTPUT NOISE VOLTAGE          = 4.720E-18 SQ V/HZ

    FREQUENCY = 1.000E+03  HZ
**** RESISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT       0:RL
   TOTAL  2.515E-21
**** DIODE SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT       0:DIODE
      ID  4.553E-19
      FN  4.263E-19
   TOTAL  8.815E-19
**** TOTAL OUTPUT NOISE VOLTAGE          = 8.841E-19 SQ V/HZ

    FREQUENCY = 9.999E+03  HZ
**** RESISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT       0:RL
   TOTAL  2.515E-21
**** DIODE SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT       0:DIODE
      ID  4.553E-19
      FN  4.262E-20
   TOTAL  4.979E-19
**** TOTAL OUTPUT NOISE VOLTAGE          = 5.004E-19 SQ V/HZ

    FREQUENCY = 9.999E+04  HZ
**** RESISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT       0:RL
   TOTAL  2.512E-21
**** DIODE SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT       0:DIODE
      ID  4.547E-19
      FN  4.257E-21
   TOTAL  4.590E-19
**** TOTAL OUTPUT NOISE VOLTAGE          = 4.615E-19 SQ V/HZ

    FREQUENCY = 1.000E+06  HZ
**** RESISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT       0:RL
   TOTAL  2.246E-21
**** DIODE SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT       0:DIODE
      ID  4.066E-19
      FN  3.807E-22
   TOTAL  4.070E-19
**** TOTAL OUTPUT NOISE VOLTAGE          = 4.092E-19 SQ V/HZ

    FREQUENCY = 9.999E+06  HZ
**** RESISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT       0:RL
   TOTAL  1.938E-22
**** DIODE SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT       0:DIODE
      ID  3.508E-20
      FN  3.284E-24
   TOTAL  3.508E-20
**** TOTAL OUTPUT NOISE VOLTAGE          = 3.527E-20 SQ V/HZ
```

11.4

Using (11.38)

$$\frac{\overline{v_o^2}}{\Delta f} = g_m^2 R_L^2 \frac{r_\pi^2}{(r_\pi + R_S)^2}\left[4kTR_S + R_S^2 2qI_B\right] + R_L^2\left(4kT\frac{1}{R_L} + 2qI_C\right)$$

$$= \frac{10^{8}}{26^2}\,\frac{50^2\times26^2}{2300^2}\Big[1.66\times10^{-20}\times10^{3} + 10^{6}\times3.2\times10^{-19}\times20\times10^{-6}\Big] + 10^{8}\times1.66\times10^{-20}\times10^{-4} + 10^{8}\times3.2\times10^{-19}\times10^{-3}$$

11-3

$$= 4.73\times10^{4}\left[1.66\times10^{-17} + 6.4\times10^{-18}\right]$$
$$+ 1.66\times10^{-16} + 3.2\times10^{-14}$$
$$= 1.12\times10^{-12}\ V^2/Hz$$

If $\Delta f = 2\ MHZ$

$$\overline{v_{oT}^2} = 1.12\times10^{-12}\times 2\times10^{6}\ V^2$$
$$= 2.24\times10^{-6}\ V^2$$

$\therefore v_{oT} = 1.5\ mV\ rms$

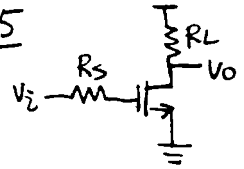
Circuit gain

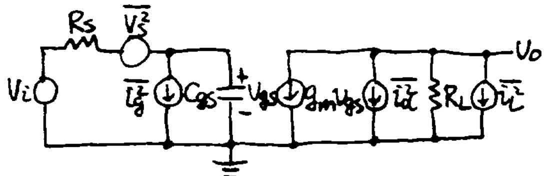
$$G = \left|\frac{v_o}{i_s}\right| = \frac{R_s r_\pi}{R_s + r_\pi} g_m R_L$$
$$= \frac{1\times1.3}{2.3}\times1000\times\frac{10{,}000}{26}$$
$$= 2.17\times10^{5}\ \Omega$$

$$MDS = \frac{v_{oT}}{G} = 6.9\ nA$$

```
COMMON EMITTER CONFIGURATION
VCC 1 0 15V
RL 1 2 10K
Q1 2 3 0 N
RS 3 0 1K
IS 0 3 794.2UA AC 1
.NOISE V(2) IS 10
.AC DEC 10 0.2MEG 20MEG
.PLOT AC V(2)
.MODEL N NPN BF=50
.WIDTH OUT=80
.OPTIONS NOMOD SPICE
.WIDTH OUT=80
.END

 ******  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
+0:1      = 1.500E+01 0:2      = 5.001E+00 0:3       = 7.742E-01

**** BIPOLAR JUNCTION TRANSISTORS
ELEMENT  0:Q1
MODEL    0:N
 IB       2.000E-05
 IC       9.998E-04
 VBE      7.742E-01
 VCE      5.001E+00
 VBC     -4.227E+00
 VS      -5.001E+00
 POWER    5.016E-03
 BETAD    5.000E+01
 GM       3.866E-02
 RPI      1.293E+03
 RX          0.
 RO       4.227E+16
 CPI         0.
 CMU         0.
 CBX         0.
 CCS         0.
 BETAAC   5.000E+01
 FT       6.152E+12

 ******  NOISE ANALYSIS                  TNOM=  27.000 TEMP=  27.000
    FREQUENCY = 2.000E+06  HZ
**** RESISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT     0:RL        0:RS
   TOTAL  1.658E-16    7.878E-13

**** TRANSISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT     0:Q1
      RB     0.
      RC     0.
      RE     0.
      IB  3.045E-13
      IC  3.204E-14
      FN     0.
   TOTAL  3.366E-13
**** TOTAL OUTPUT NOISE VOLTAGE          = 1.125E-12 SQ V/HZ
                                         = 1.060E-06 V/RT HZ
     TRANSFER FUNCTION VALUE:
       V(2)/IS                           = 2.180E+05
     EQUIVALENT INPUT NOISE AT IS        = 4.864E-12 /RT HZ
```

11.5





$g_m = \sqrt{2 \times 194 \times 100 \times 100} = 1.97\,mA/V$

$C_{ox} = 4.3\,fF/\mu m^2$

$A_v(\omega) = \frac{V_o}{V_i}(\omega) = -\frac{g_m R_L}{1 + sC_{gs}R_s}$

$C_{gs} = \frac{2}{3} 100 \times 1 \times 4.3 = 287\,fF$

$f_{-3dB} = \frac{1}{2\pi C_{gs} R_s} = 5.55\,MHz$

$\overline{v_s^2} = 4kTR_s \Delta f$

$\overline{i_g^2} = 2qI_G \Delta f \approx 0$

$\overline{i_L^2} = \frac{4kT}{R_L}\Delta f$

$\overline{i_d^2} = 4kT\frac{2}{3}g_m \Delta f + \frac{g_m^2 K_f \Delta f}{WLC_{ox} f}$

$\overline{v_s^2}$ produces $\overline{v_{o1}^2} = A_v^2(\omega)\overline{v_s^2}$

$\overline{i_d^2}$ produces $\overline{v_{o2}^2} = \overline{i_d^2} R_L^2$

$\overline{i_L^2}$ produces $\overline{v_{o3}^2} = \overline{i_L^2} R_L^2$

At 10Hz, $|A_v| = 19.7$

$\overline{v_{o1}^2} = (19.7)^2 (1.66 \times 10^{-20})(10^5)\Delta f$
$= 6.44 \times 10^{-13} \Delta f (V^2)$

$\overline{v_{o2}^2} = (1.66 \times 10^{-20}) \frac{2}{3}(1.97 \times 10^{-3})(10^4)^2 \Delta f + \frac{(1.97 \times 10^{-3})^2 (3 \times 10^{-24}) \Delta f (10^4)^2}{100(1)(4.3 \times 10^{-15})10}$
$= [2.18 \times 10^{-15} + 2.71 \times 10^{-10}]\Delta f\ (V^2)$

$\overline{v_{o3}^2} = 1.66 \times 10^{-20}(10^4)\Delta f = 1.66 \times 10^{-16} \Delta f (V^2)$

$\overline{v_{oT}^2} = \overline{v_{o1}^2} + \overline{v_{o2}^2} + \overline{v_{o3}^2} = 2.72 \times 10^{-10} \Delta f (V^2)$

$\sqrt{\overline{v_{oT}^2}} = 16.5\,\mu V \sqrt{\Delta f}$

Total input-referred noise

$\sqrt{\overline{v_{iT}^2}} = \sqrt{\overline{v_{oT}^2}}/|A_v| = 837\,nV\sqrt{\Delta f}$

At 100kHz, $|A_v| \approx 19.7$

$\overline{v_{o1}^2} = 6.44 \times 10^{-13} \Delta f (V^2)$ (same)

$\overline{v_{o2}^2} = (2.18 \times 10^{-15} + 2.71 \times 10^{-14})\Delta f (V^2)$

$\overline{v_{o3}^2} = 1.66 \times 10^{-16} \Delta f (V^2)$ (same)

$\overline{v_{oT}^2} = 6.73 \times 10^{-13} \Delta f (V^2)$

$\sqrt{\overline{v_{oT}^2}} = 821\,nV\sqrt{\Delta f}$

$\sqrt{\overline{v_{iT}^2}} = 41.7\,nV\sqrt{\Delta f}$

At 1GHz, $|A_v| = 19.7/\sqrt{1 + (1000/5.55)^2} = 0.109$

$\overline{v_{o1}^2} = (0.109)^2 (1.66 \times 10^{-20})(10^5)\Delta f$
$= 1.98 \times 10^{-17} \Delta f (V^2)$

$\overline{v_{o2}^2} = (2.18 \times 10^{-15} + 2.71 \times 10^{-18})\Delta f (V^2)$

$\overline{v_{o3}^2} = 1.66 \times 10^{-16} \Delta f (V^2)$ (same)

$\overline{v_{oT}^2} = 2.37 \times 10^{-15} \Delta f (V^2)$

$\sqrt{\overline{v_{oT}^2}} = 48.7\,nV\sqrt{\Delta f}$

$\sqrt{\overline{v_{iT}^2}} = 48.7\,nV\sqrt{\Delta f}/0.109 = 446\,nV\sqrt{\Delta f}$

At 10Hz, 1/f noise dominates

At 100kHz, thermal noise from Rs dominates

At 1GHz, thermal noise from the transistor dominates.

11-5

```
COMMON-SOURCE AMP NOISE SIMULATION
VDD 1 0 5
VI 2 0 DC 0.70154 AC 1
M1 3 4 0 0 CMOSN L=1U W=100U
RL 1 3 10K
RS 2 4 100K
.MODEL CMOSN NMOS LEVEL=1 VTO=0.6 KP=194U KF=3E-24 TOX=80E-10 CAPOP=0
.OPTIONS NOMOD
.WIDTH OUT=80
.OP
.AC DEC 10 10 1GIG
.NOISE V(3) VI 40
.PRINT AC VM(3) ONOISE INOISE
.END

****** OPERATING POINT INFORMATION      TNOM=  25.000 TEMP=  25.000

+0:1      =  5.0000  0:2       = 701.5400M 0:3       =   3.9999
+0:4      = 701.5400M

**** MOSFETS

ELEMENT  0:M1
MODEL    0:CMOSN
 ID       100.0106U
 IBS        0.
 IBD      -39.9989F
 VGS      701.5400M
 VDS        3.9999
 VBS        0.
 VTH      600.0000M
 VDSAT    101.5400M
 BETA      19.4000M
 GAM EFF   42.2100M
 GM         1.9699M
 GDS        0.
 GMB       54.5972U
 CDTOT      0.
 CGTOT    287.7634F
 CSTOT    287.7634F
 CBTOT      0.
 CGS      287.7634F
 CGD        0.

****** NOISE ANALYSIS                      TNOM=  25.000 TEMP=  25.000
    FREQUENCY =  10.0000   HZ
**** RESISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT      0:RL         0:RS
  TOTAL  1.647E-16    638.9216F
**** MOSFET SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT      0:M1
      ID     2.1623F
      RX    10.0000K
      FN   269.6959P
  TOTAL    269.6981P
**** TOTAL OUTPUT NOISE VOLTAGE             = 270.3372P SQ V/HZ
                                            =  16.4419U V/RT HZ

     TRANSFER FUNCTION VALUE:
       V(3)/VI                              =  19.6988
     EQUIVALENT INPUT NOISE AT VI           = 834.6685N /RT HZ

****** NOISE ANALYSIS                      TNOM=  25.000 TEMP=  25.000
    FREQUENCY = 100.0000K  HZ
**** RESISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT      0:RL         0:RS
  TOTAL  1.647E-16    638.7128F
**** MOSFET SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT      0:M1
      ID     2.1623F
      RX    10.0000K
      FN    26.9696F
  TOTAL     29.1319F
**** TOTAL OUTPUT NOISE VOLTAGE             = 668.0094F SQ V/HZ
                                            = 817.3184N V/RT HZ

     TRANSFER FUNCTION VALUE:
       V(3)/VI                              =  19.6955
     EQUIVALENT INPUT NOISE AT VI           =  41.4976N /RT HZ

****** NOISE ANALYSIS                      TNOM=  25.000 TEMP=  25.000
    FREQUENCY =   1.0000G  HZ
**** RESISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT      0:RL         0:RS
  TOTAL  1.647E-16    1.954E-17
**** MOSFET SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT      0:M1
      ID     2.1623F
      RX    10.0000K
      FN   2.697E-18
  TOTAL      2.1650F
**** TOTAL OUTPUT NOISE VOLTAGE             =    2.3492F SQ V/HZ
                                            =  48.4686N V/RT HZ

     TRANSFER FUNCTION VALUE:
       V(3)/VI                              = 108.9474M
     EQUIVALENT INPUT NOISE AT VI           = 444.8804N /RT HZ

****** AC ANALYSIS                         TNOM=  25.000 TEMP=  25.000
```

FREQ	VOLTAGE M	ONOISE	INOISE
	3	MAG	MAG
10.00000	19.6988	16.4419U	834.6685N
12.58925	19.6988	14.6584U	744.1275N
15.84893	19.6988	13.0693U	663.4605N
19.95262	19.6988	11.6537U	591.5971N
25.11886	19.6988	10.3927U	527.5837N
31.62278	19.6988	9.2697U	470.5707N
39.81072	19.6988	8.2696U	419.8016N
50.11872	19.6988	7.3792U	374.6025N
63.09574	19.6988	6.5867U	334.3734N
79.43282	19.6988	5.8817U	298.5803N
100.00000	19.6988	5.2546U	266.7479N
125.89254	19.6988	4.6972U	238.4530N
158.48932	19.6988	4.2021U	213.3196N
199.52623	19.6988	3.7627U	191.0131N
251.18864	19.6988	3.3731U	171.2359N
316.22776	19.6988	3.0282U	153.7236N
398.10717	19.6988	2.7232U	138.2411N
501.18723	19.6988	2.4541U	124.5792N
630.95734	19.6988	2.2171U	112.5515N
794.32826	19.6988	2.0091U	101.9916N
1.00000K	19.6988	1.8271U	92.7508N
1.25893K	19.6988	1.6684U	84.6951N
1.58489K	19.6988	1.5307U	77.7033N
1.99526K	19.6988	1.4117U	71.6650N
2.51189K	19.6988	1.3096U	66.4789N
3.16228K	19.6988	1.2223U	62.0514N
3.98107K	19.6988	1.1483U	58.2953N
5.01187K	19.6988	1.0860U	55.1296N
6.30957K	19.6987	1.0338U	52.4791N
7.94328K	19.6987	990.3405N	50.2743N
10.00000K	19.6987	954.4330N	48.4515N
12.58925K	19.6987	924.9174N	46.9532N
15.84893K	19.6987	900.7930N	45.7281N
19.95262K	19.6986	881.1404N	44.7310N
25.11887K	19.6986	865.2186N	43.9229N
31.62278K	19.6984	852.3573N	43.2703N
39.81072K	19.6982	841.9976N	42.7448N
50.11872K	19.6980	833.6711N	42.3227N
63.09573K	19.6975	826.9881N	41.9845N
79.43282K	19.6967	821.6261N	41.7138N
100.00000K	19.6955	817.3184N	41.4976N
125.89254K	19.6937	813.8430N	41.3251N
158.48932K	19.6907	811.0123N	41.1876N
199.52623K	19.6860	808.6624N	41.0781N
251.18864K	19.6785	806.6413N	40.9910N
316.22776K	19.6666	804.7951N	40.9218N
398.10715K	19.6479	802.9506N	40.8669N
501.18723K	19.6184	800.8906N	40.8235N
630.95736K	19.5718	798.3198N	40.7893N
794.32824K	19.4987	794.8152N	40.7625N
1.00000X	19.3845	789.7592N	40.7419N
1.25893X	19.2075	782.2516N	40.7265N
1.58489X	18.9366	771.0159N	40.7157N
1.99526X	18.5298	754.3361N	40.7093N
2.51189X	17.9356	730.1156N	40.7075N
3.16228X	17.1009	696.1969N	40.7112N
3.98107X	15.9877	651.0514N	40.7220N
5.01187X	14.5970	594.7236N	40.7429N
6.30957X	12.9849	529.4999N	40.7793N
7.94328X	11.2561	459.6542N	40.8360N
10.00000X	9.5339	390.2023N	40.9280N
12.58925X	7.9232	325.4326N	41.0732N
15.84893X	6.4904	268.0620N	41.3014N
19.95262X	5.2620	219.2073N	41.6589N
25.11886X	4.2359	178.8224N	42.2161N
31.62278X	3.3938	146.2063N	43.0810N
39.81072X	2.7106	120.3557N	44.4122N
50.11872X	2.1607	100.3386N	46.4379N
63.09573X	1.7201	85.0972N	49.4714N
79.43282X	1.3683	73.7801N	53.9220N
100.00000X	1.0878	65.5926N	60.2968N
125.89254X	864.5791M	59.8261N	69.1968N
158.48932X	687.0039M	55.8668N	81.3195N
199.52623X	545.8291M	53.2074N	97.4800N
251.18865X	433.6289M	51.4529N	118.6543N
316.22776X	344.4744M	50.3078N	146.0421N
398.10717X	273.6412M	49.5684N	181.1438N
501.18722X	217.3687M	49.0932N	225.8520N
630.95734X	172.6660M	48.7886N	282.5604N
794.32823X	137.1554M	48.5935N	354.2953N
999.99998X	108.9474M	48.4686N	444.8804N

11.6

Neglect R_L

$$\overline{v_i^2} = 4kT(r_b + \frac{1}{2g_m})\Delta f$$

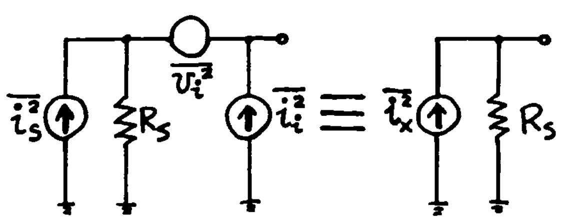
$$\therefore \frac{\overline{v_i^2}}{\Delta f} = 1.66\times10^{-20}\times 13 \ \ V^2/Hz$$

$$= 21.6\times10^{-20} \ V^2/Hz$$

$$\frac{\overline{i_i^2}}{\Delta f} = 2q(I_B + \frac{I_c}{\beta^2})$$

$$= 3.2\times10^{-19}\times 20\times10^{-6} \ A^2/Hz$$

$$= 6.4\times10^{-24} \ A^2/Hz$$



Equate voltage across R_s

$$i_sR_s + i_iR_s + v_i = i_xR_s$$

$$\therefore \overline{i_x^2} = \overline{i_s^2} + \overline{i_i^2} + \frac{\overline{v_i^2}}{R_s^2}$$

$$\therefore \frac{\overline{i_x^2}}{\Delta f} = 4kT\frac{1}{R_s} + 64\times10^{-25} + \frac{21.6\times10^{-20}}{10^6}$$

$$= 1.66\times10^{-23} + 0.64\times10^{-23} + 0.02\times10^{-23}$$

$$= 2.32\times10^{-23} \ A^2/Hz$$

If Δf = 2 MHz

$$\overline{i_x^2} = 2.32\times10^{-23}\times2\times10^6$$

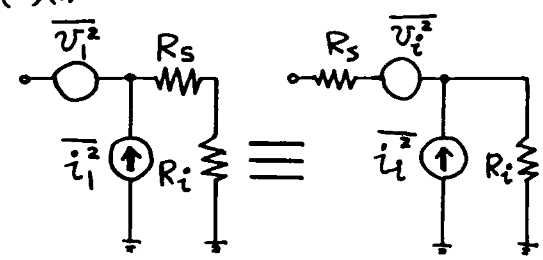
$$= 4.64\times10^{-17} \ A^2$$

$\therefore i_x = 6.8\,nA$ rms

---- the same as in 11.4

11.7

(a)(i)



Short inputs and equate noise

$$v_1 = v_i + i_iR_s$$

$$\therefore \overline{v_1^2} = \overline{v_i^2} + \overline{i_i^2}R_s^2$$

neglecting correlation

Open inputs and equate noise

$$\overline{i_1^2} = \overline{i_i^2}$$

for the transistor plus R_s

(neglect R_L)

$$\overline{v_i^2} = 4kT(r_b + \frac{1}{2g_m} + R_s)\Delta f$$

$$= 1.66\times10^{-20}(100+26+10^5)\Delta f$$

$$\frac{\overline{v_i^2}}{\Delta f} = 1.66\times10^{-15}\ \frac{V^2}{Hz}$$

$$\overline{i_i^2} = 2q(I_B + \frac{I_c}{\beta^2})\Delta f$$

$$\frac{\overline{i_i^2}}{\Delta f} = 3.2\times10^{-19}(5\times10^{-6})$$

$$= 16\times10^{-25}\ A^2/Hz = \frac{\overline{i_1^2}}{\Delta f}$$

$$\frac{\overline{v_1^2}}{\Delta f} = 1.66\times10^{-15} + 16\times10^{-25}\times10^{10}$$

$$= 17.7\times10^{-15}\ \frac{V^2}{Hz}$$

(ii)

$$\overline{v_i^2} = 4kT(r_b + R_E + \frac{1}{2g_m})\Delta f + 4kT\frac{1}{R_L}\Delta f R_E^2$$

$$\therefore \frac{\overline{v_i^2}}{\Delta f} = 1.66\times10^{-20}(100+1000+26+100)$$

$$= 2.04\times10^{-17}\ V^2$$

$$\frac{\overline{i_i^2}}{\Delta f} = 2q(I_B + \frac{I_C}{\beta^2}) = 16\times10^{-25}\ A^2/Hz$$

(iii)

$$\frac{\overline{v_i^2}}{\Delta f} = 4kT(r_b + \frac{1}{2g_m}) + \frac{4kT\frac{1}{R_L}}{g_m^2}$$

$$= 1.66\times10^{-20}(100+1000+400)$$

$$= 2.49\times10^{-17}\ V^2/Hz$$

$$\frac{\overline{i_i^2}}{\Delta f} \simeq 2q(I_B) = 3.2\times10^{-19}\times\frac{13\times10^{-6}}{50}$$

$$= 8.32\times10^{-26}\ A^2/Hz$$

(iv)

$$\frac{\overline{v_i^2}}{\Delta f} = 4kT\frac{2}{3}\frac{1}{g_m} + \frac{4kT\frac{1}{R_L}}{g_m^2}$$

$$= 4kT\frac{1}{g_m}(0.67 + \frac{1}{10})$$

$$= 1.66\times10^{-20}\times1000\times0.77$$

$$= 1.28\times10^{-17}\ V^2/Hz$$

$$\frac{\overline{i_i^2}}{\Delta f} \simeq 0$$

(b)(i) $\overline{V_{iT}^2} = 17.7\times10^{-15}\times 20{,}000\ V^2$

$V_{iT} = 18.8\ \mu V$ rms

(ii) $\overline{v_{iT}^2} = 2.04\times10^{-17}\times 20{,}000\ V^2$

$\therefore v_{iT} = 0.64\ \mu V$ rms

(iii) $\overline{v_{iT}^2} = 2.49\times10^{-17}\times 20{,}000\ V^2$

$\therefore v_{iT} = 0.71\ \mu V$ rms

(iv) $\overline{v_{iT}^2} = 1.28\times10^{-17}\times 20{,}000\ V^2$

$\therefore v_{iT} = 0.5\ \mu V$ rms

Thus the FET is best and (i) is worst.

11.8

For the FET

$$\frac{\overline{i_d^2}}{\Delta f} = 4kT(\frac{2}{3}g_m) + K\frac{I_D^a}{f}$$

$$4kT\frac{2}{3}g_m = \frac{KI_D^a}{10^5}$$

$$\therefore \frac{\overline{i_d^2}}{\Delta f} = 4kT(\frac{2}{3}g_m)[1 + \frac{10^5}{f}]$$

$$\frac{\overline{v_i^2}}{\Delta f} = 4kT\frac{2}{3g_m}(1 + \frac{10^5}{f})$$

$$\frac{\overline{i_i^2}}{\Delta f} = 2qI_G \simeq 0$$

$$\overline{v_{iT}^2} = \int_{f_1}^{f_2} 4kT\frac{2}{3g_m}(1 + \frac{10^5}{f})\,df$$

$$= 1.66\times10^{-20}\times\frac{2000}{3}\left[(f_2 - f_1) + 10^5\ln\frac{f_2}{f_1}\right]$$

$$= 1.1\times10^{-17}\left[20{,}000 + 10^5\ln\frac{20{,}000}{0.001}\right]$$

$$= 1.1\times10^{-17}\left[20{,}000 + 1.68\times10^6\right]$$

$$= 1.9\times10^{-11}\ V^2$$

$\therefore v_{iT} = 4.3\ \mu V$ rms

11.9

bias

$V_{BE} = V_T \ln \frac{I_C}{I_S}$

$= (26m) \ln \frac{10^{-3}}{10^{-16}}$

$= 0.778\,V$

$I_D = \frac{0.778 + 0.1}{300}$

$= 2.93\ mA$

mos $g_m = \sqrt{2 I_D \mu C_{ox} \frac{W}{L}}$

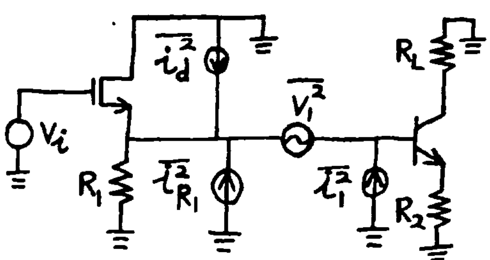
$= \sqrt{2(2.93m)(60\mu)(100)}$

$= 5.93\ mA/V$

input noise current generator

$= 0$ (mosfets have very small input noise current at low freq)

input noise voltage generator



$\overline{i_d^2} = 4kT \frac{2}{3} g_m\, \Delta f$

$\overline{i_{R_1}^2} = 4kT \frac{1}{300}\, \Delta f$

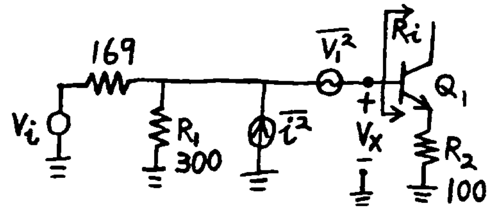
$\overline{i_1^2} = 2q I_{B_1} \Delta f = 4kT \frac{2q I_{B_1}}{4kT} \Delta f$

$\overline{v_1^2} = 4kT \left(r_b + \frac{1}{2g_m} + R_2\right) \Delta f$

neglect R_3

looking into source of m_1,

we see $\frac{1}{g_m} = 169\,\Omega$



$\overline{i^2} = \overline{i_d^2} + \overline{i_{R_1}^2} + \overline{i_1^2}$

$= 4kT(3.95m + 3.33m + 0.19m)\Delta f$

$= 4kT\ 7.47m\ \Delta f$

$\overline{v_x^2} = \overline{v_1^2} \left[\frac{R_i}{R_i + (169 \| 300)}\right]^2 + \overline{i^2}(169 \| 300 \| R_i)^2$

$R_i \gg (169 \| 300)$

$\therefore \overline{v_x^2} = \overline{v_1^2} + \overline{i^2}\,(169 \| 300)^2$

$= 4kT(100 + 13 + 100)\Delta f$

$+ 4kT(7.47m)\Delta f\ (11.7k)$

equivalent input noise voltage $= \overline{v_i^2}$

$\overline{v_i^2}\left(\frac{300}{469}\right)^2 = \overline{v_x^2}$

$0.41\,\overline{v_i^2} = 4kT\ 300\,\Delta f$

$\frac{\overline{v_i^2}}{\Delta f} = 1.66 \times 10^{-20}(300)\frac{1}{0.41}$

$= 1.22 \times 10^{-17}\ \frac{V^2}{Hz}$

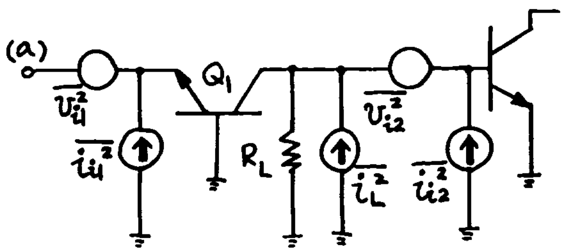
```
BICMOS DARLINGTON
VCC 1 0 5V
M1 1 2 3 0 NMOS W=100U L=1U
R1 3 0 300
Q1 5 3 4 NPN
R2 4 0 100
R3 1 5 2K
VI 2 0 2.5646V AC 1
.NOISE V(5) VI 10
.AC DEC 10 1K 1MEG
.MODEL NPN NPN BF=100 RB=100 IS=1E-16
.MODEL NMOS NMOS KP=60U VTO=0.7V
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.PROBE
.END

 ******  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000

+0:1       = 5.000E+00 0:2       = 2.564E+00 0:3       = 8.762E-01
+0:4       = 1.010E-01 0:5       = 2.999E+00

**** BIPOLAR JUNCTION TRANSISTORS

ELEMENT  0:Q1
MODEL    0:NPN
 IB       1.000E-05
 IC       1.000E-03
 VBE      7.752E-01
 VCE      2.898E+00
 VBC     -2.123E+00
 VS      -2.999E+00
 POWER    2.907E-03
 BETAD    1.000E+02
 GM       3.867E-02
 RPI      2.586E+03
 RX       1.000E+02
 RO       2.124E+16
 CPI       0.
 CMU       0.
 CBX       0.
 CCS       0.
 BETAAC   9.999E+01
 FT       6.153E+12

**** MOSFETS

ELEMENT  0:M1
MODEL    0:NMOS
 ID       2.931E-03
 IBS     -8.762E-15
 IBD     -5.000E-14
 VGS      1.688E+00
 VDS      4.123E+00
 VBS     -8.762E-01
 VTH      7.000E-01
 VDSAT    9.884E-01
 BETA     6.000E-03
 GAM EFF   0.
 GM       5.930E-03
 GDS       0.
 GMB       0.
 CDTOT     0.
 CGTOT     0.
 CSTOT     0.
 CBTOT     0.
 CGS       0.
 CGD       0.

 ******  NOISE ANALYSIS                   TNOM=  27.000 TEMP=  27.000
    FREQUENCY = 1.000E+03  HZ
**** RESISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT       0:R1        0:R2        0:R3
  TOTAL  1.549E-16    3.988E-16    3.315E-17
**** TRANSISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT       0:Q1
      RB  3.988E-16
      RC   0.
      RE   0.
      IB  7.311E-17
      IC  6.458E-17
      FN   0.
   TOTAL  5.365E-16
**** MOSFET SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT       0:M1
      RD   0.
      RS   0.
      ID  1.837E-16
      RX  1.674E+03
      FN -4.019E-03
   TOTAL -4.019E-03
**** TOTAL OUTPUT NOISE VOLTAGE           =-4.019E-03 SQ V/HZ
                                          =-2.395E+00 V/RT HZ
     TRANSFER FUNCTION VALUE:
       V(5)/VI                            = 9.929E+00
     EQUIVALENT INPUT NOISE AT VI         =-2.413E-01 /RT HZ
```

```
BICMOS DARLINGTON
VCC 1 0 5V
M1 1 2 3 0 NMOS W=100U L=1U
R1 3 0 300
Q1 5 3 4 NPN
R2 4 0 100
R3 1 5 2K
VI 2 0 2.5646V AC 1
.NOISE V(5) VI 10
.AC DEC 80 10MEG 10GIG
******
* ADJUST CJE TO ACHIEVE THE SPECIFIED FT=10GHZ FOR Q1
******
.MODEL NPN NPN BF=100 RB=100 IS=1E-16 CJE=330FF CJC=50FF
.MODEL NMOS NMOS KP=60U VTO=0.7V TOX=153E-10 CBS=50FF
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.PROBE
.END

 ******  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000

+0:1       = 5.000E+00 0:2       = 2.564E+00 0:3       = 8.762E-01
+0:4       = 1.010E-01 0:5       = 2.999E+00

**** BIPOLAR JUNCTION TRANSISTORS

ELEMENT  0:Q1
MODEL    0:NPN
 IB       1.000E-05
 IC       1.000E-03
 VBE      7.752E-01
 VCE      2.898E+00
 VBC     -2.123E+00
 VS      -2.999E+00
 POWER    2.907E-03
 BETAD    1.000E+02
 GM       3.867E-02
 RPI      2.586E+03
 RX       1.000E+02
 RO       2.124E+16
 CPI      5.605E-13
 CMU      3.209E-14
 CBX       0.
 CCS       0.
 BETAAC   9.999E+01
 FT       1.038E+10

**** MOSFETS

ELEMENT  0:M1
MODEL    0:NMOS
 ID       2.931E-03
 IBS     -8.762E-15
 IBD     -5.000E-14
 VGS      1.688E+00
 VDS      4.123E+00
 VBS     -8.762E-01
 VTH      7.000E-01
 VDSAT    9.884E-01
 BETA     6.000E-03
 GAM EFF   0.
 GM       5.930E-03
 GDS       0.
 GMB       0.
 CDTOT    1.241E-15
 CGTOT    1.549E-13
 CSTOT    1.850E-13
 CBTOT    3.772E-14
 CGS      1.505E-13
 CGD      1.241E-15

 ******  NOISE ANALYSIS                   TNOM=  27.000 TEMP=  27.000
    FREQUENCY = 9.999E+06  HZ
**** RESISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT       0:R1        0:R2        0:R3
  TOTAL  1.549E-16    3.987E-16    3.315E-17
**** TRANSISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT       0:Q1
      RB  3.987E-16
      RC   0.
      RE   0.
      IB  7.310E-17
      IC  6.458E-17
      FN   0.
   TOTAL  5.364E-16
**** MOSFET SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT       0:M1
      RD   0.
      RS   0.
      ID  1.837E-16
      RX  1.674E+03
      FN   0.
   TOTAL  1.837E-16
**** TOTAL OUTPUT NOISE VOLTAGE           = 1.307E-15 SQ V/HZ
```

```
                                        = 3.615E-08 V/RT HZ
   TRANSFER FUNCTION VALUE:
    V(5)/VI                             = 9.928E+00
   EQUIVALENT INPUT NOISE AT VI         = 3.641E-09 /RT HZ
***** LOW FREQ EQUIVALENT INPUT NOISE VOLTAGE = 1.33E-17 SQ V/HZ

 ******  NOISE ANALYSIS                   TNOM=  27.000 TEMP=  27.000
  FREQUENCY = 1.333E+07  HZ
**** TOTAL OUTPUT NOISE VOLTAGE         = 1.307E-15 SQ V/HZ
                                        = 3.615E-08 V/RT HZ
   TRANSFER FUNCTION VALUE:
    V(5)/VI                             = 9.928E+00
   EQUIVALENT INPUT NOISE AT VI         = 3.641E-09 /RT HZ

 ******  NOISE ANALYSIS                   TNOM=  27.000 TEMP=  27.000
  FREQUENCY = 1.333E+09  HZ
**** TOTAL OUTPUT NOISE VOLTAGE         = 3.658E-16 SQ V/HZ
                                        = 1.913E-08 V/RT HZ
   TRANSFER FUNCTION VALUE:
    V(5)/VI                             = 5.082E+00
   EQUIVALENT INPUT NOISE AT VI         = 3.763E-09 /RT HZ

 ******  NOISE ANALYSIS                   TNOM=  27.000 TEMP=  27.000
  FREQUENCY = 4.217E+09  HZ
**** TOTAL OUTPUT NOISE VOLTAGE         = 8.313E-17 SQ V/HZ
                                        = 9.118E-09 V/RT HZ
   TRANSFER FUNCTION VALUE:
    V(5)/VI                             = 2.044E+00
   EQUIVALENT INPUT NOISE AT VI         = 4.460E-09 /RT HZ

 ******  NOISE ANALYSIS                   TNOM=  27.000 TEMP=  27.000
  FREQUENCY = 7.498E+09  HZ
**** RESISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT     0:R1         0:R2         0:R3
  TOTAL  1.181E-18    4.269E-18    1.597E-18
**** TRANSISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT     0:Q1
     RB  5.734E-18
     RC     0.
     RE     0.
     IB  6.073E-19
     IC  3.307E-17
     FN     0.
  TOTAL  3.941E-17
**** MOSFET SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT     0:M1
     RD     0.
     RS     0.
     ID  1.401E-18
     RX  1.462E+02
     FN     0.
  TOTAL  1.401E-18
**** TOTAL OUTPUT NOISE VOLTAGE         = 4.786E-17 SQ V/HZ
                                        = 6.918E-09 V/RT HZ
   TRANSFER FUNCTION VALUE:
    V(5)/VI                             = 1.351E+00
   EQUIVALENT INPUT NOISE AT VI         = 5.119E-09 /RT HZ
***** FREQ=7.5GHZ EQUIVALENT INPUT NOISE VOLTAGE=2.62E-17 SQ V/HZ
***** (DOUBLE THE INPUT NOISE AT LOW FREQ)

BICMOS DARLINGTON
VCC 1 0 5V
M1 1 2 3 0 NMOS W=100U L=1U
R1 3 0 300
Q1 5 3 4 NPN
R2 4 0 100
R3 1 5 2K
VI 7 0 2.5646V
******
* USE INDUCTOR TO ALLOW VI TO SET DC BIAS.
* BUT CHOOSE A LARGE INDUCTOR TO GET VERY LARGE IMPEDANCE
* AT 7.5GIGAHERTZ.
******
LBIAS 2 7 1KHENRY
IS 2 0 0A AC 1
.NOISE V(5) IS 10
.AC DEC 80 10MEG 10GIG
.MODEL NPN NPN BF=100 RB=100 IS=1E-16 CJE=330FF CJC=50FF
.MODEL NMOS NMOS KP=60U VTO=0.7V TOX=153E-10 CBS=50FF
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.PROBE
.END

 ******  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000

+0:1     = 5.000E+00 0:2     = 2.564E+00 0:3     = 8.762E-01
+0:4     = 1.010E-01 0:5     = 2.999E+00 0:7     = 2.564E+00

**** BIPOLAR JUNCTION TRANSISTORS

ELEMENT  0:Q1
MODEL    0:NPN
 IB        1.000E-05
 IC        1.000E-03
 VBE       7.752E-01
 VCE       2.898E+00
 VBC      -2.123E+00
 VS       -2.999E+00
 POWER     2.907E-03
 BETAD     1.000E+02
 GM        3.867E-02
 RPI       2.586E+03
 RX        1.000E+02
 RO        2.124E+16
 CPI       5.605E-13
 CMU       3.209E-14
 CBX         0.
 CCS         0.
 BETAAC    9.999E+01
 FT        1.038E+10

**** MOSFETS

ELEMENT  0:M1
MODEL    0:NMOS
 ID        2.931E-03
 IBS      -8.762E-15
 IBD      -5.000E-14
 VGS       1.688E+00
 VDS       4.123E+00
 VBS      -8.762E-01
 VTH       7.000E-01
 VDSAT     9.884E-01
 BETA      6.000E-03
 GAM EFF     0.
 GM        5.930E-03
 GDS         0.
 GMB         0.
 CDTOT     1.241E-15
 CGTOT     1.549E-13
 CSTOT     1.850E-13
 CBTOT     3.772E-14
 CGS       1.505E-13
 CGD       1.241E-15

 ******  NOISE ANALYSIS                   TNOM=  27.000 TEMP=  27.000

  FREQUENCY = 9.999E+06  HZ
**** TOTAL OUTPUT NOISE VOLTAGE         = 3.361E-15 SQ V/HZ
                                        = 5.797E-08 V/RT HZ
   TRANSFER FUNCTION VALUE:
    V(5)/IS                             = 2.661E+06
   EQUIVALENT INPUT NOISE AT IS         = 2.178E-14 /RT HZ

  FREQUENCY = 9.999E+08  HZ
**** TOTAL OUTPUT NOISE VOLTAGE         = 7.214E-16 SQ V/HZ
                                        = 2.686E-08 V/RT HZ
   TRANSFER FUNCTION VALUE:
    V(5)/IS                             = 1.217E+04
   EQUIVALENT INPUT NOISE AT IS         = 2.206E-12 /RT HZ

  FREQUENCY = 7.498E+09  HZ
**** RESISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT     0:R1         0:R2         0:R3
  TOTAL  4.416E-18    1.802E-18    1.414E-18
**** TRANSISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT     0:Q1
     RB  2.069E-18
     RC     0.
     RE     0.
     IB  6.156E-19
     IC  3.315E-17
     FN     0.
  TOTAL  3.584E-17
**** MOSFET SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT     0:M1
     RD     0.
     RS     0.
     ID  5.237E-18
     RX  2.827E+02
     FN     0.
  TOTAL  5.237E-18
**** TOTAL OUTPUT NOISE VOLTAGE         = 4.871E-17 SQ V/HZ
                                        = 6.979E-09 V/RT HZ
   TRANSFER FUNCTION VALUE:
    V(5)/IS                             = 3.580E+02
   EQUIVALENT INPUT NOISE AT IS         = 1.949E-11 /RT HZ

FREQ=7.5GHZ
EQUIVALENT INPUT NOISE CURRENT=3.8E-22 SQ A/HZ
```

11.10

(a)

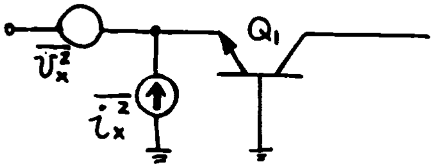


$\overline{v_{i2}^2}$ negligible.

$$\frac{\overline{i_{i1}^2}}{\Delta f} = 2q\left(I_{B1} + \frac{I_{C1}}{|\beta_1|^2}\right)$$

$$\frac{\overline{i_{i2}^2}}{\Delta f} = 2q\left(I_{B2} + \frac{I_{C2}}{|\beta_2|^2}\right)$$

Represent total noise by



Open circuit input and equate output noise, $(\alpha_1 \simeq 1)$

$$\overline{i_x^2} = \overline{i_{i1}^2} + \overline{i_{i2}^2} + \overline{i_L^2}$$

$$\therefore \frac{\overline{i_x^2}}{\Delta f} = 2 \times 2q\left(I_B + \frac{I_C}{|\beta|^2}\right) + 4kT\frac{1}{R_L}$$

$$= 4 \times 1.6 \times 10^{-19}\left[10^{-5} + \frac{10^{-3}}{10^4}\left(1 + 10^4 \times \frac{f^2}{f_T^2}\right)\right]$$

$$+ 1.66 \times 10^{-20} \times \frac{1}{5000}$$

$$= 9.7 \times 10^{-24} + 6.4 \times 10^{-22}\left(\frac{f}{f_T}\right)^2$$

Short circuit input and equate output noise

$$g_m v_x = g_m v_{i1} + i_L + i_{i2}$$

$$\therefore \overline{v_x^2} = \overline{v_{i1}^2} + \frac{\overline{i_L^2}}{g_m^2} + \frac{\overline{i_{i2}^2}}{g_m^2}$$

$$\therefore \frac{\overline{v_x^2}}{\Delta f} = 4kT\frac{1}{2g_m} + 4kT\frac{1}{g_m}\frac{1}{g_m R_L}$$

$$+ \frac{1}{g_m^2} \times 2q\left(I_{B2} + \frac{I_{C2}}{|\beta|^2}\right)$$

$$\simeq 4kT\frac{1}{2g_m}$$

$$= 1.66 \times 10^{-20} \times 13$$

$$= 2.2 \times 10^{-19}\ \mathrm{V^2/Hz}$$

(b) With $R_S = 5\,k\Omega$, $\overline{v_{i1}^2}$ is negligible.

Total input current noise is

$$\overline{i_y^2} = \overline{i_x^2} + 4kT\frac{1}{R_S}\Delta f$$

$$\therefore \frac{\overline{i_y^2}}{\Delta f} = 9.7 \times 10^{-24} + 6.4 \times 10^{-22}\left(\frac{f}{f_T}\right)^2$$

$$+ 1.66 \times 10^{-20} \times \frac{1}{5000}$$

$$= 13 \times 10^{-24} + 6.4 \times 10^{-22}\left(\frac{f}{f_T}\right)^2$$

Total current noise

$$\overline{i_T^2} = \int_0^{f_1}\left[13 \times 10^{-24} + 6.4 \times 10^{-22}\left(\frac{f}{f_T}\right)^2\right]df$$

$f_1 = 150\ \mathrm{MHz}$

$$\overline{i_T^2} = 13 \times 10^{-24} \times 150 \times 10^6 + 6.4 \times 10^{-22}\frac{1}{f_T^2}\frac{f_1^3}{3}$$

$$= 1.95 \times 10^{-15} + 4.5 \times 10^{-15}$$

$$= 6.45 \times 10^{-15}\ \mathrm{A^2}$$

$\therefore i_T = 80$ nA rms

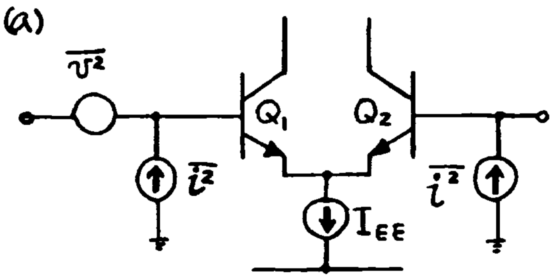
$\therefore$ for 10dB S/N $i_s = 253$ nA

```
LOW-INPUT-IMPEDANCE COMMON BASE AMP
Q1 2 0 3 NPN
Q2 1 2 0 NPN
VCC 1 0 5.82629V
R1 1 2 5K
VI 3 0 -0.774219V AC 1
.NOISE V(2) VI 10
.AC DEC 10 10K 10MEG
******
* ADJUST TF AND CJE TO GET THE SPECIFIED FT=400MEGAHERTZ
******
.MODEL NPN NPN BF=100 IS=1E-16 CJE=900FF TF=358PS
.WIDTH OUT=80
.OPTIONS SPICE NOMOD
.OP
.END

 ******  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000

+0:1        = 5.826E+00 0:2        = 7.742E-01 0:3        =-7.742E-01

**** BIPOLAR JUNCTION TRANSISTORS

ELEMENT  0:Q1        0:Q2
MODEL    0:NPN       0:NPN
 IB       1.000E-05  1.000E-05
 IC       1.000E-03  1.000E-03
 VBE      7.742E-01  7.742E-01
 VCE      1.548E+00  5.826E+00
 VBC     -7.742E-01 -5.052E+00
 VS      -7.742E-01 -5.826E+00
 POWER    1.557E-03  5.836E-03
 BETAD    1.000E+02  1.000E+02
 GM       3.868E-02  3.868E-02
 RPI      2.585E+03  2.585E+03
 RX        0.         0.
 RO       7.742E+15  5.052E+16
 CPI      1.538E-11  1.538E-11
 CMU       0.         0.
 CBX       0.         0.
 CCS       0.         0.
 BETAAC   9.999E+01  9.999E+01
 FT       4.003E+08  4.003E+08


 ******  NOISE ANALYSIS                         TNOM=  27.000 TEMP=  27.000
    FREQUENCY = 9.999E+03  HZ
**** TOTAL OUTPUT NOISE VOLTAGE              = 9.500E-16 SQ V/HZ
                                             = 3.082E-08 V/RT HZ

     TRANSFER FUNCTION VALUE:
       V(2)/VI                               = 6.591E+01
     EQUIVALENT INPUT NOISE AT VI            = 4.676E-10 /RT HZ

    FREQUENCY = 9.999E+04  HZ
**** TOTAL OUTPUT NOISE VOLTAGE              = 9.498E-16 SQ V/HZ
                                             = 3.082E-08 V/RT HZ

     TRANSFER FUNCTION VALUE:
       V(2)/VI                               = 6.591E+01
     EQUIVALENT INPUT NOISE AT VI            = 4.676E-10 /RT HZ

    FREQUENCY = 1.000E+06  HZ
**** TOTAL OUTPUT NOISE VOLTAGE              = 9.250E-16 SQ V/HZ
                                             = 3.041E-08 V/RT HZ

     TRANSFER FUNCTION VALUE:
       V(2)/VI                               = 6.504E+01
     EQUIVALENT INPUT NOISE AT VI            = 4.676E-10 /RT HZ

    FREQUENCY = 9.999E+06  HZ
**** TOTAL OUTPUT NOISE VOLTAGE              = 2.560E-16 SQ V/HZ
                                             = 1.600E-08 V/RT HZ

     TRANSFER FUNCTION VALUE:
       V(2)/VI                               = 3.422E+01
     EQUIVALENT INPUT NOISE AT VI            = 4.676E-10 /RT HZ

EQUIVALENT INPUT NOISE VOLTAGE = 2.186E-19 SQ V/HZ

LOW-INPUT-IMPEDANCE COMMON BASE AMP
Q1 2 0 3 NPN
Q2 1 2 0 NPN
VCC 1 0 5.82629V
R1 1 2 5K
******
* USE INDUCTOR TO ALLOW VI TO SET DC BIAS.
* CHOOSE A LARGE INDUCTANCE TO GET VERY LARGE IMPEDANCE.
******
LBIAS 3 7 1GIGHENRY
VI 7 0 -0.774219V
IS 3 0 0A AC 1
.NOISE V(2) IS 10
.AC DEC 10 100K 1GIG
.MODEL NPN NPN BF=100 IS=1E-16 CJE=900FF TF=358PS
.WIDTH OUT=80
.OPTIONS SPICE NOMOD
.OP
.END

 ******  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
```

```
+0:1        = 5.826E+00 0:2        = 7.742E-01 0:3        =-7.742E-01
+0:7        =-7.742E-01

**** BIPOLAR JUNCTION TRANSISTORS

ELEMENT  0:Q1        0:Q2
MODEL    0:NPN       0:NPN
 IB       1.000E-05  1.000E-05
 IC       1.000E-03  1.000E-03
 VBE      7.742E-01  7.742E-01
 VCE      1.548E+00  5.826E+00
 VBC     -7.742E-01 -5.052E+00
 VS      -7.742E-01 -5.826E+00
 POWER    1.557E-03  5.836E-03
 BETAD    1.000E+02  1.000E+02
 GM       3.868E-02  3.868E-02
 RPI      2.585E+03  2.585E+03
 RX        0.         0.
 RO       7.742E+15  5.052E+16
 CPI      1.538E-11  1.538E-11
 CMU       0.         0.
 CBX       0.         0.
 CCS       0.         0.
 BETAAC   9.999E+01  9.999E+01
 FT       4.003E+08  4.003E+08

BY HAND ANALYSIS, EQUIVALENT INPUT NOISE CURRENT =
        9.7E-24 + 6.4E-22(F/FT)^2 SQ A /HZ

     FREQUENCY = 9.999E+04  HZ
      EQUIVALENT INPUT NOISE AT IS         = 3.145E-12 /RT HZ
BY HAND 3.11E-12 A /RT HZ

     FREQUENCY = 1.000E+06  HZ
      EQUIVALENT INPUT NOISE AT IS         = 3.145E-12 /RT HZ
BY HAND 3.12E-12 A /RT HZ

     FREQUENCY = 9.999E+06  HZ
      EQUIVALENT INPUT NOISE AT IS         = 3.177E-12 /RT HZ
BY HAND 3.18E-12 A /RT HZ

     FREQUENCY = 9.999E+07  HZ
      EQUIVALENT INPUT NOISE AT IS         = 5.504E-12 /RT HZ
BY HAND 7.05E-12 A /RT HZ

     FREQUENCY = 9.999E+08  HZ
      EQUIVALENT INPUT NOISE AT IS         = 4.528E-11 /RT HZ
BY HAND 6.33E-11 A /RT HZ
```

11.11

(a)



$$\overline{v^2} = 4kT\left(2r_b + \frac{1}{g_{m1}}\right)\Delta f$$

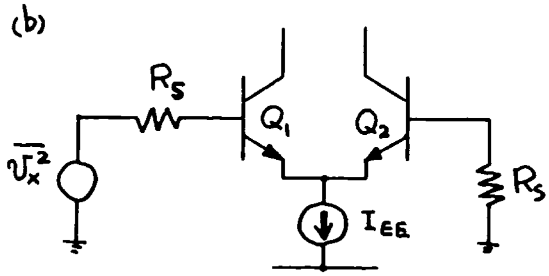
$$\therefore \frac{\overline{v^2}}{\Delta f} = 1.66\times10^{-20}(1000 + 52k)$$

$$= 8.8\times10^{-16}\ V^2/Hz$$

$$\frac{\overline{i^2}}{\Delta f} = 2qI_B = 3.2\times10^{-19}\times\frac{0.5\times10^{-6}}{5000}$$

$$= 3.2\times10^{-29}\ A^2/Hz$$

(b)

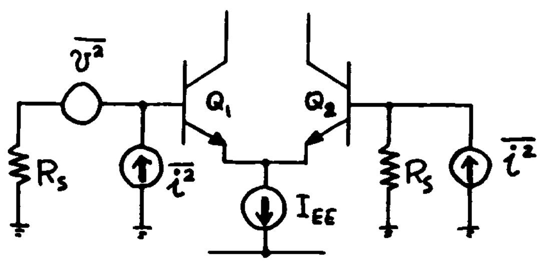


Make $\overline{v_x^2}$ equiv. to noise of the circuit.

At the base of Q_1 this produces a voltage

$$\overline{v_{1x}^2} = \left(\frac{R_i}{R_i + R_S}\right)^2 \overline{v_x^2} \text{ ------(A)}$$

where R_i is resistance seen looking in at the base of Q_1



Include noise due to R_S in $\overline{i^2}$

At the base of Q_1

$$v_1 = v\frac{R_i}{R_i + R_S} + i\,\frac{R_S R_i}{R_i + R_S}$$

At the base of $Q2$

$$v_2 = i\frac{R_S R_i}{R_i + R_S}$$

Thus total input noise voltage is

$$\overline{v_1^2} + \overline{v_2^2} = \overline{v^2}\left(\frac{R_i}{R_i + R_S}\right)^2 + 2\overline{i^2}\,\frac{R_i^2 R_S^2}{(R_i + R_S)^2}$$

Equate to $\overline{v_{1x}^2}$ in (A)

$$\therefore \overline{v_x^2} = \overline{v^2} + 2\,\overline{i^2} R_S^2$$

Include noise due to i_S in $\overline{i^2}$

$$\therefore \frac{\overline{i^2}}{\Delta f} = 2qI_B + 4kT\frac{1}{R_S}$$

$$= 3.2\times10^{-29} + 1.66\times10^{-20}\frac{1}{10^8}$$

$$= 19.8\times10^{-29}\ A^2/Hz$$

$$\therefore \frac{\overline{v_x^2}}{\Delta f} = 8.8\times10^{-16} + 2\times19.8\times10^{-29}\times10^{6}$$

$$= 3.96\times10^{-12}\ V^2/Hz$$

$\therefore$ Total input noise with $\Delta f = 1\ KHZ$

$$\overline{v_T^2} = 3.96\times10^{-12}\times1000$$

$$= 3.96\times10^{-9}\ V^2$$

$$\therefore v_T = 63\,\mu V\ \text{rms}$$

11.12

(a) $\frac{\overline{V^2}}{\Delta f} = 2\times4kT\frac{2}{3}\frac{1}{g_m}$

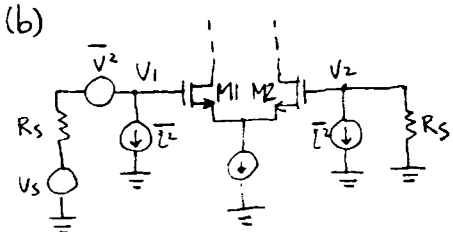
$$= 2\times4\times1.38\times10^{-23}\times300\times\frac{2}{3}\times\frac{1}{0.5\times10^{-3}}$$

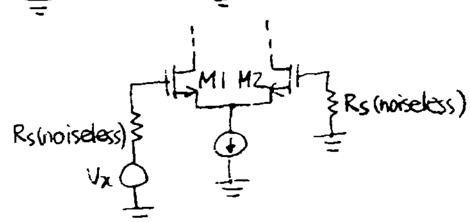
$$= 4.4\times10^{-17}\ V^2/Hz$$

$$\frac{\overline{i^2}}{\Delta f} = 2qI_G = 2\times1.6\times10^{-19}\times0.1\times10^{-15}$$

$$= 3.2\times10^{-35}\ A^2/Hz$$

(b)





The noise voltage at the gate of M1

$V_1 = v + iR_s$

At the gate of M2

$V_2 = iR_s$

$\overline{v_1^2} + \overline{v_2^2} = \overline{v^2} + 2\overline{i^2}R_s^2$

$\overline{v^2}$ is the same as previous, and $\overline{i^2}$ also includes the contribution of R_s

$$\frac{\overline{i^2}}{\Delta f} = 2qI_G + 4kT\frac{1}{R_s}$$

$$= 3.2\times10^{-35} + 4\times1.38\times10^{-23}\times300\times\frac{1}{100\times10^6}$$

$$= 3.2\times10^{-35} + 1.6\times10^{-28}$$

$$= 1.2\times10^{-28}\ A^2/Hz$$

If v_x is placed at R_s to give the same noise, its only contribution at the gate of M1 is

$\overline{v_{1x}^2} = \overline{v_x^2}$

$$\frac{\overline{v_x^2}}{\Delta f} = \frac{\overline{v_1^2}}{\Delta f} + \frac{\overline{v_2^2}}{\Delta f}$$

$$= \frac{\overline{v^2}}{\Delta f} + 2\frac{\overline{i^2}}{\Delta f}R_s^2$$

$$= 4.4\times10^{-17} + 2\times1.6\times10^{-28}\times(100\times10^6)^2$$

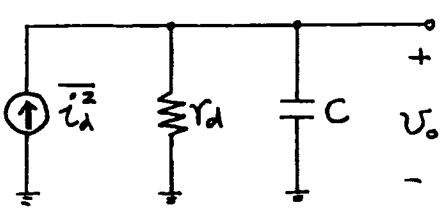
$$= 4.4\times10^{-17} + 3.2\times10^{-12}$$

$$= 3.2\times10^{-12}\ V^2/Hz$$

$V_T^2 = 3.2\times10^{-12}\times10^3 = 3.2\times10^{-9}\ V^2$

$V_T = 5.6\times10^{-5}\ V = 56\ \mu V$

11.13



Neglect noise in R

$r_d = 55.3\ \Omega$, $C = 100\ pF$

Noise bandwidth

$$= \frac{\pi}{2}\frac{1}{2\pi r_d C} = \frac{\pi}{2}\frac{1}{2\pi\times55.3\times10^{-10}}$$

$\therefore f_N = 45.2\ MHz$

$\therefore$ Total output noise is

$$\overline{v_{oT}^2} = \frac{\overline{i_d^2}}{\Delta f}\times r_d^2\times f_N$$

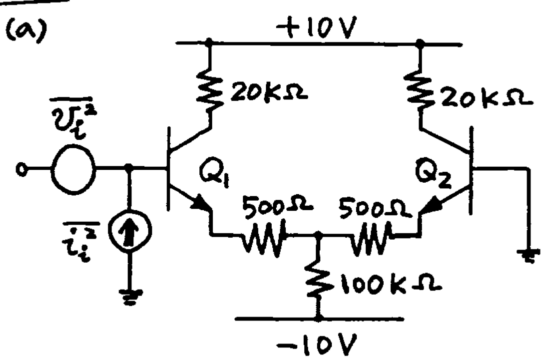
$$= 3060\times1.51\times10^{-22}\times45.2\times10^6$$

$$= 2.1\times10^{-11}\ V^2$$

$\therefore v_{oT} = 4.6\ \mu V$ rms

11.14

(a)



$$I_{C1} = \frac{1}{2}\frac{9.4}{100k} = 47\ \mu A$$

Neglect noise due to R_L

$$\overline{v_i^2} = 4kT\left(2r_b + \frac{1}{g_{m1}} + 2R_E\right)\Delta f$$

$$\therefore \frac{\overline{v_i^2}}{\Delta f} = 1.66\times10^{-20}(400+553+1000)$$

$$= 3.24\times10^{-17}\ V^2/Hz$$

$$\overline{i_i^2} = 2qI_B\Delta f$$

$$\therefore \frac{\overline{i_i^2}}{\Delta f} = 3.2\times10^{-19}\times\frac{47\times10^{-6}}{100}$$

$$= 1.5\times10^{-25}\ A^2/Hz$$

(b) Since $R_s = 50\ \Omega$, neglect $\overline{i_i^2}$

Total input noise voltage

$$\overline{v_{iT}^2} = 3.24\times10^{-17}\times30\times10^6\times\frac{\pi}{2}$$

$$= 1.53\times10^{-9}\ V^2$$

$\therefore v_{iT} = 39.1\ \mu V$ rms

Gain

$$\frac{v_o}{v_s} = \frac{g_{m1}}{1+g_{m1}R_E}R_L$$

$$= \frac{0.047}{26}\frac{1}{1+\frac{0.047}{26}\times500}\times20{,}000$$

$$= 19$$

$\therefore$ Output noise voltage

$v_{oT} = 19\times39.1 = 743\ \mu V$ rms

```
DIFFERENTIAL INPUT STAGE
RC1 1 5 20K
RC2 1 6 20K
Q1 5 3 7 NPN
Q2 6 0 8 NPN
RE1 7 9 500
RE2 8 9 500
REE 9 2 100K
VCC 1 0 10V
VEE 2 0 -10V
VI 3 0 0V AC 1
.NOISE V(5,6) VI 10
.AC DEC 10 100K 100MEG
.MODEL NPN NPN BF=100 RB=200
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.PROBE
.END

 ******  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000

+0:1        = 1.000E+01 0:2        =-1.000E+01 0:3        =  0.
+0:5        = 9.081E+00 0:6        = 9.081E+00 0:7        =-6.946E-01
+0:8        =-6.946E-01 0:9        =-7.178E-01

**** BIPOLAR JUNCTION TRANSISTORS

ELEMENT  0:Q1       0:Q2
MODEL    0:NPN      0:NPN
 IB       4.595E-07  4.595E-07
 IC       4.595E-05  4.595E-05
 VBE      6.946E-01  6.946E-01
 VCE      9.775E+00  9.775E+00
 VBC     -9.081E+00 -9.081E+00
 VS      -9.081E+00 -9.081E+00
 POWER    4.495E-04  4.495E-04
 BETAD    1.000E+02  1.000E+02
 GM       1.777E-03  1.777E-03
 RPI      5.628E+04  5.628E+04
 RX       2.000E+02  2.000E+02
 RO       9.081E+16  9.081E+16
 CPI        0.         0.
 CMU        0.         0.
 CBX        0.         0.
 CCS        0.         0.
 BETAAC   9.999E+01  9.999E+01
 FT       2.827E+11  2.827E+11

 ******  NOISE ANALYSIS                          TNOM=  27.000 TEMP=  27.000
    FREQUENCY = 9.999E+04  HZ
**** RESISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT      0:RC1        0:RC2        0:RE1        0:RE2        0:REE
  TOTAL  3.315E-16    3.315E-16    2.896E-15    2.896E-15    0.
**** TRANSISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT      0:Q1         0:Q2
      RB  1.159E-15    1.159E-15
      RC    0.           0.
      RE    0.           0.
      IB  2.521E-17    2.521E-17
      IC  1.671E-15    1.671E-15
      FN    0.           0.
   TOTAL  2.855E-15    2.855E-15
**** TOTAL OUTPUT NOISE VOLTAGE          = 1.217E-14 SQ V/HZ
                                         = 1.103E-07 V/RT HZ

     TRANSFER FUNCTION VALUE:
       V(5,6)/VI                         = 1.869E+01
     EQUIVALENT INPUT NOISE AT VI        = 5.900E-09 /RT HZ

    FREQUENCY = 1.000E+06  HZ
     EQUIVALENT INPUT NOISE AT VI        = 5.900E-09 /RT HZ

    FREQUENCY = 9.999E+06  HZ
     EQUIVALENT INPUT NOISE AT VI        = 5.900E-09 /RT HZ

    FREQUENCY = 9.999E+07  HZ
     EQUIVALENT INPUT NOISE AT VI        = 5.900E-09 /RT HZ

EQUIVALENT INPUT NOISE VOLTAGE = 3.48E-17 SQ V/HZ

DIFFERENTIAL INPUT STAGE
RC1 1 5 20K
RC2 1 6 20K
Q1 5 3 7 NPN
Q2 6 0 8 NPN
RE1 7 9 500
RE2 8 9 500
REE 9 2 100K
VCC 1 0 10V
VEE 2 0 -10V
LBIAS 3 0 1GIGHENRY
IS 3 0 0A AC 1
.NOISE V(5,6) IS 10
.AC DEC 10 100K 100MEG
.MODEL NPN NPN BF=100 RB=200
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.PROBE
.END

 ******  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000

+0:1        = 1.000E+01 0:2        =-1.000E+01 0:3        =  0.
+0:5        = 9.081E+00 0:6        = 9.081E+00 0:7        =-6.946E-01
+0:8        =-6.946E-01 0:9        =-7.178E-01

**** BIPOLAR JUNCTION TRANSISTORS

ELEMENT  0:Q1       0:Q2
MODEL    0:NPN      0:NPN
 IB       4.595E-07  4.595E-07
 IC       4.595E-05  4.595E-05
 VBE      6.946E-01  6.946E-01
 VCE      9.775E+00  9.775E+00
 VBC     -9.081E+00 -9.081E+00
 VS      -9.081E+00 -9.081E+00
 POWER    4.495E-04  4.495E-04
 BETAD    1.000E+02  1.000E+02
 GM       1.777E-03  1.777E-03
 RPI      5.628E+04  5.628E+04
 RX       2.000E+02  2.000E+02
 RO       9.081E+16  9.081E+16
 CPI        0.         0.
 CMU        0.         0.
 CBX        0.         0.
 CCS        0.         0.
 BETAAC   9.999E+01  9.999E+01
 FT       2.827E+11  2.827E+11

    FREQUENCY = 9.999E+04  HZ
**** RESISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT      0:RC1        0:RC2        0:RE1        0:RE2        0:REE
  TOTAL  3.315E-16    3.315E-16    0.           3.182E-19    6.364E-17
**** TRANSISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT      0:Q1         0:Q2
      RB    0.         1.273E-19
      RC    0.           0.
      RE    0.           0.
      IB  2.308E-12    5.733E-17
      IC  2.308E-14    1.393E-18
      FN    0.           0.
   TOTAL  2.331E-12    5.885E-17
**** TOTAL OUTPUT NOISE VOLTAGE          = 2.332E-12 SQ V/HZ
                                         = 1.527E-06 V/RT HZ

     TRANSFER FUNCTION VALUE:
       V(5,6)/IS                         = 3.979E+06
     EQUIVALENT INPUT NOISE AT IS        = 3.838E-13 /RT HZ

    FREQUENCY = 1.000E+06  HZ
     EQUIVALENT INPUT NOISE AT IS        = 3.838E-13 /RT HZ

    FREQUENCY = 9.999E+06  HZ
     EQUIVALENT INPUT NOISE AT IS        = 3.838E-13 /RT HZ

    FREQUENCY = 9.999E+07  HZ
     EQUIVALENT INPUT NOISE AT IS        = 3.838E-13 /RT HZ

EQUIVALENT INPUT NOISE CURRENT = 1.47E-25 SQ A/HZ
```

11.15

(a)
$$\frac{\overline{v_i^2}}{\Delta f} = 4kT\left(r_b + \frac{1}{2g_m}\right)$$
$$= 1.66\times10^{-20}(100 + 6.5)$$
$$= 1.77\times10^{-18}\ V^2/Hz$$
$$\frac{\overline{i_i^2}}{\Delta f} = 2qI_B = 3.2\times10^{-19}\times\frac{2\times10^{-3}}{50}$$
$$= 1.28\times10^{-23}\ A^2/Hz$$
$$R_{s_{opt}}^2 = \frac{1.77\times10^{-18}}{1.28\times10^{-23}} = 1.38\times10^5\ \Omega^2$$
$$R_{sopt} = 372\ \Omega$$
$$F_{opt} = 1 + \frac{1}{\sqrt{\beta}}\sqrt{1+2g_m r_b}$$
$$= 1 + \frac{1}{\sqrt{50}}\sqrt{1+2\frac{100}{13}}$$
$$= 1.57 = 1.97\ dB$$

(b)
$$R_{sopt} = \frac{\sqrt{\beta}}{g_m}\sqrt{1+2g_m r_b}$$
$$= 10(2600)\sqrt{1+2\frac{300}{2600}}$$
$$= 28.8\ k\Omega$$
$$F_{opt} = 1 + \frac{1}{10}\sqrt{1+2\frac{300}{2600}}$$
$$= 1.111 = 0.46\ dB$$

11.16

(a) From 11.15
$$\frac{\overline{v_i^2}}{\Delta f} = 1.77\times10^{-18}\ V^2/Hz$$
$$\frac{\overline{i_i^2}}{\Delta f} = 2qI_B + \frac{K}{f}$$
$$2qI_B = \frac{K}{f} \text{ at } f = 10^3 Hz$$
$$K = 2qI_B\,10^3$$
$$\frac{\overline{i_i^2}}{\Delta f} = 2qI_B\left(1 + \frac{10^3}{f}\right)$$
at 500 Hz
$$\frac{\overline{i_i^2}}{\Delta f} = 3.2\times10^{-19}\left(\frac{2\times10^{-3}}{50}\right)(3)$$
$$= 3.84\times10^{-23}\ A^2/Hz$$
$$R_{s_{opt}}^2 = \frac{1.77\times10^{-18}}{3.84\times10^{-23}}$$
$$R_{s_{opt}} = 215\ \Omega$$
$$F_{opt} = 1 + \frac{\overline{v_i^2}}{4kTR_s\Delta f} + \frac{\overline{i_i^2}}{4kT\frac{1}{R_s}\Delta f}$$
$$= 1 + \frac{1.77\times10^{-18}}{1.66\times10^{-20}\times215} + \frac{3.84\times10^{-23}}{1.66\times10^{-20}\times\frac{1}{215}}$$
$$= 1 + 0.496 + 0.496$$
$$= 1.992 = 3\ dB$$

(b)
$$\frac{\overline{v_i^2}}{\Delta f} = 4kT\left(r_b + \frac{1}{2g_m}\right)$$
$$= 1.66\times10^{-20}(300 + 1300)$$
$$= 2.66\times10^{-17}\ V^2/Hz$$
$$\frac{\overline{i_i^2}}{\Delta f} = 2qI_B + \frac{K}{f}$$
$$= 2qI_B\left(1 + \frac{1000}{f}\right)$$
At 500 Hz
$$\frac{\overline{i_i^2}}{\Delta f} = 3.2\times10^{-19}\times\frac{10\times10^{-6}}{100}\times3$$
$$= 9.6\times10^{-26}\ A^2/Hz$$
$$\therefore R_{s\,opt.}^2 = \frac{2.66\times10^{-17}}{9.6\times10^{-26}}$$
$$\therefore R_{s\,opt.} = 16.6\ k\Omega$$
$$F_{opt.} = 1 + 2\times\frac{2.66\times10^{-17}}{1.66\times10^{-20}\times16600}$$
$$= 1.193 = 0.77\ dB$$

11.17

The emitter resistor can be added to r_b and (11.146) and (11.147) can be used

(a)
$$R_{s\,opt} = \sqrt{50}\times13\sqrt{1+2\frac{1100}{13}}$$
$$= 1200\ \Omega$$
$$F_{opt} = 1 + \frac{1}{\sqrt{50}}\sqrt{1+2\frac{1100}{13}}$$
$$= 2.85 = 4.54\ dB$$

(b) $R_{s\,opt} = \sqrt{100} \times 2600 \sqrt{1 + 2\frac{1300}{2600}}$

$= 36.8\ k\Omega$

$F_{opt} = 1 + \frac{1}{10}\sqrt{1 + 2\frac{1300}{2600}}$

$= 1.14 = 0.57\ dB$

11.18

(a) Equivalent input noise generators for the differential pair

$\frac{\overline{v_i^2}}{\Delta f} = 4kT\left(2r_b + \frac{1}{g_m} + 2R_E\right)$

$= 3.24 \times 10^{-17}\ V^2/Hz$

from 11.13

$\frac{\overline{i_i^2}}{\Delta f} = 1.5 \times 10^{-25}\ A^2/Hz$

$F = 1 + \frac{\overline{v_i^2}}{4kTR_s\Delta f} + \frac{\overline{i_i^2}}{4kT\frac{1}{R_s}\Delta f}$

$= 1 + \frac{3.24\times10^{-17}}{1.66\times10^{-20}\times 50} + \frac{1.5\times10^{-25}}{1.66\times10^{-20}\times\frac{1}{50}}$

$= 1 + 39.0 + 0$

$= 40 = 16\ dB$

(b) $R^2_{s\,opt.} = \frac{\overline{v_i^2}}{\overline{i_i^2}} = \frac{3.24\times10^{-17}}{1.5\times10^{-25}}$

$\therefore R_{s\,opt} = 14.7\ k\Omega$

Obviously NF decreases for $R_s = 100\Omega$, because we move closer to $R_{s\,opt}$.
$R_s = 200k\Omega$ is larger than $R_{s\,opt.}$ but only 14x. This is closer to $R_{s\,opt}$ than 50Ω and thus NF for $R_s = 200k$ will be lower than for $R_s = 50\Omega$

(c) $\frac{\overline{v_i^2}}{\Delta f} = 3.24\times10^{-17}\ V^2/Hz$

$\frac{\overline{i_i^2}}{\Delta f} = 1.5\times10^{-25}\left(1 + \frac{10{,}000}{f}\right)\ A^2/Hz$

$F = 1 + \frac{\overline{v_i^2}}{4kTR_s\Delta f} + \frac{\overline{i_i^2}}{4kT\frac{1}{R_s}\Delta f}$

$= 1 + \frac{3.24\times10^{-17}}{1.66\times10^{-20}\times2\times10^5} + \frac{1.5\times10^{-25}\left(1+\frac{10000}{f}\right)}{1.66\times10^{-20}\times\frac{1}{2\times10^5}}$

$= 1 + 9.8\times10^{-3} + 1.8\left(1 + \frac{10000}{f}\right)$

$= 1.01 + 1.8 + \frac{18{,}000}{f}$

Put $F = 100$ (20dB)

$\therefore f = 185\ Hz$

11.19

(a) Neglect effect of $10k\Omega$ load

$\frac{\overline{v_i^2}}{\Delta f} = 4kT\left(r_b + \frac{1}{2g_m}\right)$

$= 1.66\times10^{-20}(100 + 26)$

$= 2.09\times10^{-18}\ V^2/Hz$

$\frac{\overline{i_i^2}}{\Delta f} = 2qI_B + 4kT\frac{1}{R_F}$

$= 3.2\times10^{-19}\times\frac{500\times10^{-6}}{50} + 1.66\times10^{-20}\times\frac{1}{10^4}$

$= 3.2\times10^{-24} + 1.66\times10^{-24}$

$= 4.86\times10^{-24}\ A^2/Hz$

$F = 1 + \frac{\overline{v_i^2}}{4kTR_s\Delta f} + \frac{\overline{i_i^2}}{4kT\frac{1}{R_s}\Delta f}$

$= 1 + \frac{2.09\times10^{-18}}{1.66\times10^{-20}\times10^4} + \frac{4.86\times10^{-24}}{1.66\times10^{-20}\times10^{-4}}$

$= 1 + 0.01 + 2.93$

$= 3.94 = 5.96\ dB$

(b) $\frac{\overline{i_i^2}}{\Delta f} = 2q\left(I_B + \frac{I_c}{|\beta|^2}\right) + 4kT\frac{1}{R_F}$

$\simeq 2q\left[I_B + I_c\left(\frac{f}{f_T}\right)^2\right] + 4kT\frac{1}{R_F}$

$$\frac{\overline{i_i^2}}{\Delta f} = 3.2\times10^{-24}\left[1+\frac{I_C}{I_B}\left(\frac{f}{f_T}\right)^2\right]+1.66\times10^{-24}$$

$$= 3.2\times10^{-24}\left[1+50\left(\frac{f}{f_T}\right)^2\right]+1.66\times10^{-24}$$

Put $F = 8.96\text{ dB} = 7.87$

$$\therefore \frac{\overline{i_i^2}}{\Delta f}\times\frac{1}{4kT\frac{1}{R_S}} = F - 1.01 = 6.86$$

$$\therefore \frac{\overline{i_i^2}}{\Delta f} = 6.86\times1.66\times10^{-20}\times10^{-4}$$

$$= 1.14\times10^{-23}$$

$$\therefore 11.4 = 3.2 + 3.2\times50\left(\frac{f}{f_T}\right)^2 + 1.66$$

$$\therefore f = 0.2 f_T = 100\text{ MHz}$$

11.20

(a) From 11.10, the total input noise current is

$$\frac{\overline{i_x^2}}{\Delta f} = 2\times2qI_B + 4kT\frac{1}{R_L}$$

$$= 2\times3.2\times10^{-19}\times10^{-5} + 1.66\times10^{-20}\times\frac{1}{5000}$$

$$= 6.4\times10^{-24} + 3.32\times10^{-24}$$

$$= 9.72\times10^{-24}\ \text{A}^2/\text{Hz}$$

$$\frac{\overline{v_i^2}}{\Delta f} = 4kT\left(r_b + \frac{1}{2g_m}\right)$$

$$= 1.66\times10^{-20}\times13 = 2.16\times10^{-19}\ \text{V}^2/\text{Hz}$$

$$F = 1 + \frac{\overline{v_i^2}}{4kTR_S\Delta f} + \frac{\overline{i_x^2}}{4kT\frac{1}{R_S}\Delta f}$$

$$= 1 + \frac{2.16\times10^{-19}}{1.66\times10^{-20}\times5000} + \frac{9.72\times10^{-24}}{1.66\times10^{-20}\times\frac{1}{5000}}$$

$$= 1 + 0 + 2.93 = 3.93 = 5.94\text{ dB}$$

(b) Put $F = 8.94\text{ dB} = 7.83$

$$\therefore \frac{\overline{i_x^2}}{4kT\frac{1}{R_S}\Delta f} = 6.83$$

$$\therefore \frac{\overline{i_x^2}}{\Delta f} = 6.83\times1.66\times10^{-20}\times\frac{1}{5000}$$

$$= 2.27\times10^{-23}\ \text{A}^2/\text{Hz}$$

With flicker noise

$$\frac{\overline{i_x^2}}{\Delta f} = 2\times2qI_B\left(1+\frac{1000}{f}\right) + 4kT\frac{1}{R_L}$$

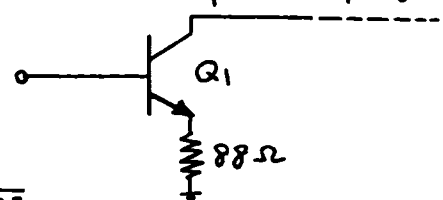
$$= 6.4\times10^{-24}\left(1+\frac{1000}{f}\right) + 3.32\times10^{-24}$$

$$\therefore 22.7 = 9.72 + \frac{6400}{f}$$

$$\therefore f = 493\text{ Hz}$$

11.21

From the basic amplifier of Fig 8.21(b)



$$\frac{\overline{v_i^2}}{\Delta f} = 4kT\left(r_{b1} + \frac{1}{2g_{m1}} + R_{E1}\right)$$

$I_{C1} = 0.58\text{ mA}$

$$\therefore \frac{\overline{v_i^2}}{\Delta f} = 1.66\times10^{-20}(100+22+88)$$

$$= 3.5\times10^{-18}\ \text{V}^2/\text{Hz}$$

For $R_S = 50\,\Omega$, $\overline{i_i^2}$ is negligible as is the effect of $R_D = 12\text{ k}\Omega$

$$\therefore \overline{v_{iT}^2} = 3.5\times10^{-18}\times50\times10^{6}\ \text{V}^2$$

$$= 1.75\times10^{-10}\ \text{V}^2$$

$$\therefore v_{iT} = 13.2\ \mu\text{V rms}$$

From R_S

$$\frac{\overline{v_s^2}}{\Delta f} = 4kTR_S = 1.66\times10^{-20}\times50$$

$$= 8.3\times10^{-19}\ \text{V}^2/\text{Hz}$$

In 50 MHz

$$\overline{v_{sT}^2} = 8.3\times10^{-19}\times50\times10^{6} = 4.15\times10^{-11}\ \text{V}^2$$

$$\therefore F = 1 + \frac{\overline{v_{iT}^2}}{\overline{v_{sT}^2}} = 1 + \frac{1.75\times10^{-10}}{4.15\times10^{-11}} = 5.22$$

$$= 7.17\text{ dB}$$

11.22

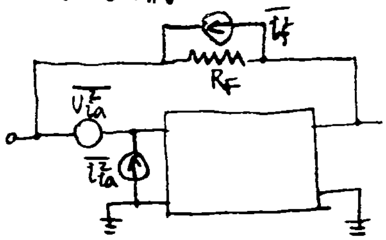
$C_{ox} = \frac{\varepsilon}{t_{ox}} = \frac{3.9\times 8.85\times 10^{-12}}{80\times 10^{-10}} = 4.3\times 10^{-3}\ F/m^2$

$C_{gs} = \frac{2}{3}WLC_{ox} = \frac{2}{3}\times 100\times 1\times 10^{-12}\times 4.3\times 10^{-3}$

$= 2.9\times 10^{-13}\ F$

$g_m = \sqrt{2k'(W/L)I_D} = \sqrt{2\times 194\times 10^{-6}\times 100\times 100\times 10^{-6}}$

$= 2.0\times 10^{-3}\ A/V$



$\overline{i_i^2} = \overline{i_{ia}^2} + \frac{\overline{v_{ia}^2}}{R_F^2} + \overline{i_f^2}$

M1 and R_F are dominant sources

$\frac{\overline{i_{ia}^2}}{\Delta f} = \frac{\omega^2 C_{gs}^2}{g_m^2}\left(4kT\frac{2}{3}g_m + K\frac{I_D^a}{f}\right)$

$\left(K\frac{I_D^a}{g_m^2 f} = \frac{K_f}{WLC_{ox}f}\right)$

$= \frac{\omega^2 C_{gs}^2}{g_m^2}4kT\frac{2}{3}g_m + \omega^2 C_{gs}^2\frac{K_f}{WLC_{ox}f}$

$= \frac{4\pi^2 C_{gs}^2}{g_m}4kT\frac{2}{3}f^2 + 4\pi^2 C_{gs}^2\frac{K_f}{\frac{3}{2}C_{gs}}f$

$= \frac{4\pi^2 C_{gs}^2}{g_m}4kT\frac{2}{3}f^2 + 4\pi^2 C_{gs}\frac{K_f}{3/2}f$

$= \frac{4\times(3.14)^2\times(2.9\times 10^{-13})^2}{2.0\times 10^{-3}}\times 1.7\times 10^{-20}\times\frac{2}{3}f^2$

$+ 4\times(3.14)^2\times 2.9\times 10^{-13}\times\frac{3\times 10^{-24}}{3/2}f$

$= 1.9\times 10^{-44}f^2 + 2.3\times 10^{-35}f\ A^2/Hz$

$\int_{10^{-2}}^{10^5}\frac{\overline{i_{ia}^2}}{\Delta f}df = 1.9\times 10^{-44}\times\frac{1}{3}f^3 + 2.3\times 10^{-35}\times\frac{1}{2}f^2\Big|_{10^{-2}}^{10^5}$

$= 6.3\times 10^{-27} + 1.2\times 10^{-25} = 1.2\times 10^{-25}\ A^2$

$\frac{\overline{v_{ia}^2}}{R_F^2}\frac{1}{\Delta f} = \frac{1}{R_F^2}4kT\frac{2}{3}g_m + \frac{1}{R_F^2}\frac{K_f}{WLC_{ox}f}$

$= \frac{1}{(10^4)^2}\times 1.7\times 10^{-20}\times\frac{2}{3}\times 2.0\times 10^{-3}$

$+ \frac{1}{(10^4)^2}\frac{3\times 10^{-24}}{100\times 1\times 10^{-12}\times 4.3\times 10^{-3}}\frac{1}{f}$

$= 2.3\times 10^{-31} + 7.0\times 10^{-20}\frac{1}{f}\ A^2/Hz$

$\int_{10^{-2}}^{10^5}\frac{\overline{v_{ia}^2}}{R_F^2}\frac{1}{\Delta f}df = 2.3\times 10^{-31}f + 7.0\times 10^{-20}\ln f\Big|_{10^{-2}}^{10^5}$

$= 2.3\times 10^{-26} + 1.1\times 10^{-18} = 1.1\times 10^{-18}\ A^2$

$\frac{\overline{i_f^2}}{\Delta f} = 4kT\frac{1}{R_F} = 1.7\times 10^{-20}\frac{1}{10^4} = 1.7\times 10^{-24}\ A^2/Hz$

$\int_{10^{-2}}^{10^5}\frac{\overline{i_f^2}}{\Delta f}df = 1.7\times 10^{-24}f\Big|_{10^{-2}}^{10^5} = 1.7\times 10^{-19}\ A^2$

$\overline{i_{iT}^2} = 1.2\times 10^{-25} + 1.1\times 10^{-18} + 1.7\times 10^{-19}$

$= 1.3\times 10^{-18}\ A^2$

$i_{iT} = 1.1\ nA$

11.23

$|\beta(j\omega)| \approx \beta_0 >> 1,\ \frac{I_C}{|\beta(j\omega)|^2} \approx \frac{I_C}{\beta_0^2} >> \frac{I_C}{\beta_0} = I_B$

$\frac{\overline{i_{ia}^2}}{\Delta f} = 2q\left[I_B + K_1'\frac{I_B}{f} + \frac{I_C}{|\beta(j\omega)|^2}\right]$

$\approx 2q\left[I_B + K_1'\frac{I_B}{f}\right]$

$= 2qI_B\left(1 + \frac{f_a}{f}\right)$

$\sim 2\times 1.6\times 10^{-19}\times\frac{10^{-3}}{200} = 1.6\times 10^{-24}\ A^2/Hz$

$\frac{\overline{v_{ia}^2}}{R_F^2}\frac{1}{\Delta f} = \frac{1}{R_F^2}4kT\left(r_b + \frac{1}{2g_m}\right)$

$\sim \frac{1}{(10^4)^2}\times 1.7\times 10^{-20}\times 10^3 = 1.7\times 10^{-25}\ A^2/Hz$

$\ll \frac{\overline{i_{ia}^2}}{\Delta f}$

$\frac{\overline{i_i^2}}{\Delta f} = \frac{\overline{i_{ia}^2}}{\Delta f} + \frac{\overline{v_{ia}^2}}{R_F^2}\frac{1}{\Delta f} + 4kT\frac{1}{R_F}$

$\approx 2qI_B\left(1 + \frac{f_a}{f}\right) + 4kT\frac{1}{R_F}$

$= 3.2\times 10^{-19}\times\frac{10^{-3}}{200}\left(1 + \frac{5000}{f}\right) + 1.7\times 10^{-20}\frac{1}{10^4}$

$= 3.3\times 10^{-24} + 8.0\times 10^{-21}\frac{1}{f}\ A^2/Hz$

$\overline{i_{iT}^2} = \int_{10^{-2}}^{10^5}\frac{\overline{i_i^2}}{\Delta f}df = 3.3\times 10^{-24}f + 8.0\times 10^{-21}\ln f\Big|_{10^{-2}}^{10^5}$

$= 4.6\times 10^{-19}\ A^2$

$i_{iT} = 0.67\ nA$

11.24

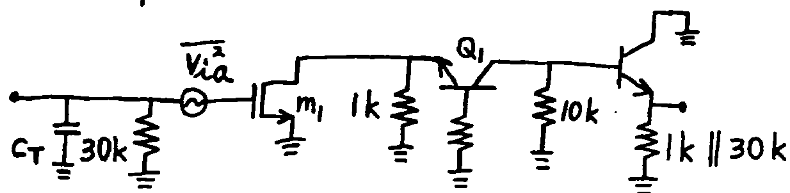
bias from Problem 3.17

$I_{D_1} = 3.79\,mA$

$I_{C_1} = 0.26\,mA$

$I_{C_2} \approx I_{D_2} = 273\,\mu A$

forward path



$C_T = C_s + C_{gs} = 1.5\,pF$

ignore Q_1 noise

$g_{m_{m_1}} = 9.54\,mA/V$

$$\frac{\overline{v_{ia}^2}}{\Delta f} = \frac{1}{g_{m_{m_1}}^2}\left(4kT\tfrac{2}{3}g_{m_{m_1}} + 4kT/1k\right)$$

$$= 4kT\left(\frac{2}{3}\frac{1}{g_{m_{m_1}}} + \frac{1}{(1k)(g_{m_{m_1}})^2}\right)$$

$$= 4kT(69.9 + 11)$$

$$= 4kT(80.9)$$

low frequency

$$\overline{i_i^2} = \frac{\overline{v_{ia}^2}}{(30k)^2} + 4kT\frac{1}{30k}\Delta f$$

$$\frac{\overline{i_i^2}}{\Delta f} = 4kT(8.99\times10^{-8} + 3.33\times10^{-5})$$

$$= 5.56\times10^{-25}\,\frac{A^2}{Hz}$$

$$\text{dominant pole} = \frac{1}{R\,C_T}$$

$$= \frac{1}{30k(1.5pF)}$$

$$= 22.2\ M\,rad/s$$

↓

3.54 MHz

loop gain $= T = af$

$$a = \frac{v_o}{i_s} = \frac{v_o}{v_i}\frac{v_i}{i_s} = \frac{v_o}{v_i}\,30k\Omega$$

$$f = \frac{1}{30k\Omega}$$

$\therefore\ T = \left|\frac{v_o}{v_i}\right| = 76.5$ from Problem 3.17

bandwidth

$BW = (1+T)\,3.54\,MHz$

$= 274\,MHz$

at 274 MHz

$$\overline{i_i^2} = \frac{\overline{v_{ia}^2}}{|Z_s|^2} + 4kT\frac{1}{30k}\Delta f$$

$$|Z_s| = \frac{1}{\omega C_T} = \frac{1}{2\pi(274M)(1.5p)}$$

$$= 387\Omega$$

$$\frac{\overline{i_i^2}}{\Delta f} = 4kT\left(\frac{80.9}{387^2} + \frac{1}{30k}\right)$$

$$= 4kT(5.4\times10^{-4} + 3.33\times10^{-5})$$

$$= 4kT(5.73\times10^{-4})$$

$$= 9.54\times10^{-24}\,\frac{A^2}{Hz}$$

```
BICMOS AMP
VCC 1 0 5V
RL1 1 4 1K
M1 4 2 0 0 NMOS W=300U L=1U
RF 2 7 30K
RE 7 0 1K
RL2 1 3 10K
RBIAS 1 5 10K
Q1 3 5 4 NPN
Q2 5 5 6 NPN
Q3 1 3 7 NPN
M2 6 6 0 0 NMOS W=30U L=1U
CS 2 0 1PF
CGS 2 0 0.5PF
IS 2 0 0A AC 1
.NOISE V(7) IS 10
.AC DEC 10 27.4K 2.74GIG
.PLOT AC VDB(7)
.MODEL NMOS NMOS KP=40U LAMBDA=0 VTO=0.8
.MODEL NPN NPN IS=1E-16 BF=100 RB=0
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.END
```

```
****** OPERATING POINT INFORMATION      TNOM=  25.000 TEMP=  25.000

+0:1     =  5.0000  0:2     =  1.5925  0:3     =  2.3733
+0:4     =  1.4810  0:5     =  2.2141  0:6     =  1.4784
+0:7     =  1.5925
```

```
**** BIPOLAR JUNCTION TRANSISTORS

ELEMENT  0:Q1         0:Q2         0:Q3
MODEL    0:NPN        0:NPN        0:NPN
 IB         2.4691U      2.7339U     15.7674U
 IC       246.9073U    273.3860U      1.5767M
 VBE      733.1133M    735.7306M    780.7485M
 VCE      892.2554M    735.7306M      3.4075
 VBC     -159.1421M      0.          -2.6267
 VS        -2.3733      -2.2141      -5.0000
 POWER    222.1145U    203.1498U      5.3850M
 BETAD    100.0000     100.0000     100.0000
 GM         9.6103M     10.6410M     61.3711M
 RPI       10.4055K      9.3976K      1.6294K
 RX         0.           0.           0.
 RO         1.258E+17    2.569E+14    2.626E+16
 CPI        0.           0.           0.
 CMU        0.           0.           0.
 CBX        0.           0.           0.
 CCS        0.           0.           0.
 BETAAC   100.0000     100.0000     100.0000
 FT         1.529E+12    1.693E+12    9.767E+12
```

```
**** MOSFETS

ELEMENT  0:M1         0:M2
MODEL    0:NMOS       0:NMOS
 ID         3.7684M    276.1198U
 IBS        0.           0.
 IBD      -14.8100F    -14.7838F
 VGS        1.5925       1.4784
 VDS        1.4810       1.4784
 VBS        0.           0.
 VTH      800.0000M    800.0000M
 VDSAT    792.5044M    678.3802M
 BETA      12.0000M      1.2000M
 GAM EFF  527.6252M    527.6252M
 GM         9.5101M    814.0563U
 GDS        0.           0.
 GMB        3.2948M    282.0302U
 CDTOT      2.046E-16    2.042E-17
 CGTOT     69.9239F      7.0031F
 CSTOT     69.0632F      6.9063F
 CBTOT      6.561E-16    7.634E-17
 CGS       69.0632F      6.9063F
 CGD        2.046E-16    2.042E-17
```

```
****** NOISE ANALYSIS                       TNOM=  25.000 TEMP=  25.000
   FREQUENCY =  27.4000K  HZ
    EQUIVALENT INPUT NOISE AT IS        = 742.0965F /RT HZ

   FREQUENCY = 274.0000K  HZ
    EQUIVALENT INPUT NOISE AT IS        = 742.1044F /RT HZ

   FREQUENCY =   2.7400M  HZ
    EQUIVALENT INPUT NOISE AT IS        = 742.8996F /RT HZ

   FREQUENCY =  27.4000M  HZ
    EQUIVALENT INPUT NOISE AT IS        = 818.5238F /RT HZ

   FREQUENCY = 274.0000M  HZ
    EQUIVALENT INPUT NOISE AT IS        =   3.5324P /RT HZ
```

```
****** AC ANALYSIS                               TNOM=  25.000 TEMP=  25.000

     FREQ      VDB(7)
(A        )    60.0000         70.0000         80.0000         90.0000        100.0000
                +               +               +               +               +
 27.4000K  89.428 -+-------+-------+-------+-------+-------+------A+-------+-------+-
 34.4946K  89.428  +       +       +       +       +       +      A+       +       +
 43.4261K  89.428  +       +       +       +       +       +      A+       +       +
 54.6702K  89.428  +       +       +       +       +       +      A+       +       +
 68.8257K  89.428  +       +       +       +       +       +      A+       +       +
 86.6464K  89.428  +       +       +       +       +       +      A+       +       +
109.0814K  89.428  +       +       +       +       +       +      A+       +       +
137.3253K  89.428  +       +       +       +       +       +      A+       +       +
172.8823K  89.428  +       +       +       +       +       +      A+       +       +
217.6459K  89.428  +       +       +       +       +       +      A+       +       +
274.0000K  89.428 -+-------+-------+-------+-------+-------+------A+-------+-------+-
344.9456K  89.428  +       +       +       +       +       +      A+       +       +
434.2607K  89.428  +       +       +       +       +       +      A+       +       +
546.7019K  89.428  +       +       +       +       +       +      A+       +       +
688.2569K  89.428  +       +       +       +       +       +      A+       +       +
866.4641K  89.428  +       +       +       +       +       +      A+       +       +
  1.0908X  89.428  +       +       +       +       +       +      A+       +       +
  1.3733X  89.428  +       +       +       +       +       +      A+       +       +
  1.7288X  89.428  +       +       +       +       +       +      A+       +       +
  2.1765X  89.428  +       +       +       +       +       +      A+       +       +
  2.7400X  89.428 -+-------+-------+-------+-------+-------+------A+-------+-------+-
  3.4495X  89.427  +       +       +       +       +       +      A+       +       +
  4.3426X  89.427  +       +       +       +       +       +      A+       +       +
  5.4670X  89.426  +       +       +       +       +       +      A+       +       +
  6.8826X  89.425  +       +       +       +       +       +      A+       +       +
  8.6646X  89.423  +       +       +       +       +       +      A+       +       +
 10.9081X  89.420  +       +       +       +       +       +      A+       +       +
 13.7325X  89.416  +       +       +       +       +       +      A+       +       +
 17.2882X  89.409  +       +       +       +       +       +      A+       +       +
 21.7646X  89.397  +       +       +       +       +       +      A+       +       +
 27.4000X  89.380 -+-------+-------+-------+-------+-------+------A+-------+-------+-
 34.4946X  89.351  +       +       +       +       +       +      A+       +       +
 43.4261X  89.307  +       +       +       +       +       +      A+       +       +
 54.6702X  89.238  +       +       +       +       +       +      A+       +       +
 68.8257X  89.131  +       +       +       +       +       +      A+       +       +
 86.6464X  88.966  +       +       +       +       +       +      A+       +       +
109.0814X  88.716  +       +       +       +       +       +     A +       +       +
137.3253X  88.348  +       +       +       +       +       +     A +       +       +
172.8823X  87.822  +       +       +       +       +       +   A   +       +       +
217.6459X  87.100  +       +       +       +       +       + A     +       +       +
274.0000X  86.157 -+-------+-------+-------+-------+-------+-A-----+-------+-------+-
344.9456X  84.985  +       +       +       +       +       A       +       +       +
434.2607X  83.604  +       +       +       +       +     A +       +       +       +
546.7019X  82.045  +       +       +       +       +  A    +       +       +       +
688.2569X  80.348  +       +       +       +       A       +       +       +       +
866.4641X  78.550  +       +       +       +     A +       +       +       +       +
  1.0908G  76.683  +       +       +       + A     +       +       +       +       +
  1.3733G  74.770  +       +       +       A       +       +       +       +       +
  1.7288G  72.825  +       +       +    A  +       +       +       +       +       +
  2.1765G  70.861  +       +       +A      +       +       +       +       +       +
  2.7400G  68.883 -+-------+-----A-+-------+-------+-------+-------+-------+-------+-
                   +               +               +               +               +
*****
-3DB AT 274 MHZ
*****
```

```
BICMOS AMP
VCC 1 0 5V
RL1 1 4 1K
M1 4 2 0 0 NMOS W=300U L=1U
RF 2 7 30K
RE 7 0 1K
RL2 1 3 10K
RBIAS 1 5 10K
Q1 3 5 4 NPN
Q2 5 5 6 NPN
Q3 1 3 7 NPN
M2 6 6 0 0 NMOS W=30U L=1U
CS 2 0 1PF
CGS 2 0 0.5PF
IS 2 0 0A AC 1
.NOISE V(7) IS 10
.AC DEC 10 27.4K 2.74GIG
.PLOT AC VDB(7)
.MODEL NMOS NMOS KP=40U LAMBDA=0 VTO=0.8
.MODEL NPN NPN IS=1E-16 BF=100 RB=200
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.END
```

```
****** OPERATING POINT INFORMATION      TNOM=  25.000 TEMP=  25.000

+0:1     =  5.0000  0:2     =  1.5925  0:3     =  2.3764
+0:4     =  1.4810  0:5     =  2.2146  0:6     =  1.4783
+0:7     =  1.5925
```

```
**** BIPOLAR JUNCTION TRANSISTORS

ELEMENT  0:Q1         0:Q2         0:Q3
MODEL    0:NPN        0:NPN        0:NPN
 IB         2.4660U      2.7334U     15.7670U
 IC       246.5960U    273.3409U      1.5767M
```

VBE	733.5741M	736.2730M	783.9014M
VCE	895.3467M	736.2730M	3.4075
VBC	-161.7726M	0.	-2.6236
VS	-2.3764	-2.2146	-5.0000
POWER	222.5979U	203.2661U	5.3850M
BETAD	100.0000	100.0000	100.0000
GM	9.5982M	10.6392M	61.3697M
RPI	10.4186K	9.3992K	1.6295K
RX	200.0000	200.0000	200.0000
RO	1.421E+17	2.624E+14	2.626E+16
CPI	0.	0.	0.
CMU	0.	0.	0.
CBX	0.	0.	0.
CCS	0.	0.	0.
BETAAC	100.0000	100.0000	100.0000
FT	1.527E+12	1.693E+12	9.767E+12

**** MOSFETS

ELEMENT	0:M1	0:M2
MODEL	0:NMOS	0:NMOS
ID	3.7680M	276.0743U
IBS	0.	0.
IBD	-14.8102F	-14.7832F
VGS	1.5925	1.4783
VDS	1.4810	1.4783
VBS	0.	0.
VTH	800.0000M	800.0000M
VDSAT	792.4686M	678.3243M
BETA	12.0000M	1.2000M
GAM EFF	527.6252M	527.6252M
GM	9.5096M	813.9891U
GDS	0.	0.
GMB	3.2946M	282.0070U
CDTOT	2.046E-16	2.042E-17
CGTOT	69.9240F	7.0031F
CSTOT	69.0632F	6.9063F
CBTOT	6.562E-16	7.634E-17
CGS	69.0632F	6.9063F
CGD	2.046E-16	2.042E-17

```
****** NOISE ANALYSIS                    TNOM=  25.000 TEMP=  25.000
   FREQUENCY =  27.4000K  HZ
    EQUIVALENT INPUT NOISE AT IS        = 742.1550F /RT HZ

   FREQUENCY = 274.0000K  HZ
    EQUIVALENT INPUT NOISE AT IS        = 742.1633F /RT HZ

   FREQUENCY =   2.7400M  HZ
    EQUIVALENT INPUT NOISE AT IS        = 742.9961F /RT HZ

   FREQUENCY =  27.4000M  HZ
    EQUIVALENT INPUT NOISE AT IS        = 822.0273F /RT HZ

   FREQUENCY = 274.0000M  HZ
**** RESISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)
```

ELEMENT	0:RL1	0:RF	0:RE	0:RL2	0:RBIAS
TOTAL	5.468E-16	2.256E-16	9.545E-20	6.958E-17	7.488E-17

**** TRANSISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)

ELEMENT	0:Q1	0:Q2	0:Q3
RB	1.096E-16	8.551E-17	1.392E-18
RC	0.	0.	0.
RE	0.	0.	0.
IB	1.475E-16	2.506E-19	2.171E-16
IC	4.301E-17	2.054E-17	2.929E-18
FN	0.	0.	0.
TOTAL	3.001E-16	1.063E-16	2.214E-16

**** MOSFET SQUARED NOISE VOLTAGES (SQ V/HZ)

ELEMENT	0:M1	0:M2
RD	0.	0.
RS	0.	0.
ID	3.4669F	3.501E-16
RX	5.7630K	6.2596K
FN	0.	0.
TOTAL	3.4669F	3.501E-16

```
**** TOTAL OUTPUT NOISE VOLTAGE         =   5.3618F SQ V/HZ
                                        =  73.2242N V/RT HZ

     TRANSFER FUNCTION VALUE:
       V(7)/IS                          =  20.2744K
     EQUIVALENT INPUT NOISE AT IS       =   3.6117P /RT HZ
```

AT HIGH FREQUENCIES, RB=200 OHMS INCREASES THE EQUIVALENT INPUT NOISE CURRENT.

<u>11.25</u>

(a) $\frac{1}{f}$ noise dominates

$$\overline{i_{\frac{1}{f}}^2} = gm^2\left(\overline{v_{i\frac{1}{f}}^2}\right)(2)$$

$$= 2\mu_n C_{ox}\frac{W}{L} I_D \frac{K_f}{WLC_{ox}}\frac{\Delta f}{f}(2)$$

$$= \frac{4\mu_n K_f I_D}{L^2}\frac{\Delta f}{f}$$

maximize L to minimize $\frac{1}{f}$ noise

$$WL = \frac{10\,\mu m^2}{2} = 5\,\mu m^2$$

$$W_1 = 0.6\,\mu m = W_2$$

$$L_1 = 8.33\,\mu m = L_2$$

(b) thermal noise dominates

$$\overline{i_{th}^2} = gm^2\,\overline{v_{th}^2}\,(2) = gm^2\,4kT\frac{2}{3}\frac{1}{gm}(2)\Delta f$$

$$= \frac{16\,kT\,gm}{3}\Delta f$$

$$= \frac{16}{3}kT\sqrt{2 I_D \mu_n C_{ox}\frac{W}{L}}\;\Delta f$$

minimize $\frac{W}{L}$

$$L_1 = L_2 = 8.33\,\mu m$$

$$W_1 = W_2 = 0.6\,\mu m$$

```
MOS CURRENT SOURCE
VDD 1 0 15V
VOUT 13 0 13V
LBIAS 13 3 1GIGAHENRY
IS 3 0 0A AC 1
IREF 1 2 50UA
M1 2 2 0 0 N W=0.6U L=8.33U
M2 3 2 0 0 N W=0.6U L=8.33U
*****
* CHOOSE ID=IREF=50UA.
* CHOOSE VT=0.7V.
*****
.MODEL N NMOS LEVEL=1 VTO=0.7 KF=3E-24
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.AC DEC 10 100 100MEG
.NOISE V(3) IS 10
.PRINT AC VM(3) ONOISE INOISE
.END

 ****** OPERATING POINT INFORMATION      TNOM=  25.000 TEMP=  25.000

+0:1       =  15.0000  0:2       =   8.8859  0:3       =  13.0000
+0:13      =  13.0000

**** MOSFETS

ELEMENT  0:M1       0:M2
MODEL    0:N        0:N
 ID        50.0000U   50.0000U
 IBS        0.         0.
 IBD      -88.8585F -130.0000F
 VGS        8.8859     8.8859
 VDS        8.8859    13.0000
 VBS        0.         0.
 VTH      700.0000M  700.0000M
 VDSAT      8.1859     8.1859
 BETA       1.4924U    1.4924U
 GAM EFF  527.6252M  527.6252M
 GM        12.2162U   12.2162U
 GDS        0.         0.
 GMB        4.2323U    4.2323U
 CDTOT    2.045E-17  2.992E-17
 CGTOT      1.1721F    1.1816F
 CSTOT      1.1506F    1.1506F
 CBTOT    1.082E-18  1.082E-18
 CGS        1.1506F    1.1506F
 CGD      2.045E-17  2.992E-17

 ****** NOISE ANALYSIS                   TNOM=  25.000 TEMP=  25.000

    FREQUENCY = 100.0000   HZ
**** MOSFET SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT      0:M1          0:M2
      ID   55.5289M      55.5289M
      FN    1.0742K       1.0742K
   TOTAL    1.0743K       1.0743K
**** TOTAL OUTPUT NOISE VOLTAGE          =   2.1485K SQ V/HZ
                                         =  46.3521  V/RT HZ
     TRANSFER FUNCTION VALUE:
       V(3)/IS                           = 643.5053G
     EQUIVALENT INPUT NOISE AT IS        =  72.0307P /RT HZ

    FREQUENCY =    1.0000K  HZ
     EQUIVALENT INPUT NOISE AT IS        =  22.7834P /RT HZ

    FREQUENCY =   10.0000K  HZ
     EQUIVALENT INPUT NOISE AT IS        =   7.2215P /RT HZ

    FREQUENCY = 100.0000K  HZ
     EQUIVALENT INPUT NOISE AT IS        =   2.3359P /RT HZ

    FREQUENCY =    1.0000X  HZ
     EQUIVALENT INPUT NOISE AT IS        = 887.1333F /RT HZ

    FREQUENCY =   10.0000X  HZ
     EQUIVALENT INPUT NOISE AT IS        = 565.7293F /RT HZ

    FREQUENCY = 100.0000X  HZ
     EQUIVALENT INPUT NOISE AT IS        = 520.9981F /RT HZ
*****
THERMAL NOISE:
AT FREQUENCY = 100 MHZ, FLICKER NOISE BECOMES
       NEGLIGIBLY SMALL; WE ONLY SEE THERMAL NOISE AT
       THAT FREQUENCY.
TO CHECK THAT THIS IS TRUE, EVALUATE THE THERMAL
       NOISE OUTPUT CURRENT:
       (16/3)*KT*GM=2.69E-25 SQ A/HZ
       (GM FROM MOSFET DATA ABOVE)
       --> 5.18E-13 A/RT HZ
THIS MATCHES THE SPICE RESULT ABOVE
COMPARING W/L=0.6UM/8.33UM, 0.8UM/6.25UM, AND 1UM/5UM,
WE SEE THAT THE SMALLEST W/L RATIO GIVES THE LEAST
THERMAL NOISE (AT 100 MHZ).

FLICKER NOISE:
AT LOW FREQUENCIES, FLICKER NOISE DOMINATES.
COMPARING W/L=0.6UM/8.33UM, 0.8UM/6.25UM, AND 1UM/5UM,
WE SEE THAT THE SMALLEST W/L RATIO ALSO GIVES THE LEAST
FLICKER NOISE.

MOS CURRENT SOURCE
VDD 1 0 15V
VOUT 13 0 13V
LBIAS 13 3 1GIGAHENRY
IS 3 0 0A AC 1
IREF 1 2 50UA
M1 2 2 0 0 N W=0.8U L=6.25U
M2 3 2 0 0 N W=0.8U L=6.25U
*****
* CHOOSE ID=IREF=50UA.
* CHOOSE VT=0.7V.
*****
.MODEL N NMOS LEVEL=1 VTO=0.7 KF=3E-24
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.AC DEC 10 100 100MEG
.NOISE V(3) IS 10
.PRINT AC VM(3) ONOISE INOISE
.END

 ****** OPERATING POINT INFORMATION      TNOM=  25.000 TEMP=  25.000

+0:1       =  15.0000  0:2       =   6.8406  0:3       =  13.0000
+0:13      =  13.0000

**** MOSFETS

ELEMENT  0:M1       0:M2
MODEL    0:N        0:N
 ID        50.0000U   50.0000U
 IBS        0.         0.
 IBD      -68.4062F -130.0000F
 VGS        6.8406     6.8406
 VDS        6.8406    13.0000
 VBS        0.         0.
 VTH      700.0000M  700.0000M
 VDSAT      6.1406     6.1406
 BETA       2.6520U    2.6520U
 GAM EFF  527.6252M  527.6252M
 GM        16.2850U   16.2850U
 GDS        0.         0.
 GMB        5.6419U    5.6419U
 CDTOT    1.575E-17  2.993E-17
 CGTOT      1.1682F    1.1824F
 CSTOT      1.1511F    1.1511F
 CBTOT    1.442E-18  1.442E-18
 CGS        1.1511F    1.1511F
 CGD      1.575E-17  2.993E-17

 ****** NOISE ANALYSIS                   TNOM=  25.000 TEMP=  25.000

    FREQUENCY = 100.0000   HZ
**** MOSFET SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT      0:M1          0:M2
      ID   74.0251M      74.0251M
      FN    1.9082K       1.9082K
   TOTAL    1.9083K       1.9083K
**** TOTAL OUTPUT NOISE VOLTAGE          =   3.8166K SQ V/HZ
                                         =  61.7783  V/RT HZ
     TRANSFER FUNCTION VALUE:
       V(3)/IS                           = 643.5115G
     EQUIVALENT INPUT NOISE AT IS        =  96.0018P /RT HZ

    FREQUENCY =    1.0000K  HZ
     EQUIVALENT INPUT NOISE AT IS        =  30.3637P /RT HZ

    FREQUENCY =   10.0000K  HZ
     EQUIVALENT INPUT NOISE AT IS        =   9.6186P /RT HZ

    FREQUENCY = 100.0000K  HZ
     EQUIVALENT INPUT NOISE AT IS        =   3.0941P /RT HZ

    FREQUENCY =    1.0000X  HZ
     EQUIVALENT INPUT NOISE AT IS        =   1.1310P /RT HZ

    FREQUENCY =   10.0000X  HZ
     EQUIVALENT INPUT NOISE AT IS        = 670.5658F /RT HZ

    FREQUENCY = 100.0000X  HZ
     EQUIVALENT INPUT NOISE AT IS        = 604.3648F /RT HZ

MOS CURRENT SOURCE
VDD 1 0 15V
VOUT 13 0 13V
LBIAS 13 3 1GIGAHENRY
IS 3 0 0A AC 1
IREF 1 2 50UA
M1 2 2 0 0 N W=1U L=5U
M2 3 2 0 0 N W=1U L=5U
*****
* CHOOSE ID=IREF=50UA.
* CHOOSE VT=0.7V.
*****
```

```
.MODEL N NMOS LEVEL=1 VTO=0.7 KP=3E-24
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.AC DEC 10 100 100MEG
.NOISE V(3) IS 10
.PRINT AC VM(3) ONOISE INOISE
.END

 ******  OPERATING POINT INFORMATION      TNOM=  25.000 TEMP=  25.000

+0:1        =  15.0000  0:2        =   5.6125  0:3        =  13.0000
+0:13       =  13.0000

**** MOSFETS

ELEMENT  0:M1        0:M2
MODEL    0:N         0:N
 ID        50.0000U   50.0000U
 IBS        0.         0.
 IBD      -56.1249F -130.0000F
 VGS        5.6125     5.6125
 VDS        5.6125    13.0000
 VBS        0.         0.
 VTH      700.0000M  700.0000M
 VDSAT      4.9125     4.9125
 BETA       4.1438U    4.1438U
 GAM EFF  527.6252M  527.6252M
 GM        20.3563U   20.3563U
 GDS        0.         0.
 GMB        7.0524U    7.0524U
 CDTOT    1.292E-17  2.993E-17
 CGTOT      1.1658F    1.1828F
 CSTOT      1.1511F    1.1511F
 CBTOT    1.801E-18  1.801E-18
 CGS        1.1511F    1.1511F
 CGD      1.292E-17  2.993E-17

 ******  NOISE ANALYSIS                    TNOM=  25.000 TEMP=  25.000

    FREQUENCY = 100.0000   HZ
**** MOSFET SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT      0:M1          0:M2
      ID   92.5314M      92.5314M
      FN    2.9816K       2.9816K
   TOTAL    2.9817K       2.9817K
**** TOTAL OUTPUT NOISE VOLTAGE          =   5.9633K SQ V/HZ
                                         =  77.2226  V/RT HZ

     TRANSFER FUNCTION VALUE:
      V(3)/IS                            = 643.5115G
     EQUIVALENT INPUT NOISE AT IS        = 120.0018P /RT HZ

    FREQUENCY =    1.0000K  HZ
     EQUIVALENT INPUT NOISE AT IS        =  37.9532P /RT HZ

    FREQUENCY =   10.0000K  HZ
     EQUIVALENT INPUT NOISE AT IS        =  12.0186P /RT HZ

    FREQUENCY =  100.0000K  HZ
     EQUIVALENT INPUT NOISE AT IS        =   3.8532P /RT HZ

    FREQUENCY =    1.0000X  HZ
     EQUIVALENT INPUT NOISE AT IS        =   1.3736P /RT HZ

    FREQUENCY =   10.0000X  HZ
     EQUIVALENT INPUT NOISE AT IS        = 768.6876F /RT HZ

    FREQUENCY =  100.0000X  HZ
     EQUIVALENT INPUT NOISE AT IS        = 678.3094F /RT HZ
```

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$k_p' = \mu_n C_{ox} = 150 \times 4.3\times10^{-7} = 64.7\,\mu A/V^2$

$k_n' = \mu_n C_{ox} = 450 \times 4.3\times10^{-7} = 194\,\mu A/V^2$

$g_{m1} = \sqrt{2\times64.7\times(150/0.72)\times100} = 1.64\,mA/V$

$g_{m3} = \sqrt{2\times194\times(50/0.72)\times100} = 1.64\,mA/V = g_{m1}$

Noise is dominated by M1–M4

At 100Hz

M1,2 thermal:

$$\frac{2}{3}\frac{4kT}{g_{m1}} = \frac{2}{3}\frac{1.66\times10^{-20}}{1.64m} = 6.75\times10^{-18}\,V^2/Hz$$

M1,2 flicker:

$$\frac{K_f}{WLC_{ox}f} = \frac{3\times10^{-24}}{150\times0.72\times4.3\times10^{-15}\times100} = 6.46\times10^{-14}\,V^2/Hz$$

M3,4 thermal:

$$\frac{2}{3}\frac{4kT}{g_{m3}}\frac{g_{m3}^2}{g_{m1}^2} = \frac{2}{3}\frac{1.66\times10^{-20}}{1.64m} = 6.75\times10^{-18}\,V^2/Hz$$

M3,4 flicker:

$$\frac{K_f}{WLC_{ox}f}\frac{g_{m3}^2}{g_{m1}^2} = \frac{3\times10^{-24}}{50\times0.72\times4.3\times10^{-15}\times100} = 1.94\times10^{-13}\,V^2/Hz$$

$$\overline{v_{iT}^2} = 2[6.75\times10^{-18} + 6.46\times10^{-14} + 6.75\times10^{-18} + 1.94\times10^{-13}] = 5.17\times10^{-13}\,V^2/Hz$$

$\sqrt{\overline{v_{iT}^2}} = 719\,nV/\sqrt{Hz}$

Flicker noise is dominant, especially from M3, M4.

At 1kHz,

M1,2 thermal: $6.75\times10^{-18}\,V^2/Hz$ (same)

M1,2 flicker: $6.46\times10^{-15}\,V^2/Hz$

M3,4 thermal: $6.75\times10^{-18}\,V^2/Hz$ (same)

M3,4 flicker: $1.94\times10^{-14}\,V^2/Hz$

$\overline{v_{iT}^2} = 5.17\times10^{-14}\,V^2/Hz$

$\sqrt{\overline{v_{iT}^2}} = 227\,nV/\sqrt{Hz}$

At 10kHz,

M1,2 thermal: $6.75\times10^{-18}\,V^2/Hz$ (same)

M1,2 flicker: $6.46\times10^{-16}\,V^2/Hz$

M3,4 thermal: $6.75\times10^{-18}\,V^2/Hz$ (same)

M3,4 flicker: $1.94\times10^{-15}\,V^2/Hz$

$\overline{v_{iT}^2} = 5.20\times10^{-15}\,V^2/Hz$

$\sqrt{\overline{v_{iT}^2}} = 72.1\,nV/\sqrt{Hz}$

```
OP AMP
VDD 1 0 1.5
VSS 2 0 -1.5
IBIAS 8 2 200U
VIP 11 0 DC -7.315U AC 1
VIN 12 0 0
M1 3 12 5 5 CMOSP L=0.72U W=150U
M2 4 11 5 5 CMOSP L=0.72U W=150U
M3 3 3 2 2 CMOSN L=0.72U W=50U
M4 4 3 2 2 CMOSN L=0.72U W=50U
M5 5 8 1 1 CMOSP L=0.72U W=150U
M6 13 4 2 2 CMOSN L=0.72U W=100U
M7 13 8 1 1 CMOSP L=0.72U W=150U
M8 8 8 1 1 CMOSP L=0.72U W=150U
M9 4 1 14 2 CMOSN L=0.72U W=8.3U
CC 14 13 5P
.MODEL CMOSN NMOS VTO=0.6  KP=194U  TOX=80E-10 LAMBDA=0.027778 KF=3.E-24 NLEV=2
.MODEL CMOSP PMOS VTO=-0.8 KP=64.7U TOX=80E-10 LAMBDA=0.055556 KF=3.E-24 NLEV=2
*NMOS: LAMBDA=(DXD/DVDS)/LEFF=0.02U/0.72U=0.027778
*PMOS: LAMBDA=(DXD/DVDS)/LEFF=0.04U/0.72U=0.055556
.OPTIONS NOMOD
.WIDTH OUT=80
.OP
.NOISE V(13) VIP 10
.TF V(13) VIP
.AC DEC 10 100 10K
.NOISE V(13) VIP 10
.PRINT AC VM(13) ONOISE INOISE
.END

****** OPERATING POINT INFORMATION      TNOM=  25.000 TEMP=  25.000

+0:1        =   1.5000  0:2        =  -1.5000  0:3        =-780.5838M
+0:4        =-778.9569M 0:5        = 915.2649M 0:8        = 532.1868M
+0:11       =  -7.3150U 0:12       =   0.      0:13       = -20.4925U
+0:14       =-778.9569M

**** MOSFETS

ELEMENT  0:M1       0:M2       0:M3       0:M4       0:M5       0:M6
MODEL    0:CMOSP    0:CMOSP    0:CMOSN    0:CMOSN    0:CMOSP    0:CMOSN
 ID       -97.9782U  -97.9825U   97.9782U   97.9825U -195.9607U  205.6117U
 IBS        0.         0.         0.         0.         0.         0.
 IBD       16.9585F   16.9422F   -7.1942F   -7.2104F    5.8474F  -14.9998F
 VGS     -915.2649M -915.2722M  719.4162M  719.4162M -967.8132M  721.0431M
 VDS       -1.6958    -1.6942   719.4162M  721.0431M -584.7351M    1.5000
 VBS        0.         0.         0.         0.         0.         0.
 VTH     -800.0000M -800.0000M  600.0000M  600.0000M -800.0000M  600.0000M
 VDSAT   -115.2649M -115.2722M  119.4162M  119.4162M -167.8132M  121.0431M
 BETA      14.7491M   14.7479M   13.7415M   13.7421M   13.9170M   28.0671M
 GAM EFF   42.2100M   42.2100M   42.2100M   42.2100M   42.2100M   42.2100M
 GM         1.7001M    1.7000M    1.6410M    1.6410M    2.3355M    3.3973M
 GDS        4.9746U    4.9752U    2.6683U    2.6683U   10.5443U    5.4830U
 GMB       47.1187U   47.1178U   45.4807U   45.4827U   64.7298U   94.1606U
 CDTOT      1.0541F    1.0531F  1.491E-16  1.494E-16  3.635E-16  6.216E-16
 CGTOT    313.6975F  313.6964F  104.3451F  104.3454F  312.4867F  208.9997F
 CSTOT    310.7845F  310.7845F  103.5948F  103.5948F  310.7845F  207.1897F
 CBTOT      1.8589F    1.8588F  6.012E-16  6.012E-16    1.3388F    1.1885F
 CGS      310.7845F  310.7845F  103.5948F  103.5948F  310.7845F  207.1897F
 CGD        1.0541F    1.0531F  1.491E-16  1.494E-16  3.635E-16  6.216E-16

ELEMENT  0:M7       0:M8       0:M9
MODEL    0:CMOSP    0:CMOSP    0:CMOSN
 ID      -205.6117U -200.0000U  728.2539F
 IBS        0.         0.        -7.2104F
 IBD       15.0002F    9.6781F   -7.2104F
 VGS     -967.8132M -967.8132M    2.2790
 VDS       -1.5000  -967.8132M  195.8190P
 VBS        0.         0.      -721.0431M
 VTH     -800.0000M -800.0000M  616.0014M
 VDSAT   -167.8132M -167.8132M  195.8190P
 BETA      14.6025M   14.2039M    2.2364M
 GAM EFF   42.2100M   42.2100M   42.2100M
 GM         2.4505M    2.3836M  437.9275F
 GDS       10.5443U   10.5443U    3.7190M
 GMB       67.9177U   66.0640U    8.1034F
 CDTOT    9.324E-16  6.016E-16   12.8976F
 CGTOT    313.0556F  312.7248F   25.8007F
 CSTOT    310.7845F  310.7845F   12.8976F
 CBTOT      1.3388F    1.3388F  5.569E-18
 CGS      310.7845F  310.7845F   12.8976F
 CGD      9.324E-16  6.016E-16   12.8976F

****     SMALL-SIGNAL TRANSFER CHARACTERISTICS

     V(13)/VIP                                 =   47.1075K
     INPUT RESISTANCE AT          VIP          =  9.999E+19
     OUTPUT RESISTANCE AT V(13)                =   62.3936K

 ******  NOISE ANALYSIS                     TNOM=  25.000 TEMP=  25.000

    FREQUENCY = 100.0000    HZ
**** MOSFET SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT     0:M1          0:M2          0:M3          0:M4          0:M5
      ID   14.2182N      14.2188N      13.6611N      13.7883N     102.2780F
      FN  141.7099U     141.7138U     394.2745U     397.9613U       1.4004N
   TOTAL  141.7241U     141.7280U     394.2881U     397.9750U       1.4005N
ELEMENT     0:M6          0:M7          0:M8          0:M9
      ID  144.0637F     103.9127F     1.048E-16       0.
      FN    4.3041N       1.4928N       1.4648P       0.
   TOTAL    4.3042N       1.4929N       1.4649P       0.
**** TOTAL OUTPUT NOISE VOLTAGE          =   1.0757M SQ V/HZ
                                         =  32.7982M V/RT HZ

     TRANSFER FUNCTION VALUE:
      V(13)/VIP                          =  46.9267K
     EQUIVALENT INPUT NOISE AT VIP       = 698.9248N /RT HZ

    FREQUENCY =   1.0000K  HZ
     EQUIVALENT INPUT NOISE AT VIP       = 221.0711N /RT HZ

    FREQUENCY =  10.0000K  HZ
     EQUIVALENT INPUT NOISE AT VIP       =  70.0720N /RT HZ
```

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```
741 OP AMP, INPUT NOISE-VOLTAGE
*** INPUT STAGE
VCC 1 0 15V
VEE 2 0 -15V
Q12 3 3 1 PNP
R5 3 4 39K
Q11 4 4 2 NPN
Q10 6 4 5 NPN
R4 5 2 5K
Q9 6 7 1 PNP
Q8 7 7 1 PNP
Q1 7 8 10 NPN
Q2 7 9 11 NPN
Q3 12 6 10 PNP
Q4 16 6 11 PNP
Q5 12 13 14 NPN
Q6 16 13 15 NPN
R1 14 2 1K
R2 15 2 1K
Q7 1 12 13 NPN
R3 13 2 50K
*** DARLINGTON GAIN STAGE
Q16 1 16 17 NPN
R9 17 2 50K
Q17 19 17 18 NPN
R8 18 2 100
Q13B 19 3 1 PNPB
*** OUTPUT STAGE
Q13A 20 3 1 PNPA
Q19 20 20 21 NPN
Q18 20 21 22 NPN
R10 21 22 40K
Q23 2 19 22 PNP
Q20 2 22 23 PNP 3
R7 23 24 22
R6 25 24 27
Q14 1 20 25 NPN 3
.MODEL NPN NPN BF=250 IS=5E-15 VAF=130
.MODEL PNP PNP BF=50 IS=2E-15 VAF=52
.MODEL PNPA PNP BF=50 IS=0.5E-15 VAF=52
.MODEL PNPB PNP BF=50 IS=1.5E-15 VAF=52
VI1 8 0 -268.625UV AC 1
VI2 9 0 0V
.TF V(24) VI1
.NOISE V(24) VI1 10
.AC DEC 10 100 10K
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.PROBE
.END
```

```
 ******  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000

+0:1       = 1.500E+01 0:2       =-1.500E+01 0:3       = 1.431E+01
+0:4       =-1.433E+01 0:5       =-1.490E+01 0:6       =-1.108E+00
+0:7       = 1.441E+01 0:8       =-2.686E-04 0:9       =  0.
+0:10      =-5.444E-01 0:11      =-5.442E-01 0:12      =-1.389E+01
+0:13      =-1.444E+01 0:14      =-1.499E+01 0:15      =-1.499E+01
+0:16      =-1.370E+01 0:17      =-1.427E+01 0:18      =-1.493E+01
+0:19      =-1.257E+00 0:20      = 5.932E-01 0:21      = 2.625E-02
+0:22      =-6.058E-01 0:23      = 6.808E-04 0:24      = 3.295E-03
+0:25      = 6.503E-03

**** BIPOLAR JUNCTION TRANSISTORS

ELEMENT  0:Q12      0:Q11      0:Q10      0:Q9       0:Q8       0:Q1
MODEL    0:PNP      0:NPN      0:NPN      0:PNP      0:PNP      0:NPN
 IB      -1.413E-05  2.926E-06  6.988E-08 -2.928E-07 -2.928E-07  2.736E-08
 IC      -7.063E-04  7.316E-04  1.925E-05 -1.901E-05 -1.464E-05  7.597E-06
 VBE     -6.877E-01  6.649E-01  5.683E-01 -5.875E-01 -5.875E-01  5.441E-01
 VCE     -6.877E-01  6.649E-01  1.379E+01 -1.610E+01 -5.875E-01  1.495E+01
 VBC       0.         0.       -1.322E+01  1.552E+01   0.       -1.441E+01
 VS      -1.431E+01  1.433E+01  1.108E+00 -1.441E+01 -1.441E+01 -1.441E+01
 POWER    4.955E-04  4.884E-04  2.656E-04  3.064E-04  8.771E-06  1.136E-04
 BETAD    5.000E+01  2.500E+02  2.754E+02  6.492E+01  5.000E+01  2.777E+02
 GM       2.729E-02  2.828E-02  7.441E-04  7.346E-04  5.657E-04  2.937E-04
 RPI      1.831E+03  8.838E+03  3.701E+05  8.834E+04  8.834E+04  9.454E+05
 RX       0.         0.         0.         0.         0.         0.
 RO       7.362E+04  1.777E+05  7.440E+06  3.552E+06  3.552E+06  1.900E+07
 CPI      0.         0.         0.         0.         0.         0.
 CMU      0.         0.         0.         0.         0.         0.
 CBX      0.         0.         0.         0.         0.         0.
 CCS      0.         0.         0.         0.         0.         0.
 BETAAC   4.997E+01  2.499E+02  2.753E+02  6.490E+01  4.997E+01  2.776E+02
 FT       4.344E+12  4.500E+12  1.184E+11  1.169E+11  9.002E+10  4.674E+10

ELEMENT  0:Q2       0:Q3       0:Q4       0:Q5       0:Q6       0:Q7
MODEL    0:NPN      0:PNP      0:PNP      0:NPN      0:NPN      0:NPN
 IB       2.746E-08 -1.205E-07 -1.213E-07  2.975E-08  2.974E-08  3.632E-08
 IC       7.626E-06 -7.504E-06 -7.532E-06  7.468E-06  7.476E-06  1.110E-05
 VBE      5.442E-01 -5.645E-01 -5.647E-01  5.463E-01  5.462E-01  5.514E-01
 VCE      1.495E+01 -1.335E+01 -1.316E+01  1.097E+00  1.285E+00  2.944E+01
 VBC     -1.441E+01  1.278E+01  1.259E+01 -5.514E-01 -7.393E-01 -2.889E+01
 VS      -1.441E+01  1.108E+00  1.108E+00  1.389E+01  1.370E+01 -1.500E+01
 POWER    1.141E-04  1.003E-04  9.921E-05  8.214E-06  9.627E-06  3.268E-04
 BETAD    2.777E+02  6.229E+01  6.211E+01  2.510E+02  2.514E+02  3.055E+02
 GM       2.948E-04  2.900E-04  2.911E-04  2.887E-04  2.890E-04  4.290E-04
 RPI      9.419E+05  2.147E+05  2.132E+05  8.695E+05  8.698E+05  7.121E+05
 RX       0.         0.         0.         0.         0.         0.
 RO       1.893E+07  8.633E+06  8.576E+06  1.748E+07  1.748E+07  1.431E+07
 CPI      0.         0.         0.         0.         0.         0.
 CMU      0.         0.         0.         0.         0.         0.
 CBX      0.         0.         0.         0.         0.         0.
 CCS      0.         0.         0.         0.         0.         0.
 BETAAC   2.776E+02  6.226E+01  6.208E+01  2.510E+02  2.513E+02  3.055E+02
 FT       4.691E+10  4.615E+10  4.633E+10  4.594E+10  4.599E+10  6.828E+10

ELEMENT  0:Q16      0:Q17      0:Q13B     0:Q13A     0:Q19      0:Q18
MODEL    0:NPN      0:NPN      0:PNPB     0:PNPA     0:NPN      0:NPN
 IB       5.593E-08  2.516E-06 -1.059E-05 -3.531E-06  6.623E-08  8.209E-07
 IC       1.707E-05  6.918E-04 -6.883E-04 -2.232E-04  1.656E-05  2.061E-04
 VBE      5.626E-01  6.610E-01 -6.877E-01 -6.877E-01  5.670E-01  6.321E-01
 VCE      2.927E+01  1.367E+01 -1.625E+01 -1.440E+01  5.670E-01  1.199E+00
 VBC     -2.870E+01 -1.301E+01  1.557E+01  1.371E+01  0.        -5.670E-01
 VS      -1.500E+01  1.257E+00 -1.431E+01 -1.431E+01 -5.932E-01 -5.932E-01
 POWER    4.996E-04  9.461E-03  1.120E-02  3.217E-03  9.424E-06  2.476E-04
 BETAD    3.052E+02  2.750E+02  6.497E+01  6.319E+01  2.500E+02  2.510E+02
 GM       6.598E-04  2.674E-02  2.660E-02  8.625E-03  6.400E-04  7.967E-03
 RPI      4.624E+05  1.028E+04  2.441E+03  7.323E+03  3.905E+05  3.150E+04
 RX       0.         0.         0.         0.         0.         0.
 RO       9.298E+06  2.067E+05  9.816E+04  2.944E+05  7.852E+06  6.334E+05
 CPI      0.         0.         0.         0.         0.         0.
 CMU      0.         0.         0.         0.         0.         0.
 CBX      0.         0.         0.         0.         0.         0.
 CCS      0.         0.         0.         0.         0.         0.
 BETAAC   3.051E+02  2.749E+02  6.494E+01  6.316E+01  2.499E+02  2.510E+02
 FT       1.050E+11  4.256E+12  4.234E+12  1.372E+12  1.018E+11  1.268E+12

ELEMENT  0:Q23      0:Q20      0:Q14
MODEL    0:PNP      0:PNP      0:NPN
 IB      -3.497E-06 -1.833E-06  4.263E-07
 IC      -2.211E-04 -1.170E-04  1.184E-04
 VBE     -6.516E-01 -6.065E-01  5.867E-01
 VCE     -1.439E+01 -1.500E+01  1.499E+01
 VBC      1.374E+01  1.439E+01 -1.440E+01
 VS       1.257E+00  6.058E-01 -1.500E+01
 POWER    3.184E-03  1.756E-03  1.775E-03
 BETAD    6.321E+01  6.384E+01  2.777E+02
 GM       8.544E-03  4.521E-03  4.577E-03
 RPI      7.395E+03  1.411E+04  6.066E+04
 RX       0.         0.         0.
 RO       2.973E+05  5.675E+05  1.219E+06
 CPI      0.         0.         0.
 CMU      0.         0.         0.
 CBX      0.         0.         0.
 CCS      0.         0.         0.
 BETAAC   6.318E+01  6.381E+01  2.776E+02
 FT       1.359E+12  7.196E+11  7.284E+11

****     SMALL-SIGNAL TRANSFER CHARACTERISTICS
     V(24)/VI1                                   =  3.126E+05
     INPUT RESISTANCE AT          VI1            =  4.759E+06
     OUTPUT RESISTANCE AT V(24)                  =  1.339E+02

 ******  NOISE ANALYSIS                       TNOM=  27.000 TEMP=  27.000
    FREQUENCY = 1.000E+02  HZ
**** RESISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT      0:R5         0:R4         0:R1         0:R2         0:R3
   TOTAL  1.346E-15    1.927E-11    3.845E-06    3.851E-06    1.883E-11
ELEMENT      0:R9         0:R8         0:R10        0:R7         0:R6
   TOTAL  1.797E-11    2.280E-13    2.276E-19    8.168E-20    1.242E-19
**** TRANSISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT      0:Q12        0:Q11        0:Q10        0:Q9         0:Q8
      IB  2.433E-14    2.719E-16    1.320E-13    1.375E-12    1.375E-12
      IC  1.216E-12    6.797E-14    2.660E-12    5.732E-11    6.876E-11
   TOTAL  1.241E-12    6.825E-14    2.792E-12    5.870E-11    7.014E-11
ELEMENT      0:Q1         0:Q2         0:Q3         0:Q4         0:Q5
      IB  9.791E-09    9.896E-09    4.287E-08    4.396E-08    2.142E-09
      IC  2.739E-06    2.729E-06    2.881E-06    2.872E-06    6.673E-06
   TOTAL  2.749E-06    2.738E-06    2.924E-06    2.916E-06    6.675E-06
ELEMENT      0:Q6         0:Q7         0:Q16        0:Q17        0:Q13B
      IB  2.283E-09    5.350E-08    8.238E-08    4.415E-11    1.825E-14
      IC  6.676E-06    2.020E-10    2.966E-10    3.686E-13    1.337E-12
   TOTAL  6.679E-06    5.370E-08    8.267E-08    4.451E-11    1.356E-12
ELEMENT      0:Q13A       0:Q19        0:Q18        0:Q23        0:Q20
      IB  6.082E-15    1.399E-20    1.445E-19    6.565E-15    8.508E-19
      IC  1.398E-16    3.497E-18    3.308E-19    1.248E-16    5.716E-19
   TOTAL  6.222E-15    3.511E-18    4.752E-19    6.690E-15    1.422E-18
ELEMENT      0:Q14
      IB  2.232E-19
      IC  5.433E-19
   TOTAL  7.666E-19
**** TOTAL OUTPUT NOISE VOLTAGE              = 3.251E-05 SQ V/HZ
                                             = 5.702E-03 V/RT HZ

     TRANSFER FUNCTION VALUE:
       V(24)/VI1                             = 3.126E+05
     EQUIVALENT INPUT NOISE AT VI1           = 1.824E-08 /RT HZ

    FREQUENCY = 1.000E+03  HZ
     EQUIVALENT INPUT NOISE AT VI1           = 1.824E-08 /RT HZ

    FREQUENCY = 9.999E+03  HZ
     EQUIVALENT INPUT NOISE AT VI1           = 1.824E-08 /RT HZ
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BY SPICE:
EQUIVALENT INPUT NOISE VOLTAGE = 3.33E-16 SQ V/HZ
BY HAND CALCULATION:
EQUIVALENT INPUT NOISE VOLTAGE = 2.66E-16 SQ V/HZ

741 OP AMP, INPUT NOISE-CURRENT
*** INPUT STAGE
VCC 1 0 15V
VEE 2 0 -15V
Q12 3 3 1 PNP
R5 3 4 39K
Q11 4 4 2 NPN
Q10 6 4 5 NPN
R4 5 2 5K
Q9 6 7 1 PNP
Q8 7 7 1 PNP
Q1 7 88 10 NPN
LBIAS 88 8 1GIGAHENRY
IS 88 0 0A AC 1
Q2 7 9 11 NPN
Q3 12 6 10 PNP
Q4 16 6 11 PNP
Q5 12 13 14 NPN
Q6 16 13 15 NPN
R1 14 2 1K
R2 15 2 1K
Q7 1 12 13 NPN
R3 13 2 50K
*** DARLINGTON GAIN STAGE
Q16 1 16 17 NPN
R9 17 2 50K
Q17 19 17 18 NPN
R8 18 2 100
Q13B 19 3 1 PNPB
*** OUTPUT STAGE
Q13A 20 3 1 PNPA
Q19 20 20 21 NPN
Q18 20 21 22 NPN
R10 21 22 40K
Q23 2 19 22 PNP
Q20 2 22 23 PNP 3
R7 23 24 22
R6 25 24 27
Q14 1 20 25 NPN 3
.MODEL NPN NPN BF=250 IS=5E-15 VAF=130
.MODEL PNP PNP BF=50 IS=2E-15 VAF=52
.MODEL PNPA PNP BF=50 IS=0.5E-15 VAF=52
.MODEL PNPB PNP BF=50 IS=1.5E-15 VAF=52
VI1 8 0 -268.625UV
VI2 9 0 0V
.TF V(24) VI1
.NOISE V(24) IS 10
.AC DEC 10 100 10K
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.PROBE
.END

 ******  NOISE ANALYSIS                      TNOM=  27.000 TEMP=  27.000
    FREQUENCY = 1.000E+02  HZ
**** RESISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT     0:R5        0:R4        0:R1        0:R2        0:R3
  TOTAL  5.745E-11   9.182E-06   6.131E-06   6.137E-06   2.773E-11
ELEMENT     0:R9        0:R8        0:R10       0:R7        0:R6
  TOTAL  2.725E-11   1.617E-13   2.271E-19   8.192E-20   1.238E-19
**** TRANSISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT     0:Q12       0:Q11       0:Q10       0:Q9        0:Q8
     IB  3.051E-14   1.285E-10   6.290E-08   6.550E-07   6.550E-07
     IC  1.525E-12   3.214E-08   1.268E-06   2.731E-05   3.275E-05
  TOTAL  1.556E-12   3.226E-08   1.330E-06   2.797E-05   3.341E-05
ELEMENT     0:Q1        0:Q2        0:Q3        0:Q4        0:Q5
     IB  1.934E-02   6.115E-08   1.338E-08   8.781E-07   3.420E-09
     IC  6.965E-05   9.643E-11   2.612E-10   1.536E-08   1.064E-05
  TOTAL  1.941E-02   6.124E-08   1.364E-08   8.935E-07   1.064E-05
ELEMENT     0:Q6        0:Q7        0:Q16       0:Q17       0:Q13B
     IB  3.635E-09   8.533E-08   1.313E-07   6.673E-11   2.288E-14
     IC  1.064E-05   2.975E-10   4.497E-10   4.441E-13   1.274E-12
  TOTAL  1.064E-05   8.562E-08   1.318E-07   6.717E-11   1.297E-12
ELEMENT     0:Q13A      0:Q19       0:Q18       0:Q23       0:Q20
     IB  7.627E-15   1.396E-20   1.441E-19   6.252E-15   8.105E-19
     IC  1.340E-16   3.489E-18   3.300E-19   1.194E-16   5.689E-19
  TOTAL  7.761E-15   3.503E-18   4.741E-19   6.372E-15   1.379E-18
ELEMENT     0:Q14
     IB  2.132E-19
     IC  5.410E-19
  TOTAL  7.542E-19
**** TOTAL OUTPUT NOISE VOLTAGE         = 1.951E-02 SQ V/HZ
                                        = 1.397E-01 V/RT HZ

    TRANSFER FUNCTION VALUE:
     V(24)/IS                           = 1.487E+12
    EQUIVALENT INPUT NOISE AT IS        = 9.388E-14 /RT HZ

   FREQUENCY = 1.000E+03  HZ
    EQUIVALENT INPUT NOISE AT IS        = 9.388E-14 /RT HZ

   FREQUENCY = 9.999E+03  HZ
    EQUIVALENT INPUT NOISE AT IS        = 9.388E-14 /RT HZ

EQUIVALENT INPUT NOISE CURRENT = 8.81E-27 SQ A/HZ

741 OP AMP, INPUT NOISE-VOLTAGE
* FLICKER NOISE
* 2*Q*IB = KF*IB/F AT CORNER FREQ = 1KHZ
* KF=3.2E-16
*** INPUT STAGE
VCC 1 0 15V
VEE 2 0 -15V
Q12 3 3 1 PNP
R5 3 4 39K
Q11 4 4 2 NPN
Q10 6 4 5 NPN
R4 5 2 5K
Q9 6 7 1 PNP
Q8 7 7 1 PNP
Q1 7 8 10 NPN
Q2 7 9 11 NPN
Q3 12 6 10 PNP
Q4 16 6 11 PNP
Q5 12 13 14 NPN
Q6 16 13 15 NPN
R1 14 2 1K
R2 15 2 1K
Q7 1 12 13 NPN
R3 13 2 50K
*** DARLINGTON GAIN STAGE
Q16 1 16 17 NPN
R9 17 2 50K
Q17 19 17 18 NPN
R8 18 2 100
Q13B 19 3 1 PNPB
*** OUTPUT STAGE
Q13A 20 3 1 PNPA
Q19 20 20 21 NPN
Q18 20 21 22 NPN
R10 21 22 40K
Q23 2 19 22 PNP
Q20 2 22 23 PNP 3
R7 23 24 22
R6 25 24 27
Q14 1 20 25 NPN 3
* ADD FLICKER NOISE
.MODEL NPN NPN BF=250 IS=5E-15 VAF=130 KF=3.2E-16 AF=1
.MODEL PNP PNP BF=50 IS=2E-15 VAF=52 KF=3.2E-16 AF=1
.MODEL PNPA PNP BF=50 IS=0.5E-15 VAF=52 KF=3.2E-16 AF=1
.MODEL PNPB PNP BF=50 IS=1.5E-15 VAF=52 KF=3.2E-16 AF=1
VI1 8 0 -268.625UV AC 1
VI2 9 0 0V
.TF V(24) VI1
.NOISE V(24) VI1 10
.AC DEC 10 1 10K
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.PROBE

 ******  NOISE ANALYSIS                      TNOM=  27.000 TEMP=  27.000

    FREQUENCY = 1.000E+00  HZ
**** RESISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT     0:R5        0:R4        0:R1        0:R2        0:R3
  TOTAL  1.346E-15   1.927E-11   3.845E-06   3.851E-06   1.883E-11
ELEMENT     0:R9        0:R8        0:R10       0:R7        0:R6
  TOTAL  1.797E-11   2.280E-13   2.276E-19   8.168E-20   1.242E-19
**** TRANSISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT     0:Q12       0:Q11       0:Q10       0:Q9        0:Q8
     IB  2.433E-14   2.719E-16   1.320E-13   1.375E-12   1.375E-12
     IC  1.216E-12   6.797E-14   2.660E-12   5.732E-11   6.876E-11
     FN  2.430E-11   2.715E-13   1.318E-10   1.373E-09   1.373E-09
  TOTAL  2.554E-11   3.398E-13   1.346E-10   1.432E-09   1.444E-09
ELEMENT     0:Q1        0:Q2        0:Q3        0:Q4        0:Q5
     IB  9.791E-09   9.896E-09   4.287E-08   4.396E-08   2.142E-09
     IC  2.739E-06   2.729E-06   2.881E-06   2.872E-06   6.673E-06
     FN  9.778E-06   9.883E-06   4.281E-05   4.390E-05   2.139E-06
  TOTAL  1.253E-05   1.262E-05   4.573E-05   4.681E-05   8.814E-06
ELEMENT     0:Q6        0:Q7        0:Q16       0:Q17       0:Q13B
     IB  2.283E-09   5.350E-08   8.238E-08   4.415E-11   1.825E-14
     IC  6.676E-06   2.020E-10   2.966E-10   3.686E-13   1.337E-12
     FN  2.280E-06   5.342E-05   8.227E-05   4.409E-08   1.822E-11
  TOTAL  8.959E-06   5.348E-05   8.235E-05   4.413E-08   1.958E-11
ELEMENT     0:Q13A      0:Q19       0:Q18       0:Q23       0:Q20
     IB  6.082E-15   1.399E-20   1.445E-19   6.565E-15   8.508E-19
     IC  1.398E-16   3.497E-18   3.308E-19   1.248E-16   5.716E-19
     FN  6.074E-12   1.397E-17   1.443E-16   6.556E-12   8.497E-16
  TOTAL  6.080E-12   1.748E-17   1.448E-16   6.563E-12   8.511E-16
ELEMENT     0:Q14
     IB  2.232E-19
     IC  5.433E-19
     FN  2.229E-16
  TOTAL  2.237E-16
**** TOTAL OUTPUT NOISE VOLTAGE         = 2.790E-04 SQ V/HZ
                                        = 1.670E-02 V/RT HZ

    TRANSFER FUNCTION VALUE:
     V(24)/VI1                          = 3.126E+05
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    EQUIVALENT INPUT NOISE AT VI1      = 5.343E-08 /RT HZ

   FREQUENCY = 9.999E+00  HZ
    EQUIVALENT INPUT NOISE AT VI1      = 2.418E-08 /RT HZ

   FREQUENCY = 1.000E+02  HZ
    EQUIVALENT INPUT NOISE AT VI1      = 1.892E-08 /RT HZ

   FREQUENCY = 1.000E+03  HZ
    EQUIVALENT INPUT NOISE AT VI1      = 1.831E-08 /RT HZ

   FREQUENCY = 9.999E+03  HZ
    EQUIVALENT INPUT NOISE AT VI1      = 1.825E-08 /RT HZ

741 OP AMP, INPUT NOISE-CURRENT
* FLICKER NOISE
* 2*Q*IB = KF*IB/F AT CORNER FREQ = 1KHZ
* KF=3.2E-16
*** INPUT STAGE
VCC 1 0 15V
VEE 2 0 -15V
Q12 3 3 1 PNP
R5 3 4 39K
Q11 4 4 2 NPN
Q10 6 4 5 NPN
R4 5 2 5K
Q9 6 7 1 PNP
Q8 7 7 1 PNP
Q1 7 88 10 NPN
LBIAS 88 8 1GIGAHENRY
IS 88 0 0A AC 1
Q2 7 9 11 NPN
Q3 12 6 10 PNP
Q4 16 6 11 PNP
Q5 12 13 14 NPN
Q6 16 13 15 NPN
R1 14 2 1K
R2 15 2 1K
Q7 1 12 13 NPN
R3 13 2 50K
*** DARLINGTON GAIN STAGE
Q16 1 16 17 NPN
R9 17 2 50K
Q17 19 17 18 NPN
R8 18 2 100
Q13B 19 3 1 PNPB
*** OUTPUT STAGE
Q13A 20 3 1 PNPA
Q19 20 20 21 NPN
Q18 20 21 22 NPN
R10 21 22 40K
Q23 2 19 22 PNP
Q20 2 22 23 PNP 3
R7 23 24 22
R6 25 24 27
Q14 1 20 25 NPN 3
* ADD FLICKER NOISE
.MODEL NPN NPN BF=250 IS=5E-15 VAF=130 KF=3.2E-16 AF=1
.MODEL PNP PNP BF=50 IS=2E-15 VAF=52 KF=3.2E-16 AF=1
.MODEL PNPA PNP BF=50 IS=0.5E-15 VAF=52 KF=3.2E-16 AF=1
.MODEL PNPB PNP BF=50 IS=1.5E-15 VAF=52 KF=3.2E-16 AF=1
VI1 8 0 -268.625UV
VI2 9 0 0V
.TF V(24) VI1
.NOISE V(24) IS 10
.AC DEC 10 1 10K
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.PROBE
.END

 ******  NOISE ANALYSIS                     TNOM=  27.000 TEMP=  27.000

   FREQUENCY = 1.000E+00  HZ
**** RESISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT     0:R5        0:R4        0:R1        0:R2        0:R3
  TOTAL  5.745E-11   9.182E-06   6.131E-06   6.137E-06   2.773E-11
ELEMENT     0:R9        0:R8        0:R10       0:R7        0:R6
  TOTAL  2.725E-11   1.617E-13   2.271E-19   8.192E-20   1.238E-19
**** TRANSISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT     0:Q12       0:Q11       0:Q10       0:Q9        0:Q8
     IB  3.051E-14   1.285E-10   6.290E-08   6.550E-07   6.550E-07
     IC  1.525E-12   3.214E-08   1.268E-06   2.731E-05   3.275E-05
     FN  3.047E-11   1.284E-07   6.281E-05   6.541E-04   6.541E-04
  TOTAL  3.202E-11   1.606E-07   6.414E-05   6.821E-04   6.875E-04
ELEMENT     0:Q1        0:Q2        0:Q3        0:Q4        0:Q5
     IB  1.934E-02   6.115E-08   1.338E-08   8.781E-07   3.420E-09
     IC  6.965E-05   9.799E-11   2.628E-10   1.536E-08   1.064E-05
     FN  1.930E+01   6.106E-05   1.337E-05   8.769E-04   3.415E-06
  TOTAL  1.932E+01   6.112E-05   1.338E-05   8.778E-04   1.406E-05
ELEMENT     0:Q6        0:Q7        0:Q16       0:Q17       0:Q13B
     IB  3.635E-09   8.533E-08   1.313E-07   6.673E-11   2.288E-14
     IC  1.064E-05   2.975E-10   4.497E-10   4.441E-13   1.274E-12
     FN  3.630E-06   8.521E-05   1.311E-04   6.663E-08   2.285E-11
  TOTAL  1.427E-05   8.530E-05   1.313E-04   6.670E-08   2.415E-11
ELEMENT     0:Q13A      0:Q19       0:Q18       0:Q23       0:Q20
     IB  7.627E-15   1.396E-20   1.441E-19   6.252E-15   8.105E-19
     IC  1.340E-16   3.489E-18   3.300E-19   1.194E-16   5.689E-19
     FN  7.617E-12   1.394E-17   1.439E-16   6.244E-12   8.094E-16
  TOTAL  7.624E-12   1.744E-17   1.444E-16   6.250E-12   8.108E-16
ELEMENT     0:Q14
     IB  2.132E-19
     IC  5.410E-19
     FN  2.129E-16
  TOTAL  2.137E-16
**** TOTAL OUTPUT NOISE VOLTAGE          = 1.933E+01 SQ V/HZ
                                         = 4.396E+00 V/RT HZ

    TRANSFER FUNCTION VALUE:
     V(24)/IS                            = 1.487E+12
    EQUIVALENT INPUT NOISE AT IS         = 2.955E-12 /RT HZ

   FREQUENCY = 9.999E+00  HZ
    EQUIVALENT INPUT NOISE AT IS         = 9.387E-13 /RT HZ

   FREQUENCY = 1.000E+02  HZ
    EQUIVALENT INPUT NOISE AT IS         = 3.099E-13 /RT HZ

   FREQUENCY = 1.000E+03  HZ
    EQUIVALENT INPUT NOISE AT IS         = 1.324E-13 /RT HZ

   FREQUENCY = 9.999E+03  HZ
    EQUIVALENT INPUT NOISE AT IS         = 9.842E-14 /RT HZ
```

11.28

(a) $C_{ox} = \frac{\varepsilon}{t_{ox}} = \frac{3.9 \times 8.85 \times 10^{-12}}{80 \times 10^{-10}} = 4.3 \times 10^{-3}\ F/m^2$

$C_{gs} = \frac{2}{3} W L C_{ox}$

$= \frac{2}{3} \times 50 \times 10^{-6} \times 0.5 \times 10^{-6} \times 4.3 \times 10^{-3}$

$= 7.2 \times 10^{-14} F = 72 fF$

$2 q I_G \Delta f = \frac{16}{15} kT 4\pi^2 f^2 C_{gs}^2 \Delta f$

$f^2 = \frac{15}{32\pi^2} \frac{1}{V_T} I_G \frac{1}{C_{gs}^2}$

$= \frac{15}{32\pi^2} \frac{1}{26 \times 10^{-3}} 0.05 \times 10^{-15} \frac{1}{(7.2 \times 10^{-14})^2}$

$= 1.8 \times 10^{10}\ Hz^2$

$f = 1.3 \times 10^5 Hz = 130 kHz$

(b) $\int_0^{f_{BW}} 2 q I_G df = 2 q I_G f_{BW}$

$\int_0^{f_{BW}} \frac{16}{15} kT 4\pi^2 f^2 C_{gs}^2 df$

$= \frac{16}{15} kT 4\pi^2 C_{gs}^2 \frac{1}{3} f_{BW}^3$

$2 q I_G f_{BW} = \frac{16}{15} kT 4\pi^2 C_{gs}^2 \frac{1}{3} f_{BW}^3$

$f_{BW}^2 = \frac{45}{32\pi^2} \frac{1}{V_T} I_G \frac{1}{C_{gs}^2}$

$= \frac{45}{32\pi^2} \frac{1}{26 \times 10^{-3}} 0.05 \times 10^{-15} \frac{1}{(7.2 \times 10^{-14})^2}$

$= 5.3 \times 10^{10}\ Hz^2$

$f_{BW} = 2.3 \times 10^5 Hz = 230 kHz$

Chapter 12

12.1

$V_{ic} - V_{tn1} < V_{O1} < V_{DD} - |V_{ov3}|$

$0 - 0.6 < V_{ov1} < 2.5 - 0.2$

$-0.6V < V_{ov1} < 2.3V$

It is the same for V_{O2}.

If $V_{OC} = \frac{2.3-0.6}{2} = 0.85V$,

the largest symmetric differential output swing can be achieved.

$V_{O1p} = \frac{2.3+0.6}{2} = 1.45V$

$V_{odp} = 2V_{O1p} = 2.9V$

12.2

$-V_{SS} + V_{ov6} < V_{O1} < V_{DD} - |V_{ov7}|$

$-2.5 + 0.2 < V_{O1} < 2.5 - 0.2$

$-2.3V < V_{O1} < 2.3V$

It is the same for V_{O2}.

If $V_{OC} = \frac{2.3-2.3}{2} = 0V$, the largest symmetric differential output swing can be achieved.

$V_{O1p} = \frac{2.3+2.3}{2} = 2.3V$

$V_{odp} = 2V_{O1p} = 4.6V$

12-2

12.3

```
FULLY DIFFERENTIAL OP AMP
VDD 1 0 1.65
VSS 2 0 -1.65
VI 3 4 DC 0 SIN (0 1E-4 1K)
VB1 14 0 0.38
VB2 15 0 -0.56
VB3 16 0 -0.67
VCM 13 0 0
M1 7 3 5 1 CMOSP W=77U L=1U
M2 8 4 5 1 CMOSP W=77U L=1U
M3 7 15 2 2 CMOSN W=4U L=1U
M4 8 15 2 2 CMOSN W=4U L=1U
M5 5 6 1 1 CMOSP W=25U L=1U
M6 9 8 2 2 CMOSN W=16U L=1U
M7 9 14 1 1 CMOSP W=50U L=1U
M9 10 7 2 2 CMOSN W=16U L=1U
M10 10 14 1 1 CMOSP W=50U L=1U
M21 6 9 11 2 CMOSN W=8.4U L=1U
M22 1 13 11 2 CMOSN W=8.4U L=1U
M23 1 13 12 2 CMOSN W=8.4U L=1U
M24 6 10 12 2 CMOSN W=8.4U L=1U
M25 6 6 1 1 CMOSP W=25U L=1U
M26 11 16 2 2 CMOSN W=14U L=1U
M27 12 16 2 2 CMOSN W=14U L=1U
R1 3 0 1G
R2 4 0 1G
C1 7 10 1.39P
C2 8 9 1.39P
.MODEL CMOSN NMOS VTO=0.6 KP=194U TOX=8E-9 LAMBDA=0.027778 KF=3.E-24 NLEV=2
.MODEL CMOSP PMOS VTO=-0.8 KP=64.7U TOX=8E-9 LAMBDA=0.055556 KF=3.E-24 NLEV=2
.OPTIONS NOMOD
.TRAN 1U 10M
.FOUR 1K V(9, 10)
.DC VI -1M, 1M, 0.1M
.PLOT DC V(9, 10)
.WIDTH OUT=80
.OPTIONS SPICE
.END
```

```
****** DC TRANSFER CURVES                    TNOM=  27.000 TEMP=  27.000

   VOLT       V(9,10)
(A       )    -2.000E+00    -1.000E-00      0.         1.000E-00    2.000E+00
                    +            +            +            +            +
-1.000E-03  1.80E+00-+------+------+------+------+------+------+------+---A--+-
-9.000E-04  1.78E+00 +      +      +      +      +      +      +      +   A  +
-8.000E-04  1.77E+00 +      +      +      +      +      +      +      +   A  +
-7.000E-04  1.76E+00 +      +      +      +      +      +      +      +   A  +
-6.000E-04  1.74E+00 +      +      +      +      +      +      +      + A    +
-5.000E-04  1.72E+00 +      +      +      +      +      +      +      + A    +
-4.000E-04  1.69E+00 +      +      +      +      +      +      +      + A    +
-3.000E-04  1.65E+00 +      +      +      +      +      +      +      +A     +
-2.000E-04  1.42E+00 +      +      +      +      +      +      +     A+      +
-1.000E-04  7.16E-01 +      +      +      +      +      +  A   +      +      +
 0.          0.      -+------+------+------+------A------+------+------+------+-
 1.000E-04 -7.16E-01 +      +      +   A  +      +      +      +      +      +
 2.000E-04 -1.42E+00 +      +A     +      +      +      +      +      +      +
 3.000E-04 -1.65E+00 +     A+      +      +      +      +      +      +      +
 4.000E-04 -1.69E+00 +    A +      +      +      +      +      +      +      +
 5.000E-04 -1.72E+00 +    A +      +      +      +      +      +      +      +
 6.000E-04 -1.74E+00 +    A +      +      +      +      +      +      +      +
 7.000E-04 -1.76E+00 +   A  +      +      +      +      +      +      +      +
 8.000E-04 -1.77E+00 +   A  +      +      +      +      +      +      +      +
 9.000E-04 -1.78E+00 +   A  +      +      +      +      +      +      +      +
 1.000E-03 -1.80E+00-+---A--+------+------+------+------+------+------+------+-
                    +            +            +            +            +
```

```
****** OPERATING POINT INFORMATION           TNOM=  27.000 TEMP=  27.000

+0:1      = 1.650E+00 0:2      =-1.650E+00 0:3      =  0.
+0:4      =  0.       0:5      = 9.884E-01 0:6      = 3.715E-01
+0:7      =-5.598E-01 0:8      =-5.598E-01 0:9      = 2.916E-03
+0:10     = 2.916E-03 0:11     =-9.397E-01 0:12     =-9.397E-01
+0:13     =  0.       0:14     = 3.800E-01 0:15     =-5.600E-01
+0:16     =-6.700E-01
```

```
******
FOURIER COMPONENTS OF TRANSIENT RESPONSE V(9,10)
DC COMPONENT =  -6.397D-05
HARMONIC  FREQUENCY  FOURIER    NORMALIZED  PHASE      NORMALIZED
  NO        (HZ)     COMPONENT  COMPONENT   (DEG)      PHASE (DEG)

   1     9.999E+02  7.143E-01  1.000E+00   1.764E+02   0.
   2     2.000E+03  7.291E-05  1.021E-04   8.825E+01  -8.814E+01
   3     3.000E+03  8.810E-06  1.233E-05   9.282E+01  -8.357E+01
   4     4.000E+03  9.318E-06  1.304E-05  -8.561E+01  -2.620E+02
   5     5.000E+03  1.470E-06  2.058E-06  -1.024E+02  -2.788E+02
   6     6.000E+03  3.794E-06  5.312E-06   7.440E+01  -1.020E+02
   7     7.000E+03  3.921E-06  5.489E-06   4.849E+00  -1.715E+02
   8     8.000E+03  4.792E-06  6.708E-06   9.902E+01  -7.738E+01
   9     9.000E+03  1.316E-05  1.842E-05  -1.747E+02  -3.511E+02

  TOTAL HARMONIC DISTORTION =    1.058E-02  PERCENT
```

```
FULLY DIFFERENTIAL OP AMP WITH MISMATCH
VDD 1 0 1.65
VSS 2 0 -1.65
VI 3 4 DC 0.941468M SIN (0 1E-4 1K)
VB1 14 0 0.38
VB2 15 0 -0.56
VB3 16 0 -0.67
VCM 13 0 0
M1 7 3 5 1 CMOSP W=77.385U L=1U
M2 8 4 5 1 CMOSP W=76.615U L=1U
M3 7 15 2 2 CMOSN W=4U L=1U
M4 8 15 2 2 CMOSN W=4U L=1U
M5 5 6 1 1 CMOSP W=25U L=1U
M6 9 8 2 2 CMOSN W=16U L=1U
M7 9 14 1 1 CMOSP W=50U L=1U
M9 10 7 2 2 CMOSN W=16U L=1U
M10 10 14 1 1 CMOSP W=50U L=1U
M21 6 9 11 2 CMOSN W=8.4U L=1U
M22 1 13 11 2 CMOSN W=8.4U L=1U
M23 1 13 12 2 CMOSN W=8.4U L=1U
M24 6 10 12 2 CMOSN W=8.4U L=1U
M25 6 6 1 1 CMOSP W=25U L=1U
M26 11 16 2 2 CMOSN W=14U L=1U
M27 12 16 2 2 CMOSN W=14U L=1U
R1 3 0 1G
R2 4 0 1G
C1 7 10 1.39P
C2 8 9 1.39P
.MODEL CMOSN NMOS VTO=0.6 KP=194U TOX=8E-9 LAMBDA=0.027778 KF=3.E-24 NLEV=2
.MODEL CMOSP PMOS VTO=-0.8 KP=64.7U TOX=8E-9 LAMBDA=0.055556 KF=3.E-24 NLEV=2
.OPTIONS NOMOD
.TRAN 1U 10M
.FOUR 1K V(9, 10)
.DC VI -0.05813M, 1.94187M, 0.1M
.PLOT DC V(9, 10)
.WIDTH OUT=80
.OPTIONS SPICE
.END
```

```
****** DC TRANSFER CURVES                    TNOM=  27.000 TEMP=  27.000

   VOLT       V(9,10)
(A       )    -2.000E+00    -1.000E-00      0.         1.000E-00    2.000E+00
                    +            +            +            +            +
-5.813E-05  1.80E+00-+------+------+------+------+------+------+------+---A--+-
 4.187E-05  1.78E+00 +      +      +      +      +      +      +      +   A  +
 1.419E-04  1.77E+00 +      +      +      +      +      +      +      +   A  +
 2.419E-04  1.76E+00 +      +      +      +      +      +      +      +   A  +
 3.419E-04  1.74E+00 +      +      +      +      +      +      +      + A    +
 4.419E-04  1.72E+00 +      +      +      +      +      +      +      + A    +
 5.419E-04  1.69E+00 +      +      +      +      +      +      +      + A    +
 6.419E-04  1.65E+00 +      +      +      +      +      +      +      +A     +
 7.419E-04  1.42E+00 +      +      +      +      +      +      +     A+      +
 8.419E-04  7.16E-01 +      +      +      +      +      +  A   +      +      +
 9.419E-04 -3.71E-04-+------+------+------+------A------+------+------+------+-
 1.042E-03 -7.16E-01 +      +      +   A  +      +      +      +      +      +
 1.142E-03 -1.42E+00 +      +A     +      +      +      +      +      +      +
 1.242E-03 -1.65E+00 +     A+      +      +      +      +      +      +      +
 1.342E-03 -1.69E+00 +    A +      +      +      +      +      +      +      +
 1.442E-03 -1.72E+00 +    A +      +      +      +      +      +      +      +
 1.542E-03 -1.74E+00 +    A +      +      +      +      +      +      +      +
 1.642E-03 -1.76E+00 +   A  +      +      +      +      +      +      +      +
 1.742E-03 -1.77E+00 +   A  +      +      +      +      +      +      +      +
 1.842E-03 -1.78E+00 +   A  +      +      +      +      +      +      +      +
 1.942E-03 -1.80E+00-+---A--+------+------+------+------+------+------+------+-
                    +            +            +            +            +
```

```
****** OPERATING POINT INFORMATION           TNOM=  27.000 TEMP=  27.000

+0:1      = 1.650E+00 0:2      =-1.650E+00 0:3      =  0.
+0:4      =  0.       0:5      = 9.888E-01 0:6      = 3.712E-01
+0:7      =-4.401E-01 0:8      =-5.679E-01 0:9      = 4.291E-01
+0:10     =-1.364E+00 0:11     =-6.577E-01 0:12     =-1.076E+00
+0:13     =  0.       0:14     = 3.800E-01 0:15     =-5.600E-01
+0:16     =-6.700E-01
```

```
******
FOURIER COMPONENTS OF TRANSIENT RESPONSE V(9,10)
DC COMPONENT =   1.793D+00
HARMONIC  FREQUENCY  FOURIER    NORMALIZED  PHASE      NORMALIZED
  NO        (HZ)     COMPONENT  COMPONENT   (DEG)      PHASE (DEG)

   1     9.999E+02  1.196E-02  1.000E+00   1.799E+02   0.
   2     2.000E+03  3.372E-04  2.819E-02   8.962E+01  -9.030E+01
   3     3.000E+03  1.324E-05  1.107E-03  -7.077E-01  -1.806E+02
   4     4.000E+03  7.553E-07  6.314E-05  -8.999E+01  -2.699E+02
   5     5.000E+03  6.191E-08  5.176E-06  -1.763E+02  -3.562E+02
   6     6.000E+03  9.223E-08  7.710E-06   8.223E+01  -9.769E+01
   7     7.000E+03  1.040E-07  8.690E-06  -4.049E+00  -1.839E+02
   8     8.000E+03  8.363E-08  6.991E-06   9.101E+01  -8.891E+01
   9     9.000E+03  3.080E-07  2.575E-05   1.725E+02  -7.341E+00

  TOTAL HARMONIC DISTORTION =    2.821E+00  PERCENT
```

12.4

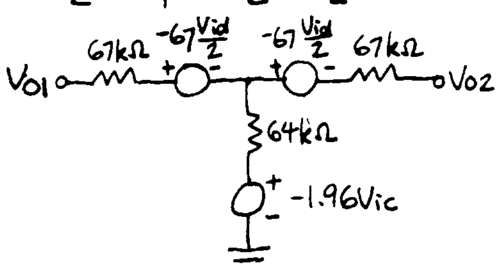
(a) $a_{dm} = -67$

$$\frac{R_{od}}{2} = r_{o1} \| r_{o3} = \frac{V_{A1}}{I_{D1}} \| \frac{|V_{A3}|}{|I_{D3}|}$$
$$= \frac{10}{0.1} \| \frac{20}{0.1} = 67\,k\Omega$$

$a_{cm} = -1.96$

$$R_{oc} = R_{o(down)} \| r_{o3}$$
$$\approx [r_{o1}(g_{m1} r_{o5h})] \| r_{o3}$$
$$= \left[\frac{V_{A1}}{I_{D1}} \frac{2I_{D1}}{V_{ov1}} \frac{V_{A5h}}{I_{D5h}}\right] \| \frac{|V_{A3}|}{|I_{D3}|}$$
$$= \left[\frac{10}{0.1} \frac{2\times 0.1}{0.2} \frac{10}{0.1}\right] \| \frac{20}{0.1}$$
$$= 196\,k\Omega$$

$$\frac{R_{oc}}{2} - \frac{R_{od}}{4} = \frac{196}{2} - \frac{67}{2} = 64\,k\Omega$$



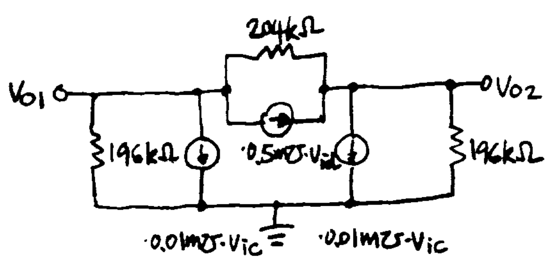
From Figs. 12.8(b) and (c),

$$G_{md} = -\frac{a_{dm}}{R_{od}} = -\frac{-67}{134} = 0.5\,mA/V$$

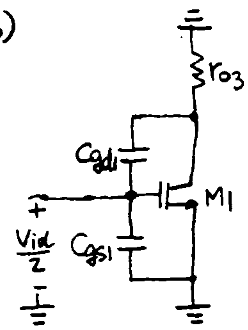
From Figs. 12.9(b) and (c),

$$G_{mc} = -\frac{a_{cm}}{R_{oc}} = -\frac{-1.96}{196} = 10^{-2}\,mA/V$$

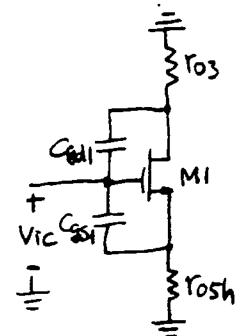
$$R_{od} \| (-2R_{oc}) = 134 \| (-392) = 204\,k\Omega$$



(b)



$$\frac{1}{2} Z_{id} = \frac{1}{sC_{gs1}} \| \frac{1}{s(1-a_{dm})C_{gd1}}$$
$$= \frac{1}{s[C_{gs1} + (1-a_{dm})C_{gd1}]}$$



The gain from V_{ic} to the drain of M1 is $a_{cm} = -1.98$. Its contribution to Z_{ic} is

$$\frac{1}{s(1-a_{cm})C_{gd1}}$$

The gain from V_{ic} to the source of M1 is

$$a_1 = \frac{g_{m1} r_{o5h}}{1 + g_{m1} r_{o5h}}$$

Its contribution to Z_{ic} is

$$\frac{1}{s(1-a_1)C_{gs1}} = \frac{1 + g_{m1} r_{o5h}}{sC_{gs1}} \approx \frac{g_{m1} r_{o5h}}{sC_{gs1}}$$

$$Z_{ic} = \frac{1}{s\left[(1-a_{cm})C_{gd1} + \frac{1}{g_{m1} r_{o5h}} C_{gs1}\right]}$$

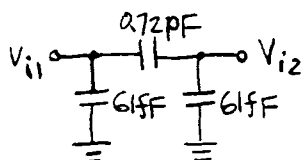
$$C_{gs1} + (1 - a_{dm}) C_{gd1}$$
$$= 180 + (1 + 67) 20$$
$$= 1540\text{fF} = 1.5\text{pF}$$

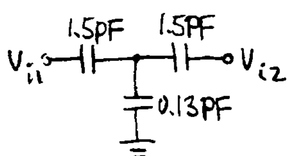
$$(1 - a_{cm}) C_{gd1} + \frac{1}{g_{m1} r_{osh}} C_{gs1}$$
$$= (1 - a_{cm}) C_{gd1} + \frac{V_{ov1}}{2 I_{D1}} \frac{I_{Dsh}}{V_{Ash}} C_{gs1}$$
$$= (1 + 1.98) 20 + \frac{0.2}{2 \times 0.1} \frac{0.1}{10} 180$$
$$= 61\text{fF}$$

$$\frac{Z_{id}}{2} = \frac{1}{S \cdot 1.5\text{pF}}, \quad Z_{ic} = \frac{1}{S \cdot 61\text{fF}}$$

$$Z_{id} \| (-2 Z_{ic}) = \frac{1}{S} \left(\frac{2}{1.5\text{pF}} \| \frac{-2}{61\text{fF}} \right)$$
$$= \frac{1}{S \cdot 0.72\text{pF}}$$

$$\frac{Z_{ic}}{2} - \frac{Z_{id}}{4} = \frac{1}{S} \left(\frac{1}{2 \times 61\text{fF}} - \frac{1}{2 \times 1.5\text{pF}} \right)$$
$$= \frac{1}{S \cdot 0.13\text{pF}}$$





12.5

(a) $a_{dm} = -g_{m1}(r_{o1} \| r_{o3}) = -\frac{2}{V_{ov1}} \frac{V_{A1}|V_{A3}|}{V_{A1}+|V_{A3}|}$

$$= -\frac{2}{0.1}\frac{10\times 20}{10+20} = -134$$

$$\frac{R_{od}}{2} = r_{o1}\|r_{o3} = \frac{V_{A1}}{I_{D1}} \| \frac{|V_{A3}|}{|I_{D3}|} = \frac{10}{0.05} \| \frac{20}{0.05}$$

$$= 134\,k\Omega$$

$$a_{cm} = -\frac{g_{m1}}{1+g_{m1}r_{o5h}}(R_{o(down)} \| r_{o3})$$

$$\approx -\frac{1}{r_{o5h}}(R_{o(down)} \| r_{o3})$$

$$\approx -\frac{1}{V_{A5h}} \frac{V_{A1}\frac{2V_{A5h}}{V_{ov1}}|V_{A3}|}{V_{A1}\frac{2V_{A5h}}{V_{ov1}} + |V_{A3}|}$$

$$= -\frac{1}{10}\frac{10\frac{2\times 10}{0.1}20}{10\frac{2\times 10}{0.1}+20} = -1.98$$

$$R_{oc} = R_{o(down)} \| r_{o3}$$

$$\approx \left(\frac{V_{A1}}{I_{D1}}\frac{2I_{D1}}{V_{ov1}}\frac{V_{A5h}}{I_{D5h}}\right) \| \frac{|V_{A3}|}{|I_{D3}|}$$

$$= \left(\frac{10}{0.05}\frac{2\times 0.05}{0.1}\frac{10}{0.05}\right) \| \frac{20}{0.05}$$

$$= 396\,k\Omega$$

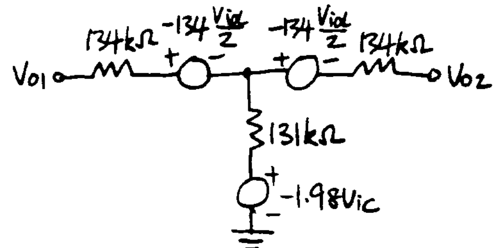
$$\frac{R_{oc}}{2} - \frac{R_{od}}{4} = \frac{396}{2} - \frac{134}{2} = 131\,k\Omega$$

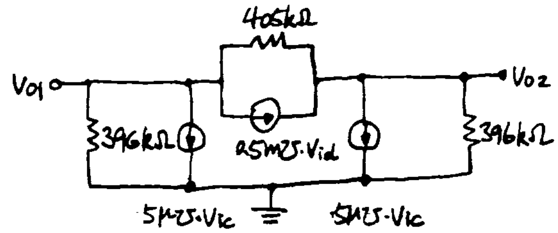
$$G_{md} = -\frac{a_{dm}}{R_{od}} = -\frac{-134}{268} = 0.5\,mA/V$$

$$G_{mc} = -\frac{a_{cm}}{R_{oc}} = -\frac{-1.98}{396} = 5\times 10^{-3}\,mA/V$$

$$= 5\,\mu A/V$$

$$R_{od} \| (-2R_{oc}) = 268 \| (-792) = 405\,k\Omega$$





(b) From 12.4,

$$C_{gs1} + (1-a_{dm})C_{gd1}$$

$$= 180 + (1+134)20$$

$$= 2880\,fF = 2.9\,pF$$

$$(1-a_{cm})C_{gd1} + \frac{1}{g_{m1}r_{o5h}}C_{gs1}$$

$$= (1-a_{cm})C_{gd1} + \frac{V_{ov1}}{2I_{D1}}\frac{I_{D5h}}{V_{A5h}}C_{gs1}$$

$$= (1+1.98)20 + \frac{0.1}{2\times 0.05}\frac{0.05}{10}180$$

$$= 60\,fF$$

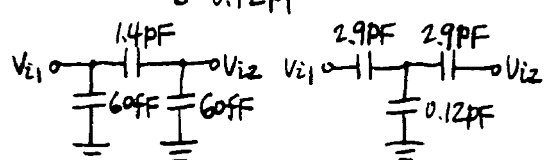
$$\frac{Z_{id}}{2} = \frac{1}{s\cdot 2.9\,pF},\quad Z_{ic} = \frac{1}{s\cdot 60\,fF}$$

$$Z_{id} \| (-2Z_{ic}) = \frac{1}{s}\left(\frac{2}{2.9\,pF} \| \frac{-2}{60\,fF}\right)$$

$$= \frac{1}{s\cdot 1.4\,pF}$$

$$\frac{Z_{ic}}{2} - \frac{Z_{id}}{4} = \frac{1}{s}\left(\frac{1}{2\times 60\,fF} - \frac{1}{2\times 2.9\,pF}\right)$$

$$= \frac{1}{s\cdot 0.12\,pF}$$



12-6

(c) $a_{cmc} = -g_{msh}(R_{o(down)} \| r_{o3})$

$$\approx -\frac{2}{V_{ovsh}} \frac{V_{A1}\frac{2V_{A5h}}{V_{ov1}}|V_{A3}|}{V_{A1}\frac{2V_{A5h}}{V_{ov1}} + |V_{A3}|}$$

$$= -\frac{2}{0.1} \frac{10\frac{2\times10}{0.1}20}{10\frac{2\times10}{0.1}+20}$$

$$= -396$$

12.6

(a) $a_{cm} = -\frac{g_{m1}}{1+g_{m1}r_{osh}}(R_{o(down)} \| r_{o3})$

$$\approx -\frac{1}{r_{osh}}(R_{o(down)} \| r_{o3})$$

$$\approx -\frac{1}{V_{A5h}} \frac{V_{A1}\frac{2V_{A5h}}{V_{ov1}}|V_{A3}|}{V_{A1}\frac{2V_{A5h}}{V_{ov1}} + |V_{A3}|}$$

$$= -\frac{1}{10} \frac{10\frac{2\times10}{0.1}20}{10\frac{2\times10}{0.1}+20} = -1.98$$

$a_{cmc} = -g_{msh}(R_{o(down)} \| r_{o3})$

$$\approx -\frac{2}{V_{osh}} \frac{V_{A1}\frac{2V_{A5h}}{V_{ov1}}|V_{A3}|}{V_{A1}\frac{2V_{A5h}}{V_{ov1}} + |V_{A3}|}$$

$$= -\frac{2}{0.1} \frac{10\frac{2\times10}{0.1}20}{10\frac{2\times10}{0.1}+20} = -396$$

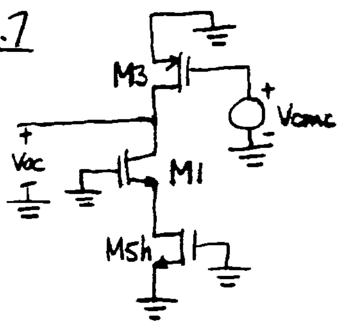
$$a'_{cm} = \frac{a_{cm}}{1 - a_{cms}a_{cmc}} = \frac{-1.98}{1-1\times(-396)}$$

$$= -5\times10^{-3}$$

(b)

```
OP AMP
VDD 1 0 2.5
VSS 2 0 -2.5
VI 3 0 AC 1
VB 9 0 1.7
M1 7 3 5 2 CMOSN W=57U L=0.8U
M2 8 4 5 2 CMOSN W=57U L=0.8U
M3 7 9 1 1 CMOSP W=124U L=0.8U
M4 8 9 1 1 CMOSP W=124U L=0.8U
M5 5 6 2 2 CMOSN W=113U L=0.8U
ECMC 6 0 POLY(2) (7,0) (8,0) -1.7 0.5 0.5
R1 3 0 1G
R2 4 0 1G
R12 3 4 0
.MODEL CMOSN NMOS VTO=0.7  KP=127U TOX=150E-10 LAMBDA=0.1  KF=3.E-24 NLEV=2
.MODEL CMOSP PMOS VTO=-0.7 KP=58U  TOX=150E-10 LAMBDA=0.05 KF=3.E-24 NLEV=2
.OPTIONS NOMOD
.AC DEC 5 100 100MEG
.PLOT V(7) V(8)
.WIDTH OUT=80
.OPTIONS SPICE
.END

******  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000

+0:1       = 2.500E+00 0:2       =-2.500E+00 0:3       =   0.
+0:4       =   0.      0:5       =-8.017E-01 0:6       =-1.701E+00
+0:7       =-1.818E-03 0:8       =-1.818E-03 0:9       = 1.700E+00

**** MOSFETS

ELEMENT  0:M1       0:M2       0:M3       0:M4       0:M5
MODEL    0:CMOSN    0:CMOSN    0:CMOSP    0:CMOSP    0:CMOSN
 ID       5.057E-05  5.057E-05 -5.057E-05 -5.057E-05  1.011E-04
 IBS     -1.698E-14 -1.698E-14   0.         0.         0.
 IBD     -2.498E-14 -2.498E-14  2.502E-14  2.502E-14 -1.698E-14
 VGS      8.017E-01  8.017E-01 -8.000E-01 -8.000E-01  7.982E-01
 VDS      7.999E-01  7.999E-01 -2.501E+00 -2.501E+00  1.698E+00
 VBS     -1.698E+00 -1.698E+00   0.         0.         0.
 VTH      7.000E-01  7.000E-01 -7.000E-01 -7.000E-01  7.000E-01
 VDSAT    1.017E-01  1.017E-01 -1.000E-01 -1.000E-01  9.818E-02
 BETA     9.773E-03  9.773E-03  1.011E-02  1.011E-02  2.099E-02
 GAM EFF   0.         0.         0.         0.         0.
 GM       9.942E-04  9.942E-04  1.011E-03  1.011E-03  2.060E-03
 GDS      4.683E-06  4.683E-06  2.247E-06  2.247E-06  8.646E-06
 GMB       0.         0.         0.         0.         0.
 CDTOT    1.120E-16  1.120E-16  7.618E-16  7.618E-16  4.712E-16
 CGTOT    8.653E-14  8.653E-14  1.893E-13  1.893E-13  1.728E-13
 CSTOT    6.998E-14  6.998E-14  1.522E-13  1.522E-13  1.387E-13
 CBTOT    1.643E-14  1.643E-14  3.629E-14  3.629E-14  3.361E-14
 CGS      6.998E-14  6.998E-14  1.522E-13  1.522E-13  1.387E-13
 CGD      1.120E-16  1.120E-16  7.618E-16  7.618E-16  4.712E-16

******  AC ANALYSIS                      TNOM=  27.000 TEMP=  27.000

LEGEND:

 A: V(7)
 B: V(8)

     FREQ       V(7)
(AB        )     4.166E-03      4.168E-03      4.170E-03      4.172E-03      4.174E-03
                     +              +              +              +              +
 1.000E+02  4.17E-03-+------+---2--+------+------+------+------+------+-
 1.584E+02  4.17E-03 +      +   2  +      +      +      +      +      +
 2.511E+02  4.17E-03 +      +   2  +      +      +      +      +      +
 3.981E+02  4.17E-03 +      +   2  +      +      +      +      +      +
 6.309E+02  4.17E-03 +      +   2  +      +      +      +      +      +
 1.000E+03  4.17E-03 +      +   2  +      +      +      +      -      +
 1.584E+03  4.17E-03 +      +   2  +      +      +      +      +      +
 2.511E+03  4.17E-03 +      +   2  +      +      +      +      -      +
 3.981E+03  4.17E-03 +      +   2  +      +      +      +      +      +
 6.309E+03  4.17E-03 +      +   2  +      +      +      +      +      +
 1.000E+04  4.17E-03-+------+---2--+------+------+------+------+------+-
 1.584E+04  4.17E-03 +      +   2  +      +      +      +      +      +
 2.511E+04  4.17E-03 +      +   2  +      +      +      +      +      +
 3.981E+04  4.17E-03 +      +   2  +      +      +      +      +      +
 6.309E+04  4.17E-03 +      +   2  +      +      +      +      +      +
 1.000E+05  4.17E-03 +      +   2  +      +      +      +      +      +
 1.584E+05  4.17E-03 +      +   2  +      +      +      +      +      +
 2.511E+05  4.17E-03 +      +   2  +      +      +      +      +      +
 3.981E+05  4.17E-03 +      +   2  +      +      +      +      -      +
 6.309E+05  4.17E-03 +      +   2  +      +      +      +      -      +
 1.000E+06  4.17E-03-+------+---2--+------+------+------+------+------+-
 1.584E+06  4.17E-03 +      +   2  -      +      +      +      +      +
 2.511E+06  4.17E-03 +      +   2  +      +      +      +      +      +
 3.981E+06  4.17E-03 +      +   2  +      +      +      +      +      +
 6.309E+06  4.17E-03 +      +   2  -      +      +      +      +      +
 1.000E+07  4.17E-03 +      +   2  -      +      +      +      +      +
 1.584E+07  4.17E-03 +      +    2 -      +      +      +      +      +
 2.511E+07  4.17E-03 +      +     2+      +      +      +      +      +
 3.981E+07  4.17E-03 +      +      + 2    +      +      +      +      +
 6.309E+07  4.17E-03 +      +      -      +  2   -      +      +      +
 1.000E+08  4.17E-03-+------+------+------+------+------+---2--+------+-
                     +             +             +             +             +
```

12.7



$$a_{cmc} = -g_{m3}(R_{o(down)} \| r_{o3})$$

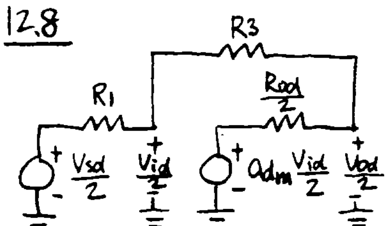
$$\approx -g_{m3}[r_{o1}(g_{m1} r_{osh}) \| r_{o3}]$$

$$= -\frac{2|I_{D3}|}{|V_{ov3}|}\left[\frac{V_{A1}}{I_{D1}}\frac{2I_{D1}}{V_{ov1}}\frac{V_{Ash}}{I_{Dsh}} \| \frac{|V_{A3}|}{|I_{D3}|}\right]$$

$$= -\frac{2}{|V_{ov3}|}\frac{V_{A1}\frac{2V_{Ash}}{V_{ov1}}|V_{A3}|}{V_{A1}\frac{2V_{Ash}}{V_{ov1}}+|V_{A3}|}$$

$$= -\frac{2}{0.1}\frac{10\frac{2\times 10}{0.1}20}{10\frac{2\times 10}{0.1}+20} = -396$$

12.8



$$\frac{V_{id}}{2} = a_{dm}\frac{V_{id}}{2}\frac{R1}{R_1+R_3+R_{od}/2} + \frac{V_{sd}}{2}\frac{R3+R_{od}/2}{R1+R3+R_{od}/2}$$

$$\frac{V_{id}}{2}\left(1-a_{dm}\frac{R1}{R1+R3+R_{od}/2}\right) = \frac{V_{sd}}{2}\frac{R3+R_{od}/2}{R1+R3+R_{od}/2}$$

$$\frac{V_{id}}{2} = \frac{R3+R_{od}/2}{R1+R3+R_{od}/2-a_{dm}R_1}\frac{V_{sd}}{2}$$

$$\frac{V_{id}}{2} = \frac{V_{sd}}{2}\frac{R3}{R1+R3} + \frac{V_{od}}{2}\frac{R1}{R1+R3}$$

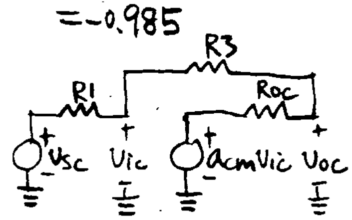
$$V_{od} = \frac{R1+R3}{R1}V_{id} - \frac{R3}{R1}V_{sd}$$

$$= \frac{R1+R3}{R1}\frac{R3+R_{od}/2}{R1+R3+R_{od}/2-a_{dm}R1}V_{sd} - \frac{R3}{R1}V_{sd}$$

$$A_{dm} = \frac{R1+R3}{R1}\frac{R3+R_{od}/2}{R1+R3+R_{od}/2-a_{dm}R1} - \frac{R3}{R1}$$

$$= \frac{100M+100M}{100M}\frac{100M+134k}{100M+100M+134k+134\times 100M} - \frac{100M}{100M}$$

$$= -0.985$$



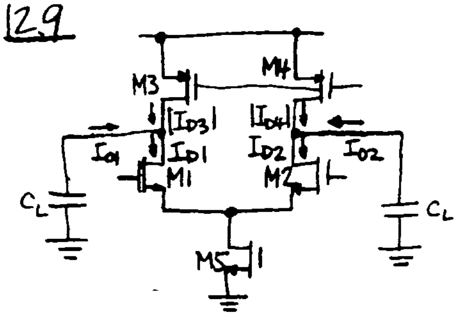
For Acm, replace Rod/2 with Roc, and adm with acm,

$$A_{cm} = \frac{R1+R3}{R1}\frac{R3+R_{oc}}{R1+R3+R_{oc}-a_{cm}R1} - \frac{R3}{R1}$$

$$= \frac{100M+100M}{100M}\frac{100M+396k}{100M+100M+396k+1.98\times 100M} - \frac{100M}{100M}$$

$$= -0.496$$

12.9



$I_{o1} = I_{D1} - |I_{D3}|$

$I_{o2} = I_{D2} - |I_{D4}|$

$I_{o1} - I_{o2} = I_{D1} - I_{D2} - (|I_{D3}| - |I_{D4}|)$

$= I_{D1} - I_{D2}$

For I_{D1} or I_{D2}, the maximum is 200μA,

$$\frac{dV_{od}}{dt} = \frac{200\mu A}{C_L} = \frac{200\mu A}{5pF} = 40V/\mu s$$

12.10

When M1, M2 are off,

$$\left.\frac{dV_{oc}}{dt}\right|_{+} = \frac{|I_{D3}|}{C_L} = \frac{100\mu A}{5pF} = 20V/\mu s$$

When M3, M4 are off,

$$\left.\frac{dV_{oc}}{dt}\right|_{-} = -\frac{I_{D1}}{C_L} = -\frac{100\mu A}{5pF} = -20V/\mu s$$

12.11

$$\frac{dV_{od}}{dt} = \frac{|I_{D5}|}{C} = \frac{200\mu A}{1.39pF} = 144V/\mu s$$

12.12

(a)

$$|a_{cmso}| = \frac{|V_{cms}|}{|V_{oc}|} = 0.95\frac{g_{m21}}{g_{m23}}$$

$$= 0.95\frac{\sqrt{2k_n'(W/L)_{21}I_{D21}}}{\sqrt{2k_p'(W/L)_{23}|I_{D23}|}}$$

$$= 0.95\sqrt{\frac{k_n'}{k_p'}}\sqrt{\frac{(W/L)_{21}}{(W/L)_{23}}} = 0.95\sqrt{\frac{194}{66}}\sqrt{\frac{(W/L)_{21}}{(W/L)_{23}}}$$

$= 0.71$

Choose M23 to match M5

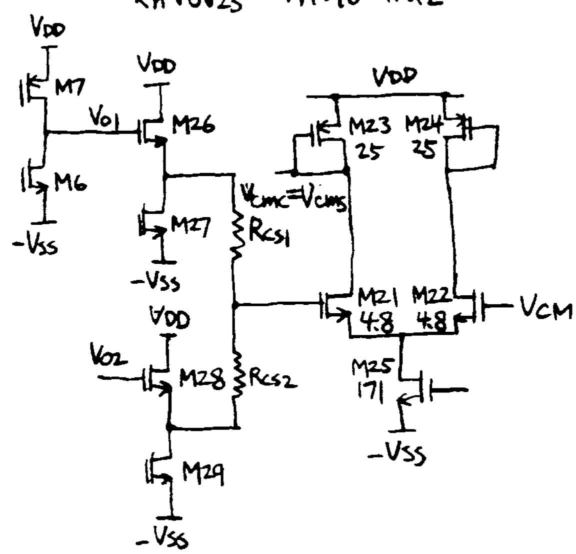
$\therefore (W/L)_{23} = (W/L)_5 = 25$

$$(W/L)_{21} = (W/L)_{23}\left(\frac{0.71}{0.95}\sqrt{\frac{66}{194}}\right)^2 = 4.8$$

Choose M25 to have an overdrive of 0.2V

$I_{D25} = 400\mu A$

$$(W/L)_{25} = \frac{2I_{D25}}{k_n' V_{ov25}^2} = \frac{2\times 400\times 10^{-6}}{194\times 10^{-6}\times 0.2^2} = 171$$



(b), (c)

$$|V_{ov7}| = \sqrt{\frac{2|I_{D7}|}{k_p'(W/L)_7}} = \sqrt{\frac{2\times 100\times 10^{-6}}{66\times 10^{-6}\times 50}} = 0.25V$$

Similarly, $V_{ov6} = 0.25V$, $V_{ov21} = 0.66V$

Consider the output stage

$-V_{SS} + V_{ov6} < V_{o1} < V_{DD} - |V_{ov7}|$

$-1.65 + 0.25 < V_{o1} < 1.65 - 0.25$

$-1.4V < V_{o1} < 1.4V$

Consider the source follower

$-V_{SS} + V_{GS26} + V_{ov27} < V_{o1} < V_{DD} + V_{t26}$

$-1.65 + 0.8 + 0.2 < V_{o1} < 1.65 + 0.6$

$-0.65V < V_{o1} < 2.25V$

12.12 continued

Consider the CMS amplifier

$-V_{SS}+V_{OV25}+V_{GS21}+V_{GS26}<V_{O1}$

$-1.65+0.2+(0.6+0.66)+0.8<V_{O1}$

$(V_{GS21}=V_{t21}+V_{OV21})$

$V_{O1}>0.61V$

$\therefore 0.61V<V_{O1}<1.4V$

To give the maximum symmetric output swing, choose the DC value of V_{O1} to be

$\frac{1.4+0.61}{2}=1V$

$V_{CM}=1V-V_{GS26}=1-0.8=0.2V$

The output swing is $V_{O1p}=\frac{1.4-0.61}{2}$

$=0.4V$

For the differential pair M21, M22 to work properly,

$0.95V_{O1p}<\sqrt{2}V_{OV21}$

should be satisfied.

$0.95V_{O1p}=0.95\times0.4=0.38V$

$\sqrt{2}V_{OV21}=\sqrt{2}\times0.66=0.93V$

Therefore, the CMS amplifier will be active over the entire output range.

12.12 (d)

```
FULLY DIFFERENTIAL OP AMP WITH CMFB
VDD 1 0 1.65
VSS 2 0 -1.65
VI 3 4 DC 0 SIN (0 100U 1K)
EVCOM 30 0 POLY(2) (9, 0) (10, 0) 0 0.5 0.5
VB1 14 0 0.38
VB2 15 0 -0.56
VB3 29 0 -0.85
VCM 24 0 0.2
M1 7 3 5 1 CMOSP W=77U L=1U
M2 8 4 5 1 CMOSP W=77U L=1U
M3 7 15 2 2 CMOSN W=4U L=1U
M4 8 15 2 2 CMOSN W=4U L=1U
M5 5 6 1 1 CMOSP W=25U L=1U
M6 9 8 2 2 CMOSN W=16U L=1U
M7 9 14 1 1 CMOSP W=50U L=1U
M9 10 7 2 2 CMOSN W=16U L=1U
M10 10 14 1 1 CMOSP W=50U L=1U
M21 6 23 27 2 CMOSN W=4.8U L=1U
M22 26 24 27 2 CMOSN W=4.8U L=1U
M23 6 6 1 1 CMOSP W=25U L=1U
M24 26 26 1 1 CMOSP W=25U L=1U
M25 27 28 2 2 CMOSN W=96U L=1U
VB4 28 0 -0.85
M26 1 9 21 21 CMOSN W=14U L=1U
M27 21 29 2 2 CMOSN W=14U L=1U
M28 1 10 22 22 CMOSN W=14U L=1U
M29 22 29 2 2 CMOSN W=14U L=1U
RCS1 21 23 15K
RCS2 22 23 15K
R1 3 0 1G
R2 4 0 1G
C1 7 10 1.39P
C2 8 9 1.39P
.MODEL CMOSN NMOS VTO=0.6 KP=194U TOX=8E-9 LAMBDA=0.027778 KF=3.E-24 MLEV=2
.MODEL CMOSP PMOS VTO=-0.8 KP=64.7U TOX=8E-9 LAMBDA=0.055556 KF=3.E-24 MLEV=2
.OPTIONS NOPAGE NOMOD
.OP
.TRAN 0.02M 1M
.PLOT TRAN V(30)
.WIDTH OUT=80
.OPTIONS SPICE
.END
```

****** OPERATING POINT INFORMATION   TNOM= 27.000 TEMP= 27.000

+0:1 = 1.650E+00	0:2 =-1.650E+00	0:3 = 0.	
+0:4 = 0.	0:5 = 9.882E-01	0:6 = 3.717E-01	
+0:7 =-5.792E-01	0:8 =-5.792E-01	0:9 = 1.030E+00	
+0:10 = 1.030E+00	0:14 = 3.800E-01	0:15 =-5.600E-01	
+0:21 = 2.288E-01	0:22 = 2.288E-01	0:23 = 2.288E-01	
+0:24 = 2.000E-01	0:26 = 3.928E-01	0:27 =-1.011E+00	
+0:28 =-8.500E-01	0:29 =-8.500E-01	0:30 = 1.030E+00	

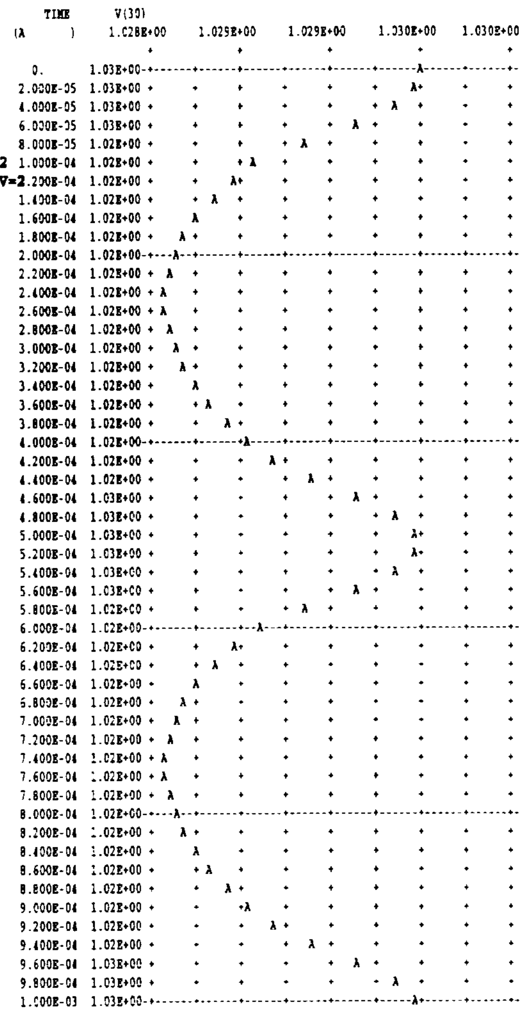
**** MOSFETS

ELEMENT	0:M1	0:M2	0:M3	0:M4	0:M5	0:M6
MODEL	0:CMOSP	0:CMOSP	0:CMOSN	0:CMOSN	0:CMOSP	0:CMOSN
ID	-9.593E-05	-9.593E-05	9.593E-05	9.593E-05	-1.919E-04	3.696E-04
IBS	6.618E-15	6.618E-15	0.	0.	0.	0.
IBD	2.229E-14	2.229E-14	-1.071E-14	-1.071E-14	6.618E-15	-2.680E-14
VGS	-9.882E-01	-9.882E-01	1.090E+00	1.090E+00	-1.278E+00	1.070E+00
VDS	-1.567E+00	-1.567E+00	1.070E+00	1.070E+00	-6.618E-01	2.680E+00
VBS	6.618E-01	6.618E-01	0.	0.	0.	0.
VTH	-8.000E-01	-8.000E-01	6.000E-01	6.000E-01	-8.000E-01	6.000E-01
VDSAT	-1.882E-01	-1.882E-01	4.900E-01	4.900E-01	-4.783E-01	4.708E-01
BETA	5.416E-03	5.416E-03	7.991E-04	7.991E-04	1.677E-03	3.335E-03
GAM EFF	0.	0.	0.	0.	0.	0.
GM	1.019E-03	1.019E-03	3.916E-04	3.916E-04	8.022E-04	1.570E-03
GDS	4.903E-06	4.903E-06	2.588E-06	2.588E-06	1.028E-05	9.556E-06
GMB	0.	0.	0.	0.	0.	0.
CDTOT	6.946E-16	6.946E-16	2.465E-17	2.465E-17	9.522E-17	2.468E-16
CGTOT	2.516E-13	2.516E-13	1.209E-14	1.209E-14	7.560E-14	4.861E-14
CSTOT	2.216E-13	2.216E-13	1.151E-14	1.151E-14	7.194E-14	4.604E-14
CBTOT	2.929E-14	2.929E-14	5.547E-16	5.547E-16	3.562E-15	2.321E-15
CGS	2.216E-13	2.216E-13	1.151E-14	1.151E-14	7.194E-14	4.604E-14
CGD	6.946E-16	6.946E-16	2.465E-17	2.465E-17	9.522E-17	2.468E-16

ELEMENT	0:M7	0:M9	0:M10	0:M21	0:M22	0:M23
MODEL	0:CMOSP	0:CMOSN	0:CMOSP	0:CMOSN	0:CMOSN	0:CMOSP
ID	-3.696E-04	3.696E-04	-3.696E-04	1.982E-04	1.809E-04	-1.982E-04
IBS	0.	0.	0.	-6.385E-15	-6.385E-15	0.
IBD	6.200E-15	-2.680E-14	6.200E-15	-2.022E-14	-2.043E-14	1.278E-14
VGS	-1.270E+00	1.070E+00	-1.270E+00	1.240E+00	1.211E+00	-1.278E+00
VDS	-6.200E-01	2.680E+00	-6.200E-01	1.383E+00	1.404E+00	-1.278E+00
VBS	0.	0.	0.	-6.385E-01	-6.385E-01	0.
VTH	-8.000E-01	6.000E-01	-8.000E-01	6.000E-01	6.000E-01	-8.000E-01
VDSAT	-4.700E-01	4.708E-01	-4.700E-01	6.403E-01	6.115E-01	-4.783E-01
BETA	3.346E-03	3.335E-03	3.346E-03	9.670E-04	9.675E-04	1.732E-03
GAM EFF	0.	0.	0.	0.	0.	0.
GM	1.573E-03	1.570E-03	1.573E-03	6.191E-04	5.916E-04	8.287E-04
GDS	1.985E-05	9.556E-06	1.985E-05	5.302E-06	4.836E-06	1.028E-05
GMB	0.	0.	0.	0.	0.	0.
CDTOT	1.784E-16	2.468E-16	1.784E-16	3.821E-17	3.879E-17	1.839E-16
CGTOT	1.513E-13	4.861E-14	1.513E-13	1.434E-14	1.437E-14	7.569E-14
CSTOT	1.439E-13	4.604E-14	1.439E-13	1.381E-14	1.381E-14	7.194E-14
CBTOT	7.266E-15	2.321E-15	7.266E-15	4.900E-16	5.169E-16	3.562E-15
CGS	1.439E-13	4.604E-14	1.439E-13	1.381E-14	1.381E-14	7.194E-14
CGD	1.784E-16	2.468E-16	1.784E-16	3.821E-17	3.879E-17	1.839E-16

ELEMENT	0:M24	0:M25	0:M26	0:M27	0:M28	0:M29
MODEL	0:CMOSP	0:CMOSN	0:CMOSN	0:CMOSN	0:CMOSN	0:CMOSN
ID	-1.809E-04	3.791E-04	5.715E-05	5.715E-05	5.715E-05	5.715E-05
IBS	0.	0.	0.	0.	0.	0.
IBD	1.257E-14	-6.385E-15	-1.421E-14	-1.879E-14	-1.421E-14	-1.879E-14
VGS	-1.257E+00	8.000E-01	8.012E-01	8.000E-01	8.012E-01	8.000E-01
VDS	-1.257E+00	6.385E-01	1.421E+00	1.878E+00	1.421E+00	1.878E+00
VBS	0.	0.	0.	0.	0.	0.
VTH	-8.000E-01	6.000E-01	6.000E-01	6.000E-01	6.000E-01	6.000E-01
VDSAT	-4.572E-01	2.000E-01	2.012E-01	2.000E-01	2.012E-01	2.000E-01
BETA	1.730E-03	1.895E-02	2.823E-03	2.858E-03	2.823E-03	2.858E-03
GAM EFF	0.	0.	0.	0.	0.	0.
GM	7.912E-04	3.791E-03	5.681E-04	5.715E-04	5.681E-04	5.715E-04
GDS	9.393E-06	1.035E-05	1.527E-06	1.509E-06	1.527E-06	1.509E-06
GMB	0.	0.	0.	0.	0.	0.
CDTOT	1.809E-16	3.528E-16	1.145E-16	1.514E-16	1.145E-16	1.514E-16
CGTOT	7.587E-14	3.110E-13	4.539E-14	4.545E-14	4.539E-14	4.545E-14
CSTOT	7.194E-14	2.763E-13	4.029E-14	4.029E-14	4.029E-14	4.029E-14
CBTOT	3.746E-15	3.439E-14	4.985E-15	5.015E-15	4.985E-15	5.015E-15
CGS	7.194E-14	2.763E-13	4.029E-14	4.029E-14	4.029E-14	4.029E-14
CGD	1.809E-16	3.528E-16	1.145E-16	1.514E-16	1.145E-16	1.514E-16

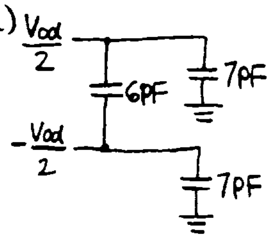
****** TRANSIENT ANALYSIS   TNOM= 27.000 TEMP= 27.000



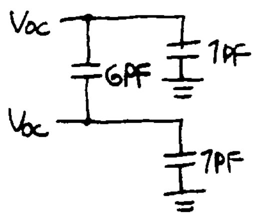
12.13

Symmetry or the Miller effect can be used.

(a)

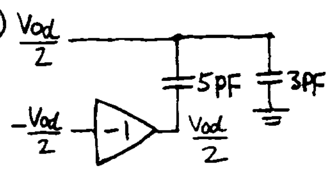


$C_{Ld} = 6 + 7/2$
$= 9.5\text{PF}$

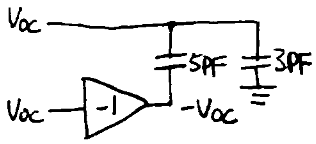


$C_{Lc} = 7\text{PF}$

(b)

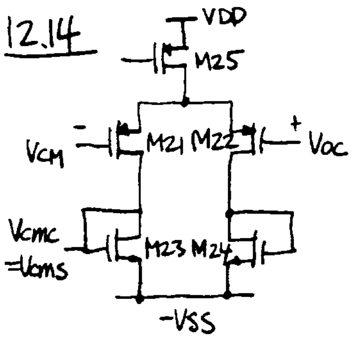


$C_{Ld} = 3/2$
$= 1.5\text{PF}$



$C_{Lc} = 5 \times 2 + 3$
$= 13\text{PF}$

12.14



(a) $C_{ox} = \frac{\varepsilon_o}{t_{ox}} = \frac{3.9\times8.85\times10^{-12}}{150\times10^{-10}} = 2.3\times10^{-3} F/m^2$

$k_n' = \mu_n C_{ox} = 550\times10^{-4}\times2.3\times10^{-3}$
$= 1.26\times10^{-4} A/V^2 = 126\mu A/V^2$

$\left(\frac{W}{L}\right)_{23} = \frac{2I_{D23}}{k_n' V_{ov23}^2} = \frac{2\times0.2\times10^{-3}}{126\times10^{-6}\times0.2^2} = 79$

$W_{23} = 79 L_{eff} = 63\mu m$

$C_{gs} = \frac{2}{3}WLC_{ox} + WC_{oL}$
$= \frac{2}{3}\times63\times10^{-6}\times0.8\times10^{-6}\times2.3\times10^{-3}$
$+63\times0.12\times10^{-15}$
$= 7.7\times10^{-14} + 7.6\times10^{-15}$
$= 8.4\times10^{-14}F = 84fF$

$g_{m23} = \frac{2I_{D23}}{V_{ov23}} = \frac{2\times0.2\times10^{-3}}{0.2} = 2\times10^{-3} A/V$

The RC time constant is

$\frac{1}{g_{m23}}(C_{gs}+90fF) = \frac{1}{2\times10^{-3}A/V}(84+90)fF$
$= 8.7\times10^{-11}s = 87ps$

(b) $\left(\frac{W}{L}\right)_{23} = 20$

$W = 16\mu m$

$C_{gs} = 21fF$

$g_{m23} = 5\times10^{-4} A/V$

The time constant is

$\frac{1}{5\times10^{-4}A/V}(21+90)fF = 2.2\times10^{-10}s$
$= 0.22ns$

(c) The size of M23 becomes $\frac{1}{4}$ the original size, hence the transconductance and gate-source capacitance, the contribution from which is the same as in the original case. The contribution from the 90fF capacitance becomes greater, so does the total time constant.

12.15

(a) $V_{OC} = V_{G3} = V_{DD} - |V_{tp}| - |V_{ov3}|$
$= 2.5 - 0.6 - 0.2 = 1.7V$

(b) $a_{dm} = -g_{m1}(r_{o1}||r_{o3}||20k)$
$= -\frac{2I_{D1}}{V_{ov1}}\left(\frac{V_{A1}}{I_{D1}}||\frac{|V_{A3}|}{|I_{D3}|}||20k\right)$
$= -\frac{2\times100\times10^{-6}}{0.2}\left(\frac{10}{100\times10^{-6}}||\frac{20}{100\times10^{-6}}||20k\right)$
$= -1\times10^{-3}(100k||200k||20k)$
$= -15.4$

$a_{cm} = -\frac{g_{m1}}{1+g_{m1}r_{osh}}(R_{o(down)}||r_{o3})$
$\approx -\frac{1}{r_{osh}}(R_{o(down)}||r_{o3})$
$= -1.96$

In the DM half circuit, the load is 20kΩ in parallel with $r_{o1}||r_{o3}$, and is less than the original load, $r_{o1}||r_{o3}$, hence the smaller DM gain. The CM circuit is not affected by the 20kΩ resistor, so the CM gain is unchanged.

12.16

(a) $a_{dm} = -g_{m1}(r_{o1} \| r_{o3}) = -66.7$

$a_{cm} = -g_{m1}(r_{o1} \| r_{o3}) = -66.7$

(b) The DM and CM half circuits are the same as the DM half circuit in the first example in Section 12.4.1; the two gains are identical to the DM gain in that example.

12.17

(a) $a_{dm0} = -g_{m1}(r_{o1} \| r_{o3})$

$$p_{dm} = -\frac{1}{2(r_{o1} \| r_{o3})C_{Ld}}$$

$$f_{dm,unity} = \frac{|a_{dm0}||p_{dm}|}{2\pi} = \frac{1}{2\pi}\frac{g_{m1}}{2C_{Ld}}$$

$$= \frac{1}{2\pi}\frac{1}{2C_{Ld}}\frac{2I_{D1}}{V_{ov1}}$$

$$= \frac{1}{2\pi}\frac{1}{2\times2\times10^{-12}}\frac{2\times100\times10^{-6}}{0.25}$$

$$= 3.2\times10^7\,Hz = 32\,MHz$$

$a_{cmc0} = -g_{m5h}(R_{o(down)} \| r_{o3})$

$$p_{cmc} = -\frac{1}{(R_{o(down)} \| r_{o3})C_{Lc}}$$

$$f_{cmc,unity} = \frac{|a_{cmc0}||p_{cmc}|}{2\pi} = \frac{1}{2\pi}\frac{g_{m5h}}{C_{Lc}}$$

$$= \frac{1}{2\pi}\frac{1}{C_{Lc}}\frac{2I_{D5h}}{V_{ov5h}}$$

$$= \frac{1}{2\pi}\frac{1}{2\times10^{-12}}\frac{2\times100\times10^{-6}}{0.25}$$

$$= 6.4\times10^7\,Hz = 64\,MHz$$

(b) $$f_{dm,unity} = \frac{1}{2\pi}\frac{1}{2C_{Ld}}\frac{2I_{D1}}{V_{ov1}}$$

$$= \frac{1}{2\pi}\frac{1}{2\times4\times10^{-12}}\frac{2\times100\times10^{-6}}{0.25}$$

$$= 1.6\times10^7\,Hz = 16\,MHz$$

$$f_{cmc,unity} = \frac{1}{2\pi}\frac{1}{C_{Lc}}\frac{2I_{D5h}}{V_{ov5h}}$$

$$= \frac{1}{2\pi}\frac{1}{2\times10^{-12}}\frac{2\times100\times10^{-6}}{0.25}$$

$$= 6.4\times10^7\,Hz = 64\,MHz$$

(c) To set $f'_{cmc,unity} = f_{dm,unity}$ in (a), replace M5 with M52

$g_{m52h} = \frac{1}{2}g_{m5h}$

$$\frac{2I_{D52h}}{V_{ov52h}} = \frac{1}{2}\frac{2I_{D5h}}{V_{ov5h}}$$

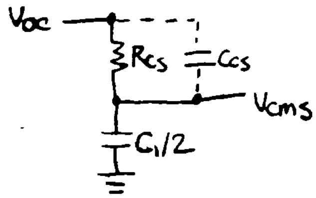
$$I_{D52h} = \frac{1}{2}I_{D5h}\frac{V_{ov52h}}{V_{ov5h}} = \frac{1}{2}100\,\mu A\,\frac{0.25V}{0.25V}$$

$= 50\,\mu A$

$I_{D52} = 100\,\mu A$

$I_{D51} = 100\,\mu A$

12.18



With $C_{cs}=0$,

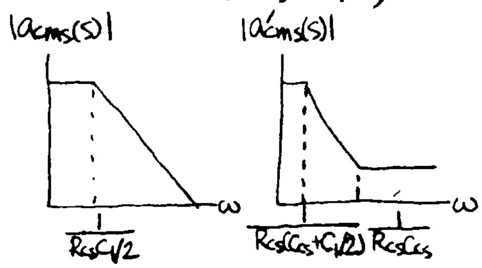
$$a_{cms}(s)=\frac{V_{cms}(s)}{V_{oc}(s)}=\frac{\frac{1}{jsC_1/2}}{R_{cs}+\frac{1}{jsC_1/2}}$$

$$=\frac{1}{1+jsR_{cs}C_1/2}$$

With $C_{cs}\neq 0$,

$$a'_{cms}(s)=\frac{\frac{1}{jsC_1/2}}{R_{cs}\|\frac{1}{jsC_{cs}}+\frac{1}{jsC_1/2}}$$

$$=\frac{1+jsR_{cs}C_{cs}}{1+jsR_{cs}(C_{cs}+C_1/2)}$$



The C_{cs} capacitors introduce a LHP zero and keep $|a'_{cms}(s)|$ from dropping at high frequencies; therefore, CMFB still works at high frequencies. Also, the phase shift of $a'_{cms}(s)$ approaches 0 at high frequencies.

12.19

In the triode region,

$$I_d=\frac{k_n'}{2}\frac{W}{L}[2(V_{gs}-V_t)V_{ds}-V_{ds}^2]$$

$$g_{m,t}=\frac{\partial I_d}{\partial V_{gs}}=\frac{k_n'}{2}\frac{W}{L}2V_{ds}=k_n'\frac{W}{L}V_{ds}$$

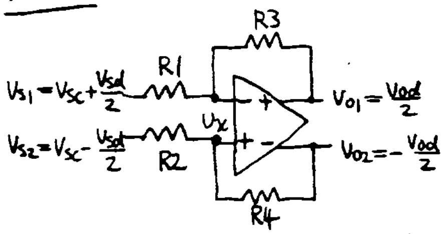
In the active region,

$$g_{m,a}=k_n'\frac{W}{L}(V_{gs}-V_t)$$

In the triode region, $V_{ds}<V_{gs}-V_t$

$g_{m,t}<g_{m,a}$

12.20



The opamp has infinite DM gain, so the voltages at its two inputs are the same and denoted by v_x.

It has zero CM gain, so there is no CM voltage at the outputs

$V_{o1}=\frac{V_{od}}{2}$, $V_{o2}=-\frac{V_{od}}{2}$

$$V_x=\frac{R_3}{R_1+R_3}\left(V_{sc}+\frac{V_{sd}}{2}\right)+\frac{R_1}{R_1+R_3}\frac{V_{od}}{2}$$

$$V_x=\frac{R_4}{R_2+R_4}\left(V_{sc}-\frac{V_{sd}}{2}\right)-\frac{R_2}{R_2+R_4}\frac{V_{od}}{2}$$

$$\left(\frac{R_1}{R_1+R_3}+\frac{R_2}{R_2+R_4}\right)\frac{V_{od}}{2}$$
$$=\left(\frac{R_4}{R_2+R_4}-\frac{R_3}{R_1+R_3}\right)V_{sc}-\left(\frac{R_3}{R_1+R_3}+\frac{R_4}{R_2+R_4}\right)\frac{V_{sd}}{2}$$

$$A_{dm}=\frac{V_{od}}{V_{sd}}=-\frac{\frac{R_3}{R_1+R_3}+\frac{R_4}{R_2+R_4}}{\frac{R_1}{R_1+R_3}+\frac{R_2}{R_2+R_4}}$$

$$A_{cm}=\frac{V_{oc}}{V_{sc}}=0$$

$$A_{cm\text{-}dm}=\frac{V_{od}}{V_{sc}}=2\frac{\frac{R_4}{R_2+R_4}-\frac{R_3}{R_1+R_3}}{\frac{R_1}{R_1+R_3}+\frac{R_2}{R_2+R_4}}$$

$$A_{dm\text{-}cm}=\frac{V_{oc}}{V_{sd}}=0$$

(a)

$$A_{dm}=-\frac{\frac{5}{1+5}+\frac{5}{1+5}}{\frac{1}{1+5}+\frac{1}{1+5}}=-5$$

$$A_{cm}=0$$

$$A_{cm\text{-}dm}=2\frac{\frac{5}{1+5}-\frac{5}{1+5}}{\frac{1}{1+5}+\frac{1}{1+5}}=0$$

$$A_{dm\text{-}cm}=0$$

(b)

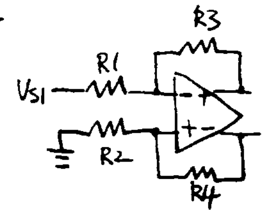
$$A_{dm}=-\frac{\frac{5}{1.01+5}+\frac{5}{0.99+5}}{\frac{1.01}{1.01+5}+\frac{0.99}{0.99+5}}\approx-5$$

$$A_{cm}=0$$

$$A_{cm\text{-}dm}=2\frac{\frac{5}{0.99+5}-\frac{5}{1.01+5}}{\frac{1.01}{1.01+5}+\frac{0.99}{0.99+5}}=0.017$$

$$A_{dm\text{-}cm}=0$$

12.21



$V_{s1}=0.2\sin(100t)$ (V)

$V_{s2}=0$

$V_{sc}=\frac{V_{s1}+V_{s2}}{2}=0.1\sin(100t)$ (V)

$V_{sd}=V_{s1}-V_{s2}=0.2\sin(100t)$ (V)

$V_{od}=A_{dm}V_{sd}+A_{cm\text{-}dm}V_{sc}$
$=-5\times0.2\sin(100t)+0=-1\sin(100t)$ (V)

$V_{oc}=A_{cm}V_{sc}+A_{dm\text{-}cm}V_{sd}=0$

$V_{o1}=V_{oc}+\frac{V_{od}}{2}=-0.5\sin(100t)$ (V)

$V_{o2}=V_{oc}-\frac{V_{od}}{2}=0.5\sin(100t)$ (V)

$V_{id}=0$ $(a_{dm}=\infty)$

$V_{ic}=\frac{R_3}{R_1+R_3}V_{sc}+\frac{R_1}{R_1+R_3}V_{oc}$
$=\frac{5}{1+5}0.1\sin(100t)+\frac{1}{1+5}\cdot0$
$=0.083\sin(100t)$ (V)

$V_{i1}=V_{ic}+\frac{V_{id}}{2}=0.083\sin(100t)$ (V)

$V_{i2}=V_{ic}-\frac{V_{id}}{2}=0.083\sin(100t)$ (V)

12.22

(a)
$$V_{cms} = \frac{R_{cs2}}{R_{cs1}+R_{cs2}} V_{o1} + \frac{R_{cs1}}{R_{cs1}+R_{cs2}} V_{o2}$$
$$= \frac{R_{cs2}}{R_{cs1}+R_{cs2}} (V_{oc} + \frac{1}{2} V_{od}) +$$
$$\frac{R_{cs1}}{R_{cs1}+R_{cs2}} (V_{oc} - \frac{1}{2} V_{od})$$
$$= V_{oc} + \frac{1}{2} \frac{R_{cs2}-R_{cs1}}{R_{cs1}+R_{cs2}} V_{od}$$

$$a_{cms} = 1$$
$$a_{dm-cms} = \frac{1}{2} \frac{R_{cs2}-R_{cs1}}{R_{cs1}+R_{cs2}} = \frac{1}{2} \frac{9.9-10.1}{10.1+9.9} = -5\times10^{-3}$$

(b)
$$V_{od} = a_{dm} V_{id}$$
$$V_{oc} = a_{cm} V_{ic} + a_{cmc} V_{cmc}$$
$$V_{cmc} = V_{cms} = a_{cms} V_{oc} + a_{dm-cms} V_{od}$$
$$V_{oc} = a_{cm} V_{ic} + a_{cmc} a_{cms} V_{oc} +$$
$$a_{cmc} a_{dm-cms} V_{od}$$
$$= \frac{a_{cm}}{1-a_{cmc} a_{cms}} V_{ic} + \frac{a_{cmc} a_{dm-cms}}{1-a_{cmc} a_{cms}} a_{dm} V_{id}$$

$$\frac{V_{od}}{V_{id}} = a_{dm} = -66.7$$
$$\frac{V_{oc}}{V_{ic}} = \frac{a_{cm}}{1-a_{cmc} a_{cms}} = \frac{-1.96}{1-(-196)1} = -1\times10^{-2}$$
$$\frac{V_{od}}{V_{ic}} = 0$$
$$\frac{V_{oc}}{V_{id}} = \frac{a_{cmc} a_{dm-cms}}{1-a_{cmc} a_{cms}} a_{dm} = \frac{-196(-5\times10^{-3})}{1-(-196)1}(-66.7)$$
$$= -0.33$$

12.22 (c)

```
OP AMP
.SUBCKT AMP (3 4 7 8 6)
VDD 1 0 2.5
VSS 2 0 -2.5
VB 9 0 1.6
M1 7 3 5 2 CMOSN W=28.5U L=0.8U
M2 8 4 5 2 CMOSN W=28.5U L=0.8U
M3 7 9 1 1 CMOSP W=62U L=0.8U
M4 8 9 1 1 CMOSP W=62U L=0.8U
M5 5 6 2 2 CMOSN W=56.5U L=0.8U
ECMC 6 0 POLY(2) (7,0) (8,0) -1.6 0.495 0.505
R1 3 0 1G
R2 4 0 1G
.MODEL CMOSN NMOS VTO=0.7  KP=127U TOX=150E-10 LAMBDA=0.1 KF=3.E-24 NLEV=2
.MODEL CMOSP PMOS VTO=-0.7 KP=58U  TOX=150E-10 LAMBDA=0.05 KF=3.E-24 NLEV=2
.ENDS AMP

* AMPLIFIER WITH DM INPUT

XDM (13 14 17 18 16) AMP
VI1D 13 51 0 AC 0.5
EI2D 14 51 13 51 -1

* AMPLIFIER WITH CM INPUT

XCM (23 24 27 28 26) AMP
EI1C 23 51 13 51 2
EI2C 24 51 23 51 1

VIC 51 0 0

* AMPLIFIER WITH DM OUTPUT

XDMO (33 34 37 38 36) AMP
VO1D 37 0 0 AC 0.5
EO2D 38 0 37 0 -1

* AMPLIFIER WITH CM OUTPUT

XCMO (43 44 47 48 46) AMP
EO1C 47 0 37 0 2
EO2C 48 0 47 0 1

.OPTIONS NOMOD
* CALCULATE THE MAGNITUDE OF THE DIFFERENCES INSTEAD OF
* THE DIFFERENCE OF THE MAGNITUDES
.OPTIONS ACOUT=0
.AC DEC 1 1 10
.PRINT AC VM(17) VM(18) VP(17) VP(18)
.PRINT AC VM(27) VM(28) VP(27) VP(28)
.PRINT AC VM(17, 18) VM(17) VM(18)
.PRINT AC VM(27, 28) VM(27) VM(28)
.MEASURE AC A_DM FIND VM(17, 18) AT=1
.MEASURE AC A_CM FIND PAR('(VM(27)+VM(28))/2.') AT=1
.MEASURE AC A_CM2DM FIND VM(27, 28) AT=1
.MEASURE AC A_DM2CM FIND PAR('(VM(17)-VM(18))/2.') AT=1
.MEASURE AC A_CMS FIND VM(46) AT=1
.MEASURE AC A_DM2CMS FIND VM(36) AT=1
* SUBTRACTION IS USED IN THE EQUATION FOR A_DM2CM BECAUSE
* THE TWO OUTPUTS HAVE OPPOSITE POLARITY.
.MEASURE A_DM/A_CM PARAM='A_DM/A_CM'
.MEASURE A_DM/A_CM2DM PARAM='A_DM/A_CM2DM'
.MEASURE A_DM/A_DM2CM PARAM='A_DM/A_DM2CM'
.WIDTH OUT=80
.OPTIONS SPICE
.END
```

```
******  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000

+0:13     =  0.         0:14      =  0.         0:16      =-1.602E+00
+0:17     =-2.780E-03   0:18      =-2.780E-03   0:23      =  0.
+0:24     =  0.         0:26      =-1.602E+00   0:27      =-2.780E-03
+0:28     =-2.780E-03   0:33      =  0.         0:34      =  0.
+0:36     =-1.600E+00   0:37      =  0.         0:38      =  0.
+0:43     =  0.         0:44      =  0.         0:46      =-1.600E+00
+0:47     =  0.         0:48      =  0.         0:51      =  0.
+1:1      = 2.500E+00   1:2       =-2.500E+00   1:5       =-9.025E-01
+1:9      = 1.600E+00   2:1       = 2.500E+00   2:2       =-2.500E+00
+2:5      =-9.025E-01   2:9       = 1.600E+00   3:1       = 2.500E+00
+3:2      =-2.500E+00   3:5       =-9.053E-01   3:9       = 1.600E+00
+4:1      = 2.500E+00   4:2       =-2.500E+00   4:5       =-9.053E-01
+4:9      = 1.600E+00
```

```
**** MOSFETS

SUBCKT   XDM        XDM        XDM        XDM        XDM        XCM
ELEMENT  1:M1       1:M2       1:M3       1:M4       1:M5       2:M1
MODEL    1:CMOSN    1:CMOSN    1:CMOSP    1:CMOSP    1:CMOSN    2:CMOSN
 ID       1.011E-04  1.011E-04 -1.011E-04 -1.011E-04  2.023E-04  1.011E-04
 IBS     -1.597E-14 -1.597E-14  0.         0.         0.        -1.597E-14
 IBD     -2.497E-14 -2.497E-14  2.503E-14  2.503E-14 -1.597E-14 -2.497E-14
 VGS      9.025E-01  9.025E-01 -9.000E-01 -9.000E-01  8.972E-01  9.025E-01
 VDS      8.998E-01  8.998E-01 -2.502E+00 -2.502E+00  1.597E+00  8.998E-01
 VBS     -1.597E+00 -1.597E+00  0.         0.         0.        -1.597E+00
 VTH      7.000E-01  7.000E-01 -7.000E-01 -7.000E-01  7.000E-01  7.000E-01
 VDSAT    2.025E-01  2.025E-01 -2.000E-01 -2.000E-01  1.972E-01  2.025E-01
 BETA     4.931E-03  4.931E-03  5.057E-03  5.057E-03  1.040E-02  4.931E-03
 GAM EFF  0.         0.         0.         0.         0.         0.
 GM       9.988E-04  9.988E-04  1.011E-03  1.011E-03  2.052E-03  9.988E-04
 GDS      9.280E-06  9.280E-06  4.495E-06  4.495E-06  1.744E-05  9.280E-06
 GMB      0.         0.         0.         0.         0.         0.
 CDTOT    6.297E-17  6.297E-17  3.810E-16  3.810E-16  2.216E-16  6.297E-17
 CGTOT    3.936E-14  3.936E-14  8.598E-14  8.598E-14  7.835E-14  3.936E-14
 CSTOT    3.499E-14  3.499E-14  7.612E-14  7.612E-14  6.937E-14  3.499E-14
 CBTOT    4.302E-15  4.302E-15  9.476E-15  9.476E-15  8.756E-15  4.302E-15
 CGS      3.499E-14  3.499E-14  7.612E-14  7.612E-14  6.937E-14  3.499E-14
 CGD      6.297E-17  6.297E-17  3.810E-16  3.810E-16  2.216E-16  6.297E-17

SUBCKT   XCM        XCM        XCM        XCM        XDMO       XDMO
ELEMENT  2:M2       2:M3       2:M4       2:M5       3:M1       3:M2
MODEL    2:CMOSN    2:CMOSP    2:CMOSP    2:CMOSN    3:CMOSN    3:CMOSN
 ID       1.011E-04 -1.011E-04 -1.011E-04  2.023E-04  1.040E-04  1.040E-04
 IBS     -1.597E-14  0.         0.         0.        -1.595E-14 -1.595E-14
 IBD     -2.497E-14  2.503E-14  2.503E-14 -1.597E-14 -2.500E-14 -2.500E-14
 VGS      9.025E-01 -9.000E-01 -9.000E-01  8.972E-01  9.053E-01  9.053E-01
 VDS      8.998E-01 -2.502E+00 -2.502E+00  1.597E+00  9.053E-01  9.053E-01
 VBS     -1.597E+00  0.         0.         0.        -1.594E+00 -1.594E+00
 VTH      7.000E-01 -7.000E-01 -7.000E-01  7.000E-01  7.000E-01  7.000E-01
 VDSAT    2.025E-01 -2.000E-01 -2.000E-01  1.972E-01  2.053E-01  2.053E-01
 BETA     4.931E-03  5.057E-03  5.057E-03  1.040E-02  4.934E-03  4.934E-03
 GAM EFF  0.         0.         0.         0.         0.         0.
 GM       9.988E-04  1.011E-03  1.011E-03  2.052E-03  1.013E-03  1.013E-03
 GDS      9.280E-06  4.495E-06  4.495E-06  1.744E-05  9.536E-06  9.536E-06
 GMB      0.         0.         0.         0.         0.         0.
 CDTOT    6.297E-17  3.810E-16  3.810E-16  2.216E-16  6.336E-17  6.336E-17
 CGTOT    3.936E-14  8.598E-14  8.598E-14  7.835E-14  3.930E-14  3.930E-14
 CSTOT    3.499E-14  7.612E-14  7.612E-14  6.937E-14  3.499E-14  3.499E-14
 CBTOT    4.302E-15  9.476E-15  9.476E-15  8.756E-15  4.244E-15  4.244E-15
 CGS      3.499E-14  7.612E-14  7.612E-14  6.937E-14  3.499E-14  3.499E-14
 CGD      6.297E-17  3.810E-16  3.810E-16  2.216E-16  6.336E-17  6.336E-17

SUBCKT   XDMO       XDMO       XDMO       XCMO       XCMO       XCMO
ELEMENT  3:M3       3:M4       3:M5       4:M1       4:M2       4:M3
MODEL    3:CMOSP    3:CMOSP    3:CMOSN    4:CMOSN    4:CMOSN    4:CMOSP
 ID      -1.011E-04 -1.011E-04  2.080E-04  1.040E-04  1.040E-04 -1.011E-04
 IBS      0.         0.         0.        -1.595E-14 -1.595E-14  0.
 IBD      2.500E-14  2.500E-14 -1.595E-14 -2.500E-14 -2.500E-14  2.500E-14
 VGS     -9.000E-01 -9.000E-01  9.000E-01  9.053E-01  9.053E-01 -9.000E-01
 VDS     -2.500E+00 -2.500E+00  1.594E+00  9.053E-01  9.053E-01 -2.500E+00
 VBS      0.         0.         0.        -1.594E+00 -1.594E+00  0.
 VTH     -7.000E-01 -7.000E-01  7.000E-01  7.000E-01  7.000E-01 -7.000E-01
 VDSAT   -2.000E-01 -2.000E-01  2.000E-01  2.053E-01  2.053E-01 -2.000E-01
 BETA     5.057E-03  5.057E-03  1.040E-02  4.934E-03  4.934E-03  5.057E-03
 GAM EFF  0.         0.         0.         0.         0.         0.
 GM       1.011E-03  1.011E-03  2.080E-03  1.013E-03  1.013E-03  1.011E-03
 GDS      4.495E-06  4.495E-06  1.794E-05  9.536E-06  9.536E-06  4.495E-06
 GMB      0.         0.         0.         0.         0.         0.
 CDTOT    3.806E-16  3.806E-16  2.212E-16  6.336E-17  6.336E-17  3.806E-16
 CGTOT    8.598E-14  8.598E-14  7.823E-14  3.930E-14  3.930E-14  8.598E-14
 CSTOT    7.612E-14  7.612E-14  6.937E-14  3.499E-14  3.499E-14  7.612E-14
 CBTOT    9.476E-15  9.476E-15  8.635E-15  4.244E-15  4.244E-15  9.476E-15
 CGS      7.612E-14  7.612E-14  6.937E-14  3.499E-14  3.499E-14  7.612E-14
 CGD      3.806E-16  3.806E-16  2.212E-16  6.336E-17  6.336E-17  3.806E-16

SUBCKT   XCMO       XCMO
ELEMENT  4:M4       4:M5
MODEL    4:CMOSP    4:CMOSN
 ID      -1.011E-04  2.080E-04
 IBS      0.         0.
 IBD      2.500E-14 -1.595E-14
 VGS     -9.000E-01  9.000E-01
 VDS     -2.500E+00  1.594E+00
 VBS      0.         0.
 VTH     -7.000E-01  7.000E-01
 VDSAT   -2.000E-01  2.000E-01
 BETA     5.057E-03  1.040E-02
 GAM EFF  0.         0.
 GM       1.011E-03  2.080E-03
 GDS      4.495E-06  1.794E-05
 GMB      0.         0.
 CDTOT    3.806E-16  2.212E-16
 CGTOT    8.598E-14  7.823E-14
 CSTOT    7.612E-14  6.937E-14
 CBTOT    9.476E-15  8.635E-15
 CGS      7.612E-14  6.937E-14
 CGD      3.806E-16  2.212E-16
```

```
 A_DM=  7.2509E+01
 A_CM=  8.3867E-03
 A_CM2DM=   .0000E+00
 A_DM2CM=  3.6092E-01
 A_CMS=  1.0000E+00
 A_DM2CMS=  5.0000E-03
 A_DM/A_CM=  8.6457E+03
 A_DM/A_CM2DM=  7.2509E+29
 A_DM/A_DM2CM=  2.0090E+02
```

12.23

(a) $I_{DS1} = I_{D1} + I_{D2} + I_{D13} - I_{DS2}$

$= 100 + 100 + 20 - 100 = 120\mu A$

$(W/L)_{S1} = (W/L)_{14}\dfrac{I_{DS1}}{I_{D14}} = \dfrac{16}{0.8}\dfrac{120}{100} = \dfrac{19.2}{0.8}$

$|I_{D12}| = |I_{D13}| = 20\mu A$

$(W/L)_{12} = (W/L)_{11}\dfrac{|I_{D12}|}{|I_{D11}|} = \dfrac{96}{1.4}\dfrac{20}{100} = \dfrac{19.2}{1.4}$

(c) $SR = \dfrac{dV_{od}}{dt} = 2\dfrac{I_{BIAS}}{C_L} = 2\dfrac{100\mu A}{4pF} = 50V/\mu s$

(d) Use $k_n' = 1.96\times10^{-4} A/V^2$, $k_p' = 6.6\times10^{-5} A/V^2$

$V_{tn} = 0.6V$

$V_{ov2} = \sqrt{\dfrac{2I_D}{k_n'(W/L)}} = \sqrt{\dfrac{2\times100\times10^{-6}}{1.96\times10^{-4}\times 640.8}} = 0.11V$

Similarly, $|V_{ov4}| = 0.21V$

$V_{ov13} = 0.34V$

$V_{ov21} = 0.45V$

$V_{omax} = V_{DD} - |V_{ov4}| = 1.65 - 0.21 = 1.44V$

$V_{omin} = V_{ic} - (V_{tn} + V_{ov2}) + (V_{tn} + V_{ov13}) - V_{tn}$

$= V_{ic} - V_{ov2} + V_{ov13} - V_{tn}$

$= -0.65 - 0.11 + 0.34 - 0.6$

$= -1.02V$

$-1.02V < V_o < 1.44V$

For the CMFB to work properly,

$V_{CM} - \sqrt{2}V_{ov21} < V_o < V_{CM} + \sqrt{2}V_{ov21}$

$-0.65 - \sqrt{2}\,0.45 < V_o < -0.65 + \sqrt{2}\,0.45$

$-1.29V < V_o < -0.01V$

$\therefore -1.02V < V_o < -0.01V$

$V_{o1max} = -0.65 - (-1.02) = 0.37V$

$V_{odmax} = 2\times0.37 = 0.74V$

12.23 (b)

```
FULLY DIFFERENTIAL OP AMP
.SUBCKT AMP (15 16 17 18)
VDD 1 0 1.65
VSS 2 0 -1.65
VCM 12 0 -0.65
IDC 14 9 -100U
M1 5 15 3 2 CMOSN W=64U L=0.8U
M2 6 16 3 2 CMOSN W=64U L=0.8U
M1C 17 4 5 2 CMOSN W=64U L=0.8U
M2C 18 4 6 2 CMOSN W=64U L=0.8U
M3 17 9 1 1 CMOSP W=96U L=1.4U
M4 18 9 1 1 CMOSP W=96U L=1.4U
M11 9 9 1 1 CMOSP W=96U L=1.4U
M12 4 9 1 1 CMOSP W=19.2U L=1.4U
M13 4 4 3 2 CMOSN W=1.4U L=0.8U
M14 14 14 2 2 CMOSN W=16U L=0.8U
M21 2 18 10  1 CMOSP W=6U L=0.8U
M22 13 12 10 1 CMOSP W=6U L=0.8U
M23 13 12 11 1 CMOSP W=6U L=0.8U
M24 2 17 11 1 CMOSP W=6U L=0.8U
M25 13 13 2 2 CMOSN W=16U L=0.8U
M26 10 9 1 1 CMOSP W=96U L=1.4U
M27 11 9 1 1 CMOSP W=96U L=1.4U
M51 3 14 2 2 CMOSN W=19.2U L=0.8U
M52 3 13 2 2 CMOSN W=16U L=0.8U
.MODEL CMOSN NMOS LEVEL=3
+ TOX=0.8000E-08 XJ=0.150000U TPG=1 PHI=0.600000
+ DELTA=2.1370E-01 LD=9.0003E-08 VTO=0.60 GAMMA=0.5947
+ UO=450.  THETA=1.9240E-01 RSH=1.7260E+01 KP=1.96E-04
+ NSUB=1.2706E+17 NFS=6.0410E+11 VMAX=1.8610E+05 ETA=2.1370E-02
+ KAPPA=8.4220E-02 CGDO=3.5E-10 CGSO=3.5E-10
+ CGBO=3.0251E-10 CJ=5.2E-04  MJ=0.59 CJSW=1.2E-10
+ MJSW=0.31 PB=0.98
+ ACM=3 HDIF=0.4U
.MODEL CMOSP PMOS LEVEL=3
+ TOX=0.8000E-08 XJ=0.150000U TPG=-1 PHI=0.600000
+ DELTA=2.0729E-01 LD=9.0000E-08 VTO=-0.80 GAMMA=0.5200
+ UO=137.3 THETA=1.6710E-01 RSH=3.6310E+00 KP=6.6E-05
+ NSUB=9.7132E+16 NFS=5.9890E+11 VMAX=3.0560E+05 ETA=1.8760E-02
+ KAPPA=5.9230E+00 CGDO=3.5E-10 CGSO=3.5E-10
+ CGBO=3.1661E-10 CJ=9.1191E-04 MJ=0.49 CJSW=1.2E-10
+ MJSW=0.201 PB=0.96
+ ACM=3 HDIF=0.4U
.ENDS AMP

* AMPLIFIER WITH DM INPUT

XDM (21 22 23 24) AMP
VI1D 21 19 0 AC 0.5
EI2D 22 19 21 19 -1

* AMPLIFIER WITH CM INPUT

XCM (31 32 33 34) AMP
EI1C 31 19 21 19 2
EI2C 32 19 31 19 1

VIC 19 0 -0.65
.OPTIONS NOMOD
* CALCULATE THE MAGNITUDE OF THE DIFFERENCES INSTEAD OF
* THE DIFFERENCE OF THE MAGNITUDES
.OPTIONS ACOUT=0
.AC DEC 1 1 10
.PRINT AC VM(23) VM(24) VP(23) VP(24)
.PRINT AC VM(33) VM(34) VP(33) VP(34)
.PRINT AC VM(23, 24) VM(23) VM(24)
.PRINT AC VM(33, 34) VM(33) VM(34)
.MEASURE AC A_DM FIND VM(23, 24) AT=1
.MEASURE AC A_CM FIND PAR('(VM(33)+VM(34))/2.') AT=1
.MEASURE AC A_CM2DM FIND VM(33, 34) AT=1
.MEASURE AC A_DM2CM FIND PAR('(VM(23)-VM(24))/2.') AT=1
* SUBTRACTION IS USED IN THE EQUATION FOR A_DM2CM BECAUSE
* THE TWO OUTPUTS HAVE OPPOSITE POLARITY.
.MEASURE A_DM/A_CM PARAM='A_DM/A_CM'
.MEASURE A_DM/A_CM2DM PARAM='A_DM/A_CM2DM'
.MEASURE A_DM/A_DM2CM PARAM='A_DM/A_DM2CM'
.OPTIONS SPICE
.WIDTH OUT=80
.END

****** OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000

+0:19       =-6.500E-01 0:21        =-6.500E-01 0:22        =-6.500E-01
+0:23       =-5.383E-01 0:24        =-5.383E-01 0:31        =-6.500E-01
+0:32       =-6.500E-01 0:33        =-5.383E-01 0:34        =-5.383E-01
+1:1        = 1.650E+00 1:2         =-1.650E+00 1:3         =-1.386E+00
+1:4        =-4.152E-01 1:5         =-1.190E+00 1:6         =-1.190E+00
+1:9        = 6.588E-01 1:10        = 7.433E-01 1:11        = 7.433E-01
+1:12       =-6.500E-01 1:13        =-8.566E-01 1:14        =-8.810E-01
+2:1        = 1.650E+00 2:2         =-1.650E+00 2:3         =-1.386E+00
+2:4        =-4.152E-01 2:5         =-1.190E+00 2:6         =-1.190E+00
+2:9        = 6.588E-01 2:10        = 7.433E-01 2:11        = 7.433E-01
+2:12       =-6.500E-01 2:13        =-8.566E-01 2:14        =-8.810E-01

**** MOSFETS

SUBCKT   XDM         XDM         XDM         XDM         XDM         XDM
ELEMENT  1:M1        1:M2        1:M1C       1:M2C       1:M3        1:M4
MODEL    1:CMOSN     1:CMOSN     1:CMOSN     1:CMOSN     1:CMOSP     1:CMOSP
 ID       1.023E-04   1.023E-04   1.023E-04   1.023E-04  -1.023E-04  -1.023E-04
 IBS     -2.636E-15  -2.636E-15  -4.594E-15  -4.594E-15   1.548E-20   1.548E-20
 IBD     -4.594E-15  -4.594E-15  -1.112E-14  -1.112E-14   2.188E-14   2.188E-14
 VGS      7.365E-01   7.365E-01   7.754E-01   7.754E-01  -9.912E-01  -9.912E-01
 VDS      1.959E-01   1.959E-01   6.523E-01   6.523E-01  -2.188E+00  -2.188E+00
 VBS     -2.635E-01  -2.635E-01  -4.594E-01  -4.594E-01   0.          0.
 VTH      6.259E-01   6.259E-01   6.656E-01   6.656E-01  -7.733E-01  -7.733E-01
 VDSAT    9.503E-02   9.503E-02   9.563E-02   9.563E-02  -1.875E-01  -1.875E-01
 BETA     1.912E-02   1.912E-02   1.912E-02   1.912E-02   4.978E-03   4.978E-03
 GAM EFF  5.270E-01   5.270E-01   5.218E-01   5.218E-01   4.909E-01   4.909E-01
 GM       1.807E-03   1.807E-03   1.820E-03   1.820E-03   9.225E-04   9.225E-04
 GDS      3.055E-05   3.055E-05   3.076E-05   3.076E-05   1.936E-06   1.936E-06
 GMB      4.560E-04   4.560E-04   4.081E-04   4.081E-04   2.671E-04   2.671E-04
 CDTOT    5.743E-14   5.743E-14   5.172E-14   5.172E-14   9.103E-14   9.103E-14
 CGTOT    1.592E-13   1.592E-13   1.592E-13   1.592E-13   4.046E-13   4.046E-13
 CSTOT    1.742E-13   1.742E-13   1.716E-13   1.716E-13   4.639E-13   4.639E-13
 CBTOT    7.279E-14   7.279E-14   6.453E-14   6.453E-14   1.511E-13   1.511E-13
 CGS      1.366E-13   1.366E-13   1.366E-13   1.366E-13   3.706E-13   3.706E-13
 CGD      2.240E-14   2.240E-14   2.240E-14   2.240E-14   3.360E-14   3.360E-14

SUBCKT   XDM         XDM         XDM         XDM         XDM         XDM
ELEMENT  1:M11       1:M12       1:M13       1:M14       1:M21       1:M22
MODEL    1:CMOSP     1:CMOSP     1:CMOSN     1:CMOSN     1:CMOSP     1:CMOSP
 ID      -1.000E-04  -2.037E-05   2.037E-05   1.000E-04  -3.905E-05  -6.079E-05
 IBS      1.513E-20   1.541E-20  -2.636E-15  -4.315E-19   9.067E-15   9.067E-15
 IBD      9.912E-15   2.065E-14  -1.235E-14  -7.690E-15   3.300E-14   2.507E-14
 VGS     -9.912E-01  -9.912E-01   9.712E-01   7.690E-01  -1.281E+00  -1.393E+00
 VDS     -9.912E-01  -2.065E+00   9.712E-01   7.690E-01  -2.393E+00  -1.599E+00
 VBS      0.          0.         -2.635E-01   0.          9.067E-01   9.067E-01
 VTH     -7.756E-01  -7.737E-01   6.177E-01   5.414E-01  -9.043E-01  -9.161E-01
 VDSAT   -1.855E-01  -1.870E-01   2.908E-01   1.870E-01  -3.418E-01  -4.310E-01
 BETA     4.980E-03   9.956E-04   3.746E-04   4.529E-03   5.871E-04   5.749E-04
 GAM EFF  4.909E-01   4.909E-01   5.270E-01   5.354E-01   4.404E-01   4.404E-01
 GM       9.110E-04   1.841E-04   1.065E-04   8.345E-04   2.003E-04   2.431E-04
 GDS      1.909E-06   3.862E-07   1.860E-06   1.429E-05   3.334E-06   4.291E-06
 GMB      2.639E-04   5.336E-05   2.656E-05   2.527E-04   3.036E-05   3.647E-05
 CDTOT    1.032E-13   1.851E-14   1.260E-15   1.370E-14   5.419E-15   5.694E-15
 CGTOT    4.046E-13   8.123E-14   3.665E-15   3.993E-14   1.510E-14   1.510E-14
 CSTOT    4.639E-13   9.293E-14   3.984E-15   4.483E-14   1.739E-14   1.739E-14
 CBTOT    1.633E-13   3.099E-14   1.954E-15   1.897E-14   8.103E-15   8.378E-15
 CGS      3.706E-13   7.413E-14   2.988E-15   3.415E-14   1.280E-14   1.280E-14
 CGD      3.360E-14   6.720E-15   4.900E-16   5.600E-15   2.100E-15   2.100E-15

SUBCKT   XDM         XDM         XDM         XDM         XDM         XDM
ELEMENT  1:M23       1:M24       1:M25       1:M26       1:M27       1:M51
MODEL    1:CMOSP     1:CMOSP     1:CMOSN     1:CMOSP     1:CMOSP     1:CMOSN
 ID      -6.079E-05  -3.905E-05   1.216E-04  -9.984E-05  -9.984E-05   1.115E-04
 IBS      9.067E-15   9.067E-15  -5.246E-19   1.510E-20   1.510E-20  -4.011E-19
 IBD      2.507E-14   3.300E-14  -7.933E-15   9.067E-15   9.067E-15  -2.635E-15
 VGS     -1.393E+00  -1.281E+00   7.934E-01  -9.912E-01  -9.912E-01   7.690E-01
 VDS     -1.599E+00  -2.393E+00   7.934E-01  -9.067E-01  -9.067E-01   2.635E-01
 VBS      9.067E-01   9.067E-01   0.          0.          0.          0.
 VTH     -9.161E-01  -9.043E-01   5.409E-01  -7.758E-01  -7.758E-01   5.498E-01
 VDSAT   -4.310E-01  -3.418E-01   2.065E-01  -1.853E-01  -1.853E-01   1.803E-01
 BETA     5.749E-04   5.871E-04   4.480E-03   4.980E-03   4.980E-03   5.456E-03
 GAM EFF  4.404E-01   4.404E-01   5.354E-01   4.909E-01   4.909E-01   5.354E-01
 GM       2.431E-04   2.003E-04   9.100E-04   9.102E-04   9.102E-04   9.683E-04
 GDS      4.291E-06   3.334E-06   1.563E-05   1.907E-06   1.907E-06   1.656E-05
 GMB      3.647E-05   3.036E-05   2.742E-04   2.637E-04   2.637E-04   2.937E-04
 CDTOT    5.694E-15   5.419E-15   1.365E-14   1.045E-13   1.045E-13   1.812E-14
 CGTOT    1.510E-14   1.510E-14   3.993E-14   4.046E-13   4.046E-13   4.788E-14
 CSTOT    1.739E-14   1.739E-14   4.483E-14   4.639E-13   4.639E-13   5.376E-14
 CBTOT    8.378E-15   8.103E-15   1.892E-14   1.645E-13   1.645E-13   2.437E-14
 CGS      1.280E-14   1.280E-14   3.415E-14   3.706E-13   3.706E-13   4.098E-14
 CGD      2.100E-15   2.100E-15   5.600E-15   3.360E-14   3.360E-14   6.720E-15

SUBCKT   XDM         XCM         XCM         XCM         XCM         XCM
ELEMENT  1:M52       2:M1        2:M2        2:M1C       2:M2C       2:M3
MODEL    1:CMOSN     2:CMOSN     2:CMOSN     2:CMOSN     2:CMOSN     2:CMOSP
 ID       1.134E-04   1.023E-04   1.023E-04   1.023E-04   1.023E-04  -1.023E-04
 IBS     -4.895E-19  -2.636E-15  -2.636E-15  -4.594E-15  -4.594E-15   1.548E-20
 IBD     -2.635E-15  -4.594E-15  -4.594E-15  -1.112E-14  -1.112E-14   2.188E-14
 VGS      7.934E-01   7.365E-01   7.365E-01   7.754E-01   7.754E-01  -9.912E-01
 VDS      2.635E-01   1.959E-01   1.959E-01   6.523E-01   6.523E-01  -2.188E+00
 VBS      0.         -2.635E-01  -2.635E-01  -4.594E-01  -4.594E-01   0.
 VTH      5.499E-01   6.259E-01   6.259E-01   6.656E-01   6.656E-01  -7.733E-01
 VDSAT    1.995E-01   9.503E-02   9.503E-02   9.563E-02   9.563E-02  -1.875E-01
 BETA     4.498E-03   1.912E-02   1.912E-02   1.912E-02   1.912E-02   4.978E-03
 GAM EFF  5.354E-01   5.270E-01   5.270E-01   5.218E-01   5.218E-01   4.909E-01
 GM       8.816E-04   1.807E-03   1.807E-03   1.820E-03   1.820E-03   9.225E-04
 GDS      1.513E-05   3.055E-05   3.055E-05   3.076E-05   3.076E-05   1.936E-06
 GMB      2.661E-04   4.560E-04   4.560E-04   4.081E-04   4.081E-04   2.671E-04
 CDTOT    1.513E-14   5.743E-14   5.743E-14   5.172E-14   5.172E-14   9.103E-14
 CGTOT    3.993E-14   1.592E-13   1.592E-13   1.592E-13   1.592E-13   4.046E-13
 CSTOT    4.483E-14   1.742E-13   1.742E-13   1.716E-13   1.716E-13   4.639E-13
 CBTOT    2.040E-14   7.279E-14   7.279E-14   6.453E-14   6.453E-14   1.511E-13
 CGS      3.415E-14   1.366E-13   1.366E-13   1.366E-13   1.366E-13   3.706E-13
 CGD      5.600E-15   2.240E-14   2.240E-14   2.240E-14   2.240E-14   3.360E-14

SUBCKT   XCM         XCM         XCM         XCM         XCM         XCM
ELEMENT  2:M4        2:M11       2:M12       2:M13       2:M14       2:M21
MODEL    2:CMOSP     2:CMOSP     2:CMOSP     2:CMOSN     2:CMOSN     2:CMOSP
 ID      -1.023E-04  -1.000E-04  -2.037E-05   2.037E-05   1.000E-04  -3.905E-05
 IBS      1.548E-20   1.513E-20   1.541E-20  -2.636E-15  -4.315E-19   9.067E-15
 IBD      2.188E-14   9.912E-15   2.065E-14  -1.235E-14  -7.690E-15   3.300E-14
 VGS     -9.912E-01  -9.912E-01  -9.912E-01   9.712E-01   7.690E-01  -1.281E+00
 VDS     -2.188E+00  -9.912E-01  -2.065E+00   9.712E-01   7.690E-01  -2.393E+00
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VBS	0.	0.	0.	-2.635E-01	0.	9.067E-01
VTH	-7.733E-01	-7.756E-01	-7.737E-01	6.177E-01	5.414E-01	-9.043E-01
VDSAT	-1.875E-01	-1.855E-01	-1.870E-01	2.908E-01	1.870E-01	-3.418E-01
BETA	4.978E-03	4.980E-03	9.956E-04	3.746E-04	4.529E-03	5.871E-04
GAM EFF	4.909E-01	4.909E-01	4.909E-01	5.270E-01	5.354E-01	4.404E-01
GM	9.225E-04	9.110E-04	1.841E-04	1.065E-04	8.345E-04	2.003E-04
GDS	1.936E-06	1.909E-06	3.862E-07	1.860E-06	1.429E-05	3.334E-06
GMB	2.671E-04	2.639E-04	5.336E-05	2.656E-05	2.527E-04	3.036E-05
CDTOT	9.103E-14	1.032E-13	1.851E-14	1.260E-15	1.370E-14	5.419E-15
CGTOT	4.046E-13	4.046E-13	8.123E-14	3.665E-15	3.993E-14	1.510E-14
CSTOT	4.639E-13	4.639E-13	9.293E-14	3.984E-15	4.483E-14	1.739E-14
CBTOT	1.511E-13	1.633E-13	3.099E-14	1.954E-15	1.897E-14	8.103E-15
CGS	3.706E-13	3.706E-13	7.413E-14	2.988E-15	3.415E-14	1.280E-14
CGD	3.360E-14	3.360E-14	6.720E-15	4.900E-16	5.600E-15	2.100E-15

SUBCKT	XCM	XCM	XCM	XCM	XCM	XCM
ELEMENT	2:M22	2:M23	2:M24	2:M25	2:M26	2:M27
MODEL	2:CMOSP	2:CMOSP	2:CMOSP	2:CMOSN	2:CMOSP	2:CMOSP
ID	-6.079E-05	-6.079E-05	-3.905E-05	1.216E-04	-9.984E-05	-9.984E-05
IBS	9.067E-15	9.067E-15	9.067E-15	-5.246E-19	1.510E-20	1.510E-20
IBD	2.507E-14	2.507E-14	3.300E-14	-7.933E-15	9.067E-15	9.067E-15
VGS	-1.393E+00	-1.393E+00	-1.281E+00	7.934E-01	-9.912E-01	-9.912E-01
VDS	-1.599E+00	-1.599E+00	-2.393E+00	7.934E-01	-9.067E-01	-9.067E-01
VBS	9.067E-01	9.067E-01	9.067E-01	0.	0.	0.
VTH	-9.161E-01	-9.161E-01	-9.043E-01	5.409E-01	-7.758E-01	-7.758E-01
VDSAT	-4.310E-01	-4.310E-01	-3.418E-01	2.065E-01	-1.853E-01	-1.853E-01
BETA	5.749E-04	5.749E-04	5.871E-04	4.480E-03	4.980E-03	4.980E-03
GAM EFF	4.404E-01	4.404E-01	4.404E-01	5.354E-01	4.909E-01	4.909E-01
GM	2.431E-04	2.431E-04	2.003E-04	9.100E-04	9.102E-04	9.102E-04
GDS	4.291E-06	4.291E-06	3.334E-06	1.563E-05	1.907E-06	1.907E-06
GMB	3.647E-05	3.647E-05	3.036E-05	2.742E-04	2.637E-04	2.637E-04
CDTOT	5.694E-15	5.694E-15	5.419E-15	1.365E-14	1.045E-13	1.045E-13
CGTOT	1.510E-14	1.510E-14	1.510E-14	3.993E-14	4.046E-13	4.046E-13
CSTOT	1.739E-14	1.739E-14	1.739E-14	4.483E-14	4.639E-13	4.639E-13
CBTOT	8.378E-15	8.378E-15	8.103E-15	1.892E-14	1.645E-13	1.645E-13
CGS	1.280E-14	1.280E-14	1.280E-14	3.415E-14	3.706E-13	3.706E-13
CGD	2.100E-15	2.100E-15	2.100E-15	5.600E-15	3.360E-14	3.360E-14

SUBCKT	XCM	XCM
ELEMENT	2:M51	2:M52
MODEL	2:CMOSN	2:CMOSN
ID	1.115E-04	1.134E-04
IBS	-4.011E-19	-4.895E-19
IBD	-2.635E-15	-2.635E-15
VGS	7.690E-01	7.934E-01
VDS	2.635E-01	2.635E-01
VBS	0.	0.
VTH	5.498E-01	5.499E-01
VDSAT	1.803E-01	1.995E-01
BETA	5.456E-03	4.498E-03
GAM EFF	5.354E-01	5.354E-01
GM	9.683E-04	8.816E-04
GDS	1.656E-05	1.513E-05
GMB	2.937E-04	2.661E-04
CDTOT	1.812E-14	1.513E-14
CGTOT	4.788E-14	3.993E-14
CSTOT	5.376E-14	4.483E-14
CBTOT	2.437E-14	2.040E-14
CGS	4.098E-14	3.415E-14
CGD	6.720E-15	5.600E-15

A_DM= 7.5957E+02
A_CM= 1.2148E-01
A_CM2DM= 4.4409E-16
A_DM2CM= .0000E+00
A_DM/A_CM= 6.2526E+03
A_DM/A_CM2DM= 1.7104E+18
A_DM/A_DM2CM= 7.5957E+30

12.23(e)

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FULLY DIFFERENTIAL OP AMP
.SUBCKT AMP (15 16 17 18)
VDD 1 0 1.65
VSS 2 0 -1.65
VCM 12 0 -0.65
IDC 14 9 -100U
M1 5 15 3 2 CMOSN W=63U L=0.8U
M2 6 16 3 2 CMOSN W=65U L=0.8U
M1C 17 4 5 2 CMOSN W=64U L=0.8U
M2C 18 4 6 2 CMOSN W=64U L=0.8U
M3 17 9 1 1 CMOSP W=96U L=1.4U
M4 18 9 1 1 CMOSP W=96U L=1.4U
M11 9 9 1 1 CMOSP W=96U L=1.4U
M12 4 9 1 1 CMOSP W=19.2U L=1.4U
M13 4 4 3 2 CMOSN W=1.4U L=0.8U
M14 14 14 2 2 CMOSN W=16U L=0.8U
M21 2 18 10  1 CMOSP W=6U L=0.8U
M22 13 12 10 1 CMOSP W=6U L=0.8U
M23 13 12 11 1 CMOSP W=6U L=0.8U
M24 2 17 11 1 CMOSP W=6U L=0.8U
M25 13 13 2 2 CMOSN W=16U L=0.8U
M26 10 9 1 1 CMOSP W=96U L=1.4U
M27 11 9 1 1 CMOSP W=96U L=1.4U
M51 3 14 2 2 CMOSN W=19.2U L=0.8U
M52 3 13 2 2 CMOSN W=16U L=0.8U
.MODEL CMOSN NMOS LEVEL=3
+ TOX=0.8000E-08 XJ=0.150000U TPG=1 PHI=0.600000
+ DELTA=2.1370E-01 LD=9.0003E-08 VTO=0.60 GAMMA=0.5947
+ UO=450.  THETA=1.9240E-01 RSH=1.7260E+01 KP=1.96E-04
+ NSUB=1.2706E+17 NFS=6.0410E+11 VMAX=1.8610E+05 ETA=2.1370E-02
+ KAPPA=8.4220E-02 CGDO=3.5E-10 CGSO=3.5E-10
+ CGBO=3.0251E-10 CJ=5.2E-04  MJ=0.59 CJSW=1.2E-10
+ MJSW=0.31 PB=0.98
+ ACM=3 HDIF=0.4U
.MODEL CMOSP PMOS LEVEL=3
+ TOX=0.8000E-08 XJ=0.150000U TPG=-1 PHI=0.600000
+ DELTA=2.0729E-01 LD=9.0000E-08 VTO=-0.80 GAMMA=0.5200
+ UO=137.3 THETA=1.6710E-01 RSH=3.6310E+00 KP=6.6E-05
+ NSUB=9.7132E+16 NFS=5.9890E+11 VMAX=3.0560E+05 ETA=1.8760E-02
+ KAPPA=5.9230E+00 CGDO=3.5E-10 CGSO=3.5E-10
+ CGBO=3.1661E-10 CJ=9.1191E-04 MJ=0.49 CJSW=1.2E-10
+ MJSW=0.201 PB=0.96
+ ACM=3 HDIF=0.4U
.ENDS AMP

* AMPLIFIER WITH DM INPUT

XDM (21 22 23 24) AMP
VI1D 21 19 0 AC 0.5
EI2D 22 19 21 19 -1

* AMPLIFIER WITH CM INPUT

XCM (31 32 33 34) AMP
EI1C 31 19 21 19 2
EI2C 32 19 31 19 1

VIC 19 0 -0.65
.OPTIONS NOMOD
* CALCULATE THE MAGNITUDE OF THE DIFFERENCES INSTEAD OF
* THE DIFFERENCE OF THE MAGNITUDES
.OPTIONS ACOUT=0
.AC DEC 1 1 10
.PRINT AC VM(23) VM(24) VP(23) VP(24)
.PRINT AC VM(33) VM(34) VP(33) VP(34)
.PRINT AC VM(23, 24) VM(23) VM(24)
.PRINT AC VM(33, 34) VM(33) VM(34)
.MEASURE AC A_DM FIND VM(23, 24) AT=1
.MEASURE AC A_CM FIND PAR('(VM(33)+VM(34))/2.') AT=1
.MEASURE AC A_CM2DM FIND VM(33, 34) AT=1
.MEASURE AC A_DM2CM FIND PAR('(VM(23)-VM(24))/2.') AT=1
* SUBTRACTION IS USED IN THE EQUATION FOR A_DM2CM BECAUSE
* THE TWO OUTPUTS HAVE OPPOSITE POLARITY.
.MEASURE A_DM/A_CM PARAM='A_DM/A_CM'
.MEASURE A_DM/A_CM2DM PARAM='A_DM/A_CM2DM'
.MEASURE A_DM/A_DM2CM PARAM='A_DM/A_DM2CM'
.OPTIONS SPICE
.WIDTH OUT=80
.END

****** OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000

+0:19       =-6.500E-01 0:21       =-6.500E-01 0:22       =-6.500E-01
+0:23       = 4.319E-01 0:24       =-9.111E-01 0:31       =-6.500E-01
+0:32       =-6.500E-01 0:33       = 4.319E-01 0:34       =-9.111E-01
+1:1        = 1.650E+00 1:2        =-1.650E+00 1:3        =-1.386E+00
+1:4        =-4.148E-01 1:5        =-1.176E+00 1:6        =-1.195E+00
+1:9        = 6.588E-01 1:10       = 5.682E-01 1:11       = 8.648E-01
+1:12       =-6.500E-01 1:13       =-8.579E-01 1:14       =-8.810E-01
+2:1        = 1.650E+00 2:2        =-1.650E+00 2:3        =-1.386E+00
+2:4        =-4.148E-01 2:5        =-1.176E+00 2:6        =-1.195E+00
+2:9        = 6.588E-01 2:10       = 5.682E-01 2:11       = 8.648E-01
+2:12       =-6.500E-01 2:13       =-8.579E-01 2:14       =-8.810E-01

 A_DM=  7.5617E+02
 A_CM=  2.7842E-01
 A_CM2DM=  2.0399E-02
 A_DM2CM=  3.6278E+02

A_DM/A_CM=  2.7160E+03
A_DM/A_CM2DM=  3.7069E+04
A_DM/A_DM2CM=  2.0844E+00
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12.23(f)

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FULLY DIFFERENTIAL OP AMP
.SUBCKT AMP (15 16 17 18)
VDD 1 0 1.65
VSS 2 0 -1.65
VCM 12 0 -0.65
IDC 14 9 -100U
M1 5 15 3 2 CMOSN W=64U L=0.8U
M2 6 16 3 2 CMOSN W=64U L=0.8U
M1C 17 4 5 2 CMOSN W=64U L=0.8U
M2C 18 4 6 2 CMOSN W=64U L=0.8U
M3 17 9 1 1 CMOSP W=95U L=1.4U
M4 18 9 1 1 CMOSP W=97U L=1.4U
M11 9 9 1 1 CMOSP W=96U L=1.4U
M12 4 9 1 1 CMOSP W=19.2U L=1.4U
M13 4 4 3 2 CMOSN W=1.4U L=0.8U
M14 14 14 2 2 CMOSN W=16U L=0.8U
M21 2 18 10  1 CMOSP W=6U L=0.8U
M22 13 12 10 1 CMOSP W=6U L=0.8U
M23 13 12 11 1 CMOSP W=6U L=0.8U
M24 2 17 11 1 CMOSP W=6U L=0.8U
M25 13 13 2 2 CMOSN W=16U L=0.8U
M26 10 9 1 1 CMOSP W=96U L=1.4U
M27 11 9 1 1 CMOSP W=96U L=1.4U
M51 3 14 2 2 CMOSN W=19.2U L=0.8U
M52 3 13 2 2 CMOSN W=16U L=0.8U
.MODEL CMOSN NMOS LEVEL=3
+ TOX=0.8000E-08 XJ=0.150000U TPG=1 PHI=0.600000
+ DELTA=2.1370E-01 LD=9.0003E-08 VTO=0.60 GAMMA=0.5947
+ UO=450.  THETA=1.9240E-01 RSH=1.7260E+01 KP=1.96E-04
+ NSUB=1.2706E+17 NFS=6.0410E+11 VMAX=1.8610E+05 ETA=2.1370E-02
+ KAPPA=8.4220E-02 CGDO=3.5E-10 CGSO=3.5E-10
+ CGBO=3.0251E-10 CJ=5.2E-04  MJ=0.59 CJSW=1.2E-10
+ MJSW=0.31 PB=0.98
+ ACM=3 HDIF=0.4U
.MODEL CMOSP PMOS LEVEL=3
+ TOX=0.8000E-08 XJ=0.150000U TPG=-1 PHI=0.600000
+ DELTA=2.0729E-01 LD=9.0000E-08 VTO=-0.80 GAMMA=0.5200
+ UO=137.3 THETA=1.6710E-01 RSH=3.6310E+00 KP=6.6E-05
+ NSUB=9.7132E+16 NFS=5.9890E+11 VMAX=3.0560E+05 ETA=1.8760E-02
+ KAPPA=5.9230E+00 CGDO=3.5E-10 CGSO=3.5E-10
+ CGBO=3.1661E-10 CJ=9.1191E-04 MJ=0.49 CJSW=1.2E-10
+ MJSW=0.201 PB=0.96
+ ACM=3 HDIF=0.4U
.ENDS AMP

* AMPLIFIER WITH DM INPUT

XDM (21 22 23 24) AMP
VI1D 21 19 0 AC 0.5
EI2D 22 19 21 19 -1

* AMPLIFIER WITH CM INPUT

XCM (31 32 33 34) AMP
EI1C 31 19 21 19 2
EI2C 32 19 31 19 1

VIC 19 0 -0.65
.OPTIONS NOMOD
* CALCULATE THE MAGNITUDE OF THE DIFFERENCES INSTEAD OF
* THE DIFFERENCE OF THE MAGNITUDES
.OPTIONS ACOUT=0
.AC DEC 1 1 10
.PRINT AC VM(23) VM(24) VP(23) VP(24)
.PRINT AC VM(33) VM(34) VP(33) VP(34)
.PRINT AC VM(23, 24) VM(23) VM(24)
.PRINT AC VM(33, 34) VM(33) VM(34)
.MEASURE AC A_DM FIND VM(23, 24) AT=1
.MEASURE AC A_CM FIND PAR('(VM(33)+VM(34))/2.') AT=1
.MEASURE AC A_CM2DM FIND VM(33, 34) AT=1
.MEASURE AC A_DM2CM FIND PAR('(VM(23)-VM(24))/2.') AT=1
* SUBTRACTION IS USED IN THE EQUATION FOR A_DM2CM BECAUSE
* THE TWO OUTPUTS HAVE OPPOSITE POLARITY.
.MEASURE A_DM/A_CM PARAM='A_DM/A_CM'
.MEASURE A_DM/A_CM2DM PARAM='A_DM/A_CM2DM'
.MEASURE A_DM/A_DM2CM PARAM='A_DM/A_DM2CM'
.OPTIONS SPICE
.WIDTH OUT=80
.END

 ******  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000

+0:19      =-6.500E-01 0:21     =-6.500E-01 0:22     =-6.500E-01
+0:23      =-9.018E-01 0:24     = 5.783E-03 0:31     =-6.500E-01
+0:32      =-6.500E-01 0:33     =-9.018E-01 0:34     = 5.783E-03
+1:1       = 1.650E+00 1:2      =-1.650E+00 1:3      =-1.386E+00
+1:4       =-4.151E-01 1:5      =-1.195E+00 1:6      =-1.183E+00
+1:9       = 6.588E-01 1:10     = 8.646E-01 1:11     = 5.734E-01
+1:12      =-6.500E-01 1:13     =-8.570E-01 1:14     =-8.810E-01
+2:1       = 1.650E+00 2:2      =-1.650E+00 2:3      =-1.386E+00
+2:4       =-4.151E-01 2:5      =-1.195E+00 2:6      =-1.183E+00
+2:9       = 6.588E-01 2:10     = 8.646E-01 2:11     = 5.734E-01
+2:12      =-6.500E-01 2:13     =-8.570E-01 2:14     =-8.810E-01

  A_DM= 7.5724E+02
  A_CM= 2.6762E-01
  A_CM2DM= 1.4495E-02
  A_DM2CM= -3.4873E+02

A_DM/A_CM= 2.8295E+03
A_DM/A_CM2DM= 5.2242E+04
A_DM/A_DM2CM= -2.1714E+00
```

12.24

(a) $C_{Ld} = \frac{1}{2}(0.5 + \frac{1.5 \times 1}{1.5+1}) = 0.55pF$

$C_{Lc} = 0.5 + \frac{1.5 \times 1}{1.5+1} = 1.1pF$

(b) $\frac{dV_{od}}{dt} = \frac{2|I_{D1}|}{2C_{Ld}} = \frac{200\mu A}{1.1pF} = 182V/\mu s$

(c) $-V_{SS} + V_{OV11} + V_{OV1A} < V_{O1} < V_{DD} - |V_{ov3}| - |V_{ov3A}|$

$-2 + 0.15 + 0.15 < V_{O1} < 2 - 0.15 - 0.15$

$-1.7V < V_{O1} < 1.7V$

$V_{od(peak)} = 1.7 - (-1.7) = 3.4V$

12.25

(a) $V_{CM} - V_{OC} = V_{CBIAS} - V_{cmc}$

$0.5 - 0.5 = -1 - V_{cmc}$

$V_{cmc} = -1V$

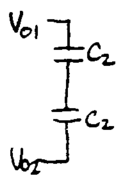
$V_{CM} - V'_{OC} = V'_{CBIAS} - V_{cmc}$

$0.5 - V'_{OC} = -1.1 - (-1)$

$V'_{OC} = 0.6V$

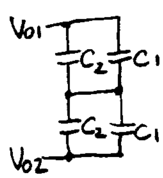
(b) $C_{Lc} = 0$

$C_{Ld} = \frac{1}{2}C_2 = 0.25pF$



(c) $C_{Lc} = 0$

$C_{Ld} = \frac{1}{2}(C_1 + C_2) = 0.3pF$



12.26

(a) $a_{dm} = -\frac{g_{m1}}{g_{m3}} g_{m8}(r_{o8} \| r_{o9})$

$$= -\frac{2I_{D1}}{V_{ov1}} \frac{|V_{ov3}|}{2|I_{D3}|} \frac{2|I_{D8}|}{|V_{ov8}|}\left(\frac{|V_{A8}|}{|I_{D8}|} \| \frac{V_{A9}}{I_{D9}}\right)$$

$$= -\frac{2}{0.2}(20 \| 10) = -67$$

$$\frac{R_{od}}{2} = r_{o8} \| r_{o9} = \frac{|V_{A8}|}{|I_{D8}|} \| \frac{V_{A9}}{I_{D9}}$$

$$= \frac{20}{100\times10^{-6}} \| \frac{10}{100\times10^{-6}} = 6.7\times10^{4}\Omega = 67k\Omega$$

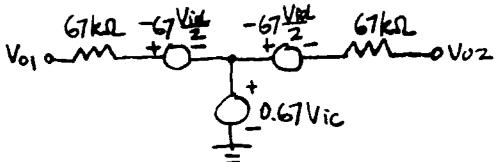
$$a_{cm} = \frac{g_{m1}}{1+g_{m1}r_{o5h}} \frac{1}{g_{m3}} g_{m8}(r_{o8} \| r_{o9})$$

$$\approx \frac{1}{r_{o5h}} \frac{g_{m8}}{g_{m3}}(r_{o8} \| r_{o9})$$

$$= \frac{I_{D5h}}{V_{A5h}} \frac{|V_{ov3}|}{2|I_{D3}|} \frac{2|I_{D8}|}{|V_{ov8}|}\left(\frac{|V_{A8}|}{|I_{D8}|} \| \frac{V_{A9}}{I_{D9}}\right)$$

$$= \frac{1}{10}(20 \| 10) = 0.67$$

$$R_{oc} = \frac{R_{od}}{2} = 67k\Omega$$



(b) $a_{cmc} = g_{m5h}\left[R_{o(down)} \| \frac{1}{g_{m3}}\right] g_{m8}(r_{o8} \| r_{o9})$

$$\approx \frac{g_{m5h}}{g_{m3}} g_{m8}(r_{o8} \| r_{o9})$$

$$= \frac{2I_{D5h}}{V_{ov5h}} \frac{|V_{ov3}|}{2|I_{D3}|} \frac{2|I_{D8}|}{|V_{ov8}|}\left(\frac{|V_{A8}|}{|I_{D8}|} \| \frac{V_{A9}}{I_{D9}}\right)$$

$$= \frac{2}{0.2}(20 \| 10) = 67$$

(c) $a_{cmc} = -g_{m9}(r_{o8} \| r_{o9})$

$$= -\frac{2I_{D9}}{V_{ov9}}\left(\frac{|V_{A8}|}{|I_{D8}|} \| \frac{V_{A9}}{I_{D9}}\right)$$

$$= -\frac{2}{0.2}(20 \| 10) = -67$$

(d) $-V_{SS} + V_{ov7} < V_{O1} < V_{DD} - |V_{ov6}|$

$-1.65 + 0.2 < V_{O1} < 1.65 - 0.2$

$-1.45V < V_{O1} < 1.45V$

If $V_{oc} = 0V$, the maximum symmetric output swing (2.9V peak to peak) can be achieved.

12.27

$V_{oc} = a_{cm}V_{ic} + a_{cmc}V_{cmc}$

$= a_{cm}V_{ic} + a_{cmc}a_{cms}V_{oc}$

$$a'_{cm} = \frac{V_{oc}}{V_{ic}} = \frac{a_{cm}}{1 - a_{cmc}a_{cms}}$$

$$V_{An} = \frac{L_{eff}}{dX_d/dV_{ds}} = \frac{1-2\times0.09}{0.02} = 41V$$

$$|V_{Ap}| = \frac{L_{eff}}{dX_d/dV_{ds}} = \frac{1-2\times0.09}{0.04} = 20.5V$$

$$a_{cm} = \left.\frac{V_{oc}}{V_{ic}}\right|_{V_{cmc}=0}$$

$$= \frac{g_{m2}}{1+g_{m2}r_{o5h}}[R_{o(down)}||r_{o4}]g_{m6}(r_{o6}||r_{o7})$$

$$\approx \frac{1}{r_{o5h}}[(r_{o2}g_{m2}r_{o5h})||r_{o4}]g_{m6}(r_{o6}||r_{o7})$$

$$= \frac{|I_{D5h}|}{|V_{A5h}|}\left[\left(\frac{|V_{A2}|}{|I_{D2}|}\frac{2|I_{D2}|}{|V_{ov2}|}\frac{|V_{A5h}|}{|I_{D5h}|}\right)||\frac{V_{A4}}{I_{D4}}\right]\times \frac{2I_{D6}}{V_{ov6}}\left(\frac{V_{A6}}{I_{D6}}||\frac{|V_{A7}|}{|I_{D7}|}\right)$$

$$= \frac{100}{20.5}\left[\left(\frac{20.5}{100}\frac{2\times100}{0.2}\frac{20.5}{100}\right)||\frac{41}{100}\right]\times \frac{2\times400}{0.5}\left(\frac{41}{400}||\frac{20.5}{400}\right)$$

$$= 108$$

$$a_{cmc} = \left.\frac{V_{oc}}{V_{cmc}}\right|_{V_{ic}=0}$$

$$= g_{m5h}[(r_{o2}g_{m2}r_{o5h})||r_{o4}]g_{m6}(r_{o6}||r_{o7})$$

$$= \frac{2|I_{D5h}|}{|V_{ov5h}|}[(r_{o2}g_{m2}r_{o5h})||r_{o4}]g_{m6}(r_{o6}||r_{o7})$$

$$= \frac{2\times100}{0.5}\times2.22\times10^3$$

$$= 8.88\times10^3$$

$$a_{cms} = \frac{V_{cms}}{V_{oc}} = \frac{V_{cmc}}{V_{oc}} = -\frac{g_{m21}}{g_{m25}} = -\frac{2I_{D21}}{V_{ov21}}\frac{|V_{ov25}|}{2|I_{D25}|}$$

$$= -\frac{2\times100}{0.35}\frac{0.5}{2\times200} = -0.71$$

$$a'_{cm} = \frac{108}{1-8.88\times10^3(-0.71)} = 0.0171$$

12.28

For the CMC loop,

$$C = \frac{g_{m5h}}{g_{m6}}|a_{cms0}|C_{2c}$$

$$= \frac{2\times100\times10^{-6}}{0.5}\frac{1}{1.55\times10^{-3}}2.5\times3.43\times10^{-12}$$

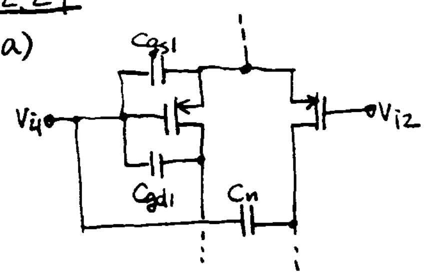
$$= 2.22\times10^{-12}F = 2.22pF$$

For the DM loop, C=1.39 pF acording to the example.

Choose the larger one, that is, C=2.22pF.

12.29

(a)

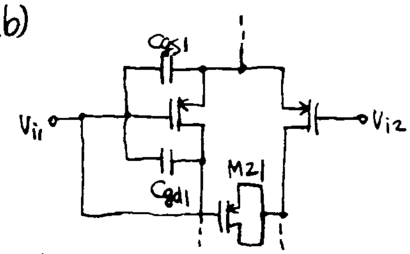


If $C_n = C_{gd1}$,

$$C_{idn} = C_{gs1} + (1-a_{dm1})C_{gd1} + (1+a_{dm1})C_n$$

$$= C_{gs1} + 2C_{gd1}$$

(b)



The transistor, M21, should be PMOS.

$W_{21} = W_1/2$

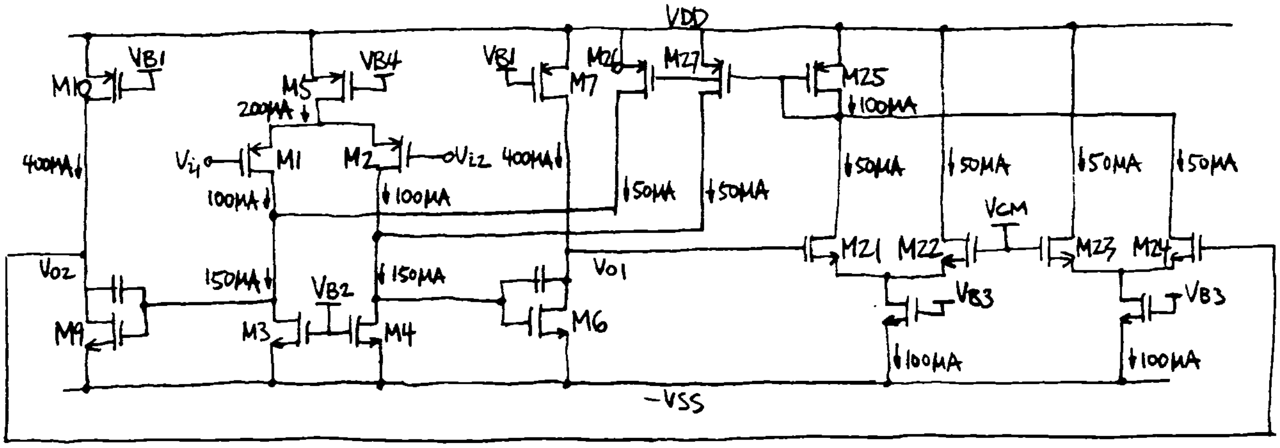
$C_{gd1} = C_{ol}W_1$

$C_n = C_{gd21} + C_{gs21} = 2C_{ol}W_{21}$

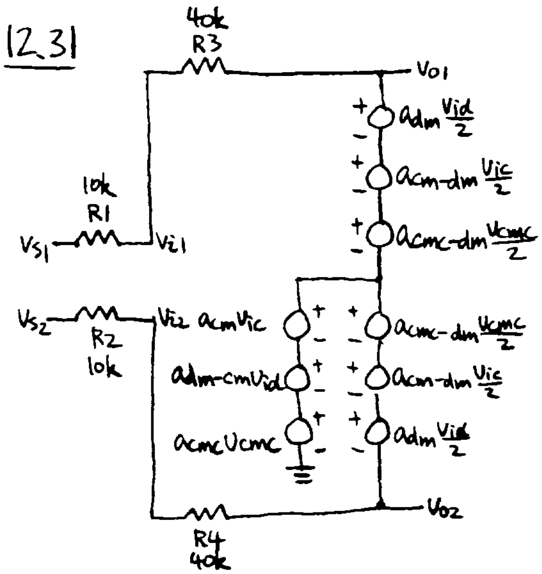
$C_n = C_{gd1}$

12.30

One solution



12.31



$V_{cmc} = V_{cms} = a_{cms} V_{oc}$

$= a_{cms}(a_{cm}V_{ic} + a_{dm\text{-}cm}V_{id} + a_{cmc}V_{cmc})$

$V_{cmc} = \dfrac{a_{cms}}{1 - a_{cms}a_{cmc}}(a_{cm}V_{ic} + a_{dm\text{-}cm}V_{id})$

$= \dfrac{0.76}{1 - 0.76 \times (-226)}(-2.89V_{ic} + 8.95V_{id})$

$= -0.0127V_{ic} + 0.0394V_{id}$

$\frac{1}{2}V_{id} = \dfrac{R_3}{R_1 + R_3}\dfrac{V_{sd}}{2} +$

$\dfrac{R_1}{R_1 + R_3}\left[a_{dm}\dfrac{V_{id}}{2} + a_{cm\text{-}dm}\dfrac{V_{ic}}{2} + a_{cmc\text{-}dm}\dfrac{V_{cmc}}{2}\right]$

$V_{id} = \frac{4}{5}V_{sd} + \frac{1}{5}[-181V_{id} + 0.15V_{ic} +$

$11.6(-0.0127V_{ic} + 0.0394V_{id})]$

$37.1V_{id} - 5.36 \times 10^{-4}V_{ic} = 0.8V_{sd}$

$V_{ic} = \dfrac{R_3}{R_1 + R_3}V_{sc}$

$+ \dfrac{R_1}{R_1 + R_3}[a_{cm}V_{ic} + a_{dm\text{-}cm}V_{id} + a_{cmc}V_{cmc}]$

$V_{ic} = \frac{4}{5}V_{sc} + \frac{1}{5}[-2.89V_{ic} + 8.95V_{id}$

$-226(-0.0127V_{ic} + 0.0394V_{id})]$

$V_{ic} - 9.12 \times 10^{-3}V_{id} = 0.8V_{sc}$

$$\begin{cases} 37.1V_{id} - 5.36 \times 10^{-4}V_{ic} = 0.8V_{sd} \\ -9.12 \times 10^{-3}V_{id} + V_{ic} = 0.8V_{sc} \end{cases}$$

$V_{id} = \dfrac{1}{37.1}(0.8V_{sd} + 5.36 \times 10^{-4} \times 0.8V_{sc})$

$= 0.0216V_{sd} + 1.16 \times 10^{-5}V_{sc}$

$V_{ic} = \dfrac{1}{37.1}(37.1 \times 0.8V_{sc} + 9.12 \times 10^{-3} \times 0.8V_{sd})$

$= 1.97 \times 10^{-4}V_{sd} + 0.8V_{sc}$

$V_{od} = a_{dm}V_{id} + a_{cm\text{-}dm}V_{ic} + a_{cmc\text{-}dm}V_{cmc}$

$= (a_{dm} + 0.0394a_{cmc\text{-}dm})V_{id}$

$+ (a_{cm\text{-}dm} - 0.0127a_{cmc\text{-}dm})V_{ic}$

$= (-181 + 0.0394 \times 11.6)V_{id}$

$+ (0.15 - 0.0127 \times 11.6)V_{ic}$

$= -180V_{id} + 2.68 \times 10^{-3}V_{ic}$

$= -180(0.0216V_{sd} + 1.16 \times 10^{-5}V_{sc})$

$+ 2.68 \times 10^{-3}(1.97 \times 10^{-4}V_{sd} + 0.8V_{sc})$

$= -3.89V_{sd} + 5.6 \times 10^{-5}V_{sc}$

$V_{oc} = a_{cm}V_{ic} + a_{dm\text{-}cm}V_{id} + a_{cmc}V_{cmc}$

$= (a_{cm} - 0.0127a_{cmc})V_{ic}$

$+ (a_{dm\text{-}cm} + 0.0394a_{cmc})V_{id}$

$= [-2.89 - 0.0127 \times (-226)]V_{ic}$

$+ [8.95 + 0.0394 \times (-226)]V_{id}$

$= -0.0198V_{ic} + 0.0456V_{id}$

$= -0.0198(1.97 \times 10^{-4}V_{sd} + 0.8V_{sc})$

$+ 0.0456(0.0216V_{sd} + 1.16 \times 10^{-5}V_{sc})$

$= 9.81 \times 10^{-4}V_{sd} - 0.0158V_{sc}$

$A_{dm} = \dfrac{V_{od}}{V_{sd}} = -3.89$

$A_{cm} = \dfrac{V_{oc}}{V_{sc}} = -0.0158$

$A_{dm\text{-}cm} = \dfrac{V_{oc}}{V_{sd}} = 9.81 \times 10^{-4}$

$A_{cm\text{-}dm} = \dfrac{V_{od}}{V_{sc}} = 5.6 \times 10^{-5}$