Microelectronic Circuit Design
Third Edition - Part III
Solutions to Exercises

CHAPTER 10

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$V_o = \sqrt{2P_oR_L} = \sqrt{2(20W)(16\Omega)} = 25.3\ V \quad A_v = \frac{V_o}{V_i} = \frac{25.3V}{0.005V} = 5.06x10^3$

$I_o = \frac{V_o}{R_L} = \frac{25.3V}{16\Omega} = 1.58\ A \quad I_i = \frac{V_i}{R_S + R_{in}} = \frac{0.005V}{10k\Omega + 20k\Omega} = 0.167\mu A \quad A_i = \frac{I_o}{I_i} = \frac{1.58A}{0.167\mu A} = 9.48x10^6$

$A_P = \frac{P_o}{P_S} = \frac{25.3V(1.58A)}{0.005V(0.167\mu A)} = 4.79x10^{10} \quad \text{Checking}: A_p = (5.06x10^3)(9.48x10^6) = 4.80x10^{10}$

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$(i)\ A_{vdB} = 20\log(5060) = 74.1\ dB \quad A_{idB} = 20\log(9.48x10^6) = 140\ dB \quad A_{PdB} = 10\log(4.80x10^{10}) = 107\ dB$

$(ii)\ A_{vdB} = 20\log(4x10^4) = 92.0\ dB \quad A_{idB} = 20\log(2.75x10^8) = 169\ dB \quad A_{PdB} = 10\log(1.10x10^{13}) = 130\ dB$

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(i) The constant slope region spanning a maximum input range is between $0.4 \le v_I \le 0.65$,

and the bias voltage V_I should be centered in this range: $V_I = \frac{0.4 + 0.65}{2}V = 0.525\ V$.

$v_i \le 0.65 - 0.525 = 0.125\ V$ and $v_i \le 0.525 - 0.40 = 0.125\ V$. For $v_I = 0.8V$, the slope is 0. $A_v = 0$.

$(ii)\ v_O = V_O + v_o$ For $v_i = 0$, $v_I = V_I = 0.6$, $V_O = 14V$ and $A_v = +40$. $V_o = A_vV_i = 40(0.01V) = 4V$

$v_O = (14.0 + 4.00\sin 1000\pi t)$ volts $\quad V_O = 14\ V$

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$$g_{11} = \frac{1}{20k\Omega + 76(50k\Omega)} = 0.262\ \mu S \quad g_{21} = 0.262\mu S(76)(50k\Omega) = 0.995$$

$$g_{22} = \frac{1}{50k\Omega} + \frac{1}{20k\Omega} + \frac{75}{20k\Omega} = 3.82\ mS \quad g_{12} = -\frac{1}{g_{22}(20k\Omega)} = -\frac{1}{3.82mS(20k\Omega)} = \text{-}0.0131$$

$$R_{in} = \frac{1}{g_{11}} = 3.82\ M\Omega \quad A = g_{21} = 0.995 \quad R_{out} = \frac{1}{g_{22}} = 262\ \Omega$$

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$$(i)\ P = A_v A_i = A_v^2 \frac{R_S + R_{in}}{R_L}$$

$$(ii)\ V_o = \sqrt{2(100W)(8\Omega)} = 40\ V \quad 40 = 0.001\left(\frac{50k\Omega}{5k\Omega + 50k\Omega}\right)A\left(\frac{8\Omega}{0.5\Omega + 8\Omega}\right) \rightarrow A = 46,800$$

$$P = \frac{I_o^2 R_L}{2} = \frac{0.5\Omega}{2}\left(\frac{40V}{8\Omega}\right)^2 = 6.25\ W \quad A_i = \left(\frac{40V}{8\Omega}\right)\left(\frac{5k\Omega + 50k\Omega}{0.001V}\right) = 2.75\ x\ 10^8$$

$$(iii)\ 40 = 0.001\left(\frac{5k\Omega}{5k\Omega + 5k\Omega}\right)A\left(\frac{8\Omega}{8\Omega + 8\Omega}\right) \rightarrow A = 160,000$$

$$P = \frac{I_o^2 R_L}{2} = \frac{8\Omega}{2}\left(\frac{40V}{8\Omega}\right)^2 = 100\ W! \quad A_i = \left(\frac{40V}{8\Omega}\right)\left(\frac{5k\Omega + 5k\Omega}{0.001V}\right) = 5.00\ x\ 10^7$$

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$$A_v(s) = \frac{300s}{(s + 5000)(s + 100)}$$ Zeros at s = 0 and s = ∞; Poles at s = -5000 and s = −100.

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$$A_v(s) = -\frac{2\pi\ x\ 10^6}{s + 5000\pi} = \frac{-400}{1 + \frac{s}{5000\pi}} \rightarrow A_{mid} = -400 \quad f_H = \frac{5000\pi}{2\pi} = 2.50\ kHz$$

$$BW = f_H - f_L = 2.50\ kHz - 0 = 2.50\ kHz \quad GBW = (400)(2.50kHz) = 1.00\ MHz$$

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$$(i)\ \left|A_v(j5)\right| = 50\frac{\left|5^2-4\right|}{\sqrt{\left(5^2-2\right)^2+4\left(5^2\right)}} = 41.87 \quad 20\log(41.87) = 32.4\ dB$$

$$\angle A_v(j5) = \angle\left(5^2-4\right) - \tan^{-1}\left[\frac{-2(5)}{5^2-2}\right] = 0-\left(-23.5^o\right) = 23.5^o$$

$$\left|A_v(j1)\right| = 50\frac{\left|1^2-4\right|}{\sqrt{\left(1^2-2\right)^2+4\left(1^2\right)}} = 67.08 \quad 20\log(41.87) = 36.5\ dB$$

$$\angle A_v(j1) = \angle\left(1^2-4\right) - \tan^{-1}\left[\frac{-2(1)}{1^2-2}\right] = 180^o-\left(-63.43^o\right) = 243^o = -117^o$$

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$$(ii)\ \mathrm{A_v}(j\omega) = \frac{20}{1+j\dfrac{0.1\omega}{1-\omega^2}}$$

$$\left|A_v(j0.95)\right| = \frac{20}{\sqrt{1^2+\dfrac{(0.1)^2\left(0.95^2\right)}{\left(1-0.95^2\right)^2}}} = 14.3 \qquad \angle A_v(j0.95) = \angle 20 - \tan^{-1}\left[\frac{0.1(0.95)}{1-0.95^2}\right] = 0-\left(44.3^o\right) = -44.3^o$$

$$\left|A_v(j1)\right| = \frac{20}{\sqrt{1^2+\dfrac{(0.1)^2\left(1^2\right)}{\left(1-1^2\right)^2}}} = 0 \qquad \angle A_v(j1) = \angle 20 - \tan^{-1}\left[\frac{0.1(1)}{1-1^2}\right] = 0-\left(90^o\right) = -90.0^o$$

$$\left|A_v(j1.1)\right| = \frac{20}{\sqrt{1^2+\dfrac{(0.1)^2\left(1.1^2\right)}{\left(1-1.1^2\right)^2}}} = 17.7 \qquad \angle A_v(j1.1) = \angle 20 - \tan^{-1}\left[\frac{0.1(1.1)}{1-1.1^2}\right] = 0-\left(-27.6^o\right) = 27.6^o$$

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$$f_H = \frac{1}{2\pi}\frac{1}{(1k\Omega\|100k\Omega)(200\,pF)} = 804\ kHz$$

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$$A_v(s) = \frac{250}{1+\dfrac{250\pi}{s}} \qquad A_o = 250 \qquad f_L = \frac{250\pi}{2\pi} = 125\ Hz \qquad f_H = \infty \qquad BW = \infty - 125 = \infty$$

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$$f_L = \frac{1}{2\pi}\frac{1}{\left(1k\Omega \| 100k\Omega\right)\left(0.1\mu F\right)} = 15.8\ Hz$$

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$$(i)\ A_v(s) = \frac{-400}{\left(1+\frac{100}{s}\right)\left(1+\frac{s}{50000}\right)} \qquad A_o = 400 \text{ or } 52\ dB$$

$$f_L = \frac{100}{2\pi} = 15.9\ Hz \quad f_H = \frac{50000}{2\pi} = 7.96\ kHz \quad BW = 7960 - 15.9 = 7.94\ kHz$$

$$(ii)\ \angle A_v(j0) = -90 - 0 - 0 = -90^o$$

$$\angle A_v(j100) = -90^o - \tan^{-1}\left(\frac{100}{100}\right) - \tan^{-1}\left(\frac{100}{50000}\right) = -90 - 45 - 0.57 = -136^o$$

$$\angle A_v(j50000) = -90^o - \tan^{-1}\left(\frac{50000}{100}\right) - \tan^{-1}\left(\frac{50000}{50000}\right) = -90 - 89.9 - 45 = -225^o$$

$$\angle A_v(j\infty) = -90 - 90 - 90 = -270^o$$

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The numerator coefficient should be 6 x10^6.

$$A_v(s) = 30\frac{2x10^5 s}{s^2 + 2x10^5 s + 10^{14}} \qquad A_o = 30$$

$$f_o = \frac{1}{2\pi}\sqrt{10^{14}} = 1.59\ MHz \quad Q = \frac{10^7}{2x10^5} = 50 \quad BW = \frac{1.59\, MHz}{50} = 31.8\ kHz$$

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The transfer fucntion should be $A_v(s) = \dfrac{6.4x10^{12}\pi^2 s}{(s+200\pi)(s+80000\pi)^2}$.

$$A_v(s) = \frac{1000}{\left(1+\frac{200\pi}{s}\right)\left(1+\frac{s}{80000\pi}\right)^2} \qquad A_o = 1000 \text{ or } 60\ dB$$

$$f_L = \frac{200\pi}{2\pi} = 100\ Hz \qquad f_H = 0.644\left(\frac{80000\pi}{2\pi}\right) = 25.8\ kHz \quad BW = 25800 - 100 = 25.7\ kHz$$

CHAPTER 11

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$$v_{id} = \frac{10V}{100} = 0.100V = 100\ mV \quad v_{id} = \frac{10V}{10^4} = 0.001\ V = 1.00\ mV \quad v_{id} = \frac{10V}{10^6} = 1.00x10^{-5}V = 10.0\ \mu V$$

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$$A_v = -\frac{360k\Omega}{68k\Omega} = -5.29 \quad v_O = -5.29(0.5V) = -2.65\ V \quad i_S = \frac{0.5V}{68k\Omega} = 7.35\ \mu A \quad i_O = -i_2 = -i_S = -7.35\ \mu A$$

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$$I_S = \frac{2V}{4.7k\Omega} = 426\ \mu A \quad I_2 = I_S = 426\ \mu A \quad A_v = -\frac{24k\Omega}{4.7k\Omega} = -5.11 \quad V_O = -5.11(2V) = -10.2\ V$$

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$$A_v = 1 + \frac{36k\Omega}{2k\Omega} = +19.0 \quad v_O = 19.0(-0.2V) = -\ 3.80\ V \quad i_O = \frac{-3.80V}{36k\Omega + 2k\Omega} = -100\ \mu A$$

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$$(i)\ A_v = 1 + \frac{39k\Omega}{1k\Omega} = +40.0 \quad A_{vdB} = 20\log(40.0) = 32.0\ \text{dB} \quad R_{in} = 100k\Omega \| \infty = 100k\Omega$$

$$v_O = 40.0(0.25V) = 10.0\ V \quad i_O = \frac{10.0V}{39k\Omega + 1k\Omega} = 250\ \mu A$$

$$(ii)\ A_v = 10^{\frac{54}{20}} = 501 \quad 1 + \frac{R_2}{R_1} = 501 \quad \frac{R_2}{R_1} = 500 \quad i_O = \frac{v_O}{R_2 + R_1} \quad \frac{10}{R_2 + R_1} \le 0.1\ mA$$

$R_1 + R_2 \ge 100k\Omega \quad 501R_1 \ge 100k\Omega \rightarrow R_1 \ge 200\ \Omega$ There are many possibilities. ($R_1 = 200\ \Omega$, $R_2 = 100\ k\Omega$), but ($R_1 = 220\ \Omega$, $R_2 = 110\ k\Omega$) is a better solution since resistor tolerances could cause i_O to exceed 0.1 mA in the first case.

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Inverting Amplifier: $A_v = -\frac{30k\Omega}{1.5k\Omega} = -20.0 \quad R_{in} = R_1 = 1.5\ k\Omega$

$$v_O = -20.0(0.15V) = -3.00\ V \quad i_O = \frac{v_O}{R_2} = \frac{-3.00V}{30k\Omega} = -100\ \mu A$$

Non-Inverting Amplifier: $A_v = 1 + \frac{30k\Omega}{1.5k\Omega} = +21.0 \quad R_{in} = \frac{v_S}{i_S} = \frac{0.15V}{0A} = \infty$

$$v_O = 21.0(0.15V) = 3.15\ V \quad i_O = \frac{v_O}{R_2 + R_1} = \frac{3.15V}{30k\Omega + 1.5k\Omega} = 100\ \mu A$$

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$$V_{o1} = 2V\left(-\frac{3k\Omega}{1k\Omega}\right) = -6V \quad V_{o2} = 4V\left(-\frac{3k\Omega}{2k\Omega}\right) = -6V \quad v_O = \left(-6\sin 1000\pi t - 6\sin 2000\pi t\right)\ V$$

The summing junction is a virtual ground: $R_{in1} = \frac{v_1}{i_1} = R_1 = 1\ k\Omega \quad R_{in2} = \frac{v_2}{i_2} = R_2 = 2\ k\Omega$

$$I_{o1} = \frac{V_{o1}}{R_3} = \frac{-6V}{3k\Omega} = -2mA \quad I_{o2} = \frac{V_{o2}}{R_3} = \frac{-6V}{3k\Omega} = -2mA \quad i_O = \left(-2\sin 1000\pi t - 2\sin 2000\pi t\right)\ mA$$

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$$(i)\ I_2 = \frac{3V}{10k\Omega + 100k\Omega} = 27.3\ \mu A$$

$$(ii)\ A_v = -\frac{100k\Omega}{10k\Omega} = -10.0 \quad V_O = -10\left(3V - 5V\right) = 20.0\ V \quad I_O = \frac{V_O - V_-}{100k\Omega} = \frac{V_O - V_+}{100k\Omega}$$

$$V_+ = V_2\frac{R_4}{R_3 + R_4} = 5\frac{100k\Omega}{10k\Omega + 100k\Omega} = 4.545V \quad I_O = \frac{20.0 - 4.545}{100k\Omega} = 155\ \mu A \quad I_2 = \frac{5V}{10k\Omega + 100k\Omega} = 45.5\ \mu A$$

$$(iii)\ A_v = -\frac{36k\Omega}{2k\Omega} = -18.0 \quad V_O = -18\left(8V - 8.25V\right) = 4.50\ V \quad I_O = \frac{V_O - V_-}{36k\Omega} = \frac{V_O - V_+}{36k\Omega}$$

$$V_+ = V_2\frac{R_2}{R_1 + R_2} = 8.25\frac{36k\Omega}{2k\Omega + 36k\Omega} = 7.816V \quad I_O = \frac{4.50 - 7.816}{36k\Omega} = -92.1\ \mu A$$

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$$I = \frac{V_A - V_B}{2R_1} = \frac{5.001V - 4.999V}{2k\Omega} = 1.00\ \mu A$$

$$V_A = V_1 + IR_2 = 5.001V + 1.00\mu A\left(49k\Omega\right) = 5.05\ V$$

$$V_B = V_2 - IR_2 = 4.999V - 1.00\mu A\left(49k\Omega\right) = 4.95\ V$$

$$V_O = \left(-\frac{R_4}{R_3}\right)\left(V_A - V_B\right) = \left(-\frac{10k\Omega}{10k\Omega}\right)\left(5.05 - 4.95\right) = -0.100\ V$$

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$$(i)\ A_v = -\frac{R_2}{R_1} = -10^{\frac{26}{20}} = -20.0 \quad R_1 = R_{in} = 10k\Omega \quad R_2 = 20R_1 = 200k\Omega$$

$$C = \frac{1}{2\pi\left(3kHz\right)\left(200k\Omega\right)} = 265\ pF \quad \text{Closest values: } R_1 = 10k\Omega \quad R_2 = 200k\Omega \quad C = 270\ pF$$

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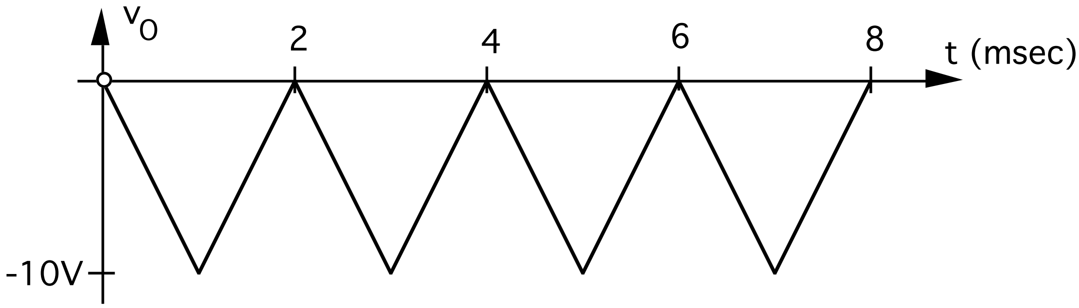
$(ii)\ R_{in} = R_1 = 10\ k\Omega \qquad \Delta V = -\frac{I}{C}\Delta T \qquad \text{C} = \frac{5V}{10k\Omega}\left(\frac{1}{10V}\right)(1ms) = 0.05\mu F$



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$$v_O = -RC\frac{dv_S}{dt} = -(20k\Omega)(0.02\mu F)(2.50V)(2000\pi)(\cos 2000\pi t) = -6.28\cos 2000\pi t \text{ V}$$

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$(i)\ A_{vA} = A_{vB} = A_{vC} = -\frac{R_2}{R_1} = -\frac{68k\Omega}{2.7k\Omega} = -25.2 \qquad R_{inA} = R_{inB} = R_{inC} = R_1 = 2.7\ k\Omega$

The op-amps are ideal: $R_{outA} = R_{outB} = R_{outC} = 0$

$(ii)\ A_v = A_{vA}A_{vB}A_{vC} = (-25.2)^3 = -16,000 \qquad R_{in} = R_{inA} = 2.7\ k\Omega \qquad R_{out} = R_{outC} = 0$

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$$A_v = (-25.2)^3\left(\frac{2.7k\Omega}{R_{out} + 2.7k\Omega}\right)^2 \geq 0.99(25.2)^3 \qquad \left(\frac{2.7k\Omega}{R_{out} + 2.7k\Omega}\right)^2 \geq 0.99$$

$$\frac{2.7k\Omega}{R_{out} + 2.7k\Omega} \geq 0.9950 \qquad R_{out} \geq 13.6\ \Omega$$

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$$\text{(i)}\ A_v(0) = +1 \qquad A_v(s) = \frac{\omega_o^2}{s^2 + s\sqrt{2}\omega_o + \omega_o^2} \qquad A_v(j\omega) = \frac{\omega_o^2}{j\omega\sqrt{2}\omega_o + \omega_o^2 - \omega^2}$$

$$|A_v(j\omega_H)| = \frac{1}{\sqrt{2}} \rightarrow \frac{\omega_o^2}{\sqrt{(\omega_o^2 - \omega_H^2)^2 + 2\omega_H^2\omega_o^2}} = \frac{1}{\sqrt{2}} \rightarrow 2\omega_o^4 = \omega_o^4 + \omega_H^4 \rightarrow \omega_o = \omega_H$$

$$(ii)\ \frac{1}{\sqrt{2}} = \sqrt{\frac{C_1}{C_2}}\frac{\sqrt{R^2}}{2R} \rightarrow C_1 = 2C_2 \rightarrow C_2 = \frac{1}{\sqrt{2}(2.26k\Omega)(20000\pi)} = 4.98nF$$

$C_2 = 0.005\ \mu F \qquad C_1 = 0.01\ \mu F$

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(iii) To decrease the cutoff frequency from 5kHz to 2 kHz, we must increase the resistances by a factor of $\frac{5\text{kHz}}{2\text{kHz}} = 2.50 \rightarrow R_1 = R_2 = 2.50(2.26k\Omega) = 5.65\ k\Omega$

$$(iv)\ \frac{1}{\sqrt{2}} = \sqrt{\frac{C}{C}}\frac{\sqrt{R_1R_2}}{R_1+R_2} \rightarrow R_1^2 + 2R_1R_2 + R_2^2 = 2R_1R_2 \rightarrow R_1^2 = -R_2^2 \quad \text{-- can't be done!}$$

$$Q = \frac{\sqrt{R_1R_2}}{R_1+R_2} \qquad \frac{dQ}{dR_2} = \frac{1}{(R_1+R_2)^2}\left[\frac{R_1(R_1+R_2)}{2\sqrt{R_1R_2}} - \sqrt{R_1R_2}\right] = 0 \rightarrow R_2 = R_1 \rightarrow Q_{\max} = \frac{1}{2}$$

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$$S_{C_1}^Q = \frac{C_1}{Q}\frac{dQ}{dC_1} = \frac{C_1}{Q}\left[\frac{1}{2\sqrt{C_1C_2}}\frac{\sqrt{R_1R_2}}{R_1+R_2}\right] = \frac{C_1}{Q}\frac{Q}{2C_1} = 0.5$$

$$S_{R_2}^Q = \frac{R_2}{Q}\frac{dQ}{dR_2} \qquad \mathrm{R}_1 = R_2 \rightarrow Q = \frac{1}{2}\sqrt{\frac{C_1}{C_2}} \rightarrow S_{R_2}^Q = 0$$

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$$(i)\ \left|A_v(j\omega_o)\right| = K\left|\frac{-\omega_o^2}{-\omega_o^2 + j(3-K)\omega_o^2 + \omega_o^2}\right| = \frac{K}{3-K} \qquad A_v(j\omega_o) = \frac{K}{3-K}\angle 90^o$$

$$(ii)\ f_o = \frac{1}{2\pi\sqrt{10k\Omega(20k\Omega)(0.0047\mu F)(0.001\mu F)}} = 5.19\ kHz$$

$$Q = \left[\sqrt{\frac{10k\Omega}{20k\Omega}}\frac{4.7nF + 1.0nF}{\sqrt{4.7nF(1.0nF)}} + (1-2)\sqrt{\frac{20k\Omega(1.0nF)}{10k\Omega(4.7nF)}}\right]^{-1} = 0.829$$

$$(iii)\ S_K^Q = \frac{K}{Q}\frac{dQ}{dK} \quad Q = \frac{1}{3-K} \quad \frac{dQ}{dK} = \frac{-1}{(3-K)^2}(-1) = Q^2 \quad S_K^Q = \frac{K}{Q}\frac{dQ}{dK} = KQ$$

$$Q = \frac{1}{3-K} \rightarrow KQ = 3Q - 1 \quad S_K^Q = 3Q - 1 = 1.12$$

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$$R_{th} = 2k\Omega \| 2k\Omega = 1k\Omega \quad f_o = \frac{1}{2\pi\sqrt{1k\Omega(82k\Omega)(0.02\mu F)(0.02\mu F)}} = 879\ Hz \quad Q = \frac{1}{2}\sqrt{\frac{82k\Omega}{1k\Omega}} = 4.53$$

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$(ii)\ \left|A_{BP}(j\omega_o)\right| = KQ = \frac{R_2}{R_1} \quad 10 = \frac{294k\Omega}{R_1} \rightarrow R_1 = 29.4\ k\Omega$

$(iii)\ f_o = \frac{1}{2\pi RC} = \frac{1}{2\pi(40.2k\Omega)(2nF)} = 1.98\ kHz \quad BW = \frac{1}{2\pi R_2 C} = \frac{1}{2\pi(402k\Omega)(2nF)} = 198\ Hz$

$A_{BP}(j\omega_o) = -\frac{R_2}{R_1} = -\frac{402k\Omega}{20.0k\Omega} = -20.1$

(iv) Blindly using the equations at the top of page 580 yields

$$f_o^{min} = \frac{1}{2\pi RC} = \frac{1}{2\pi(1.01)(29.4k\Omega)(1.02)(2.7nF)} = 1946\ Hz$$

$$f_o^{max} = \frac{1}{2\pi RC} = \frac{1}{2\pi(0.99)(29.4k\Omega)(0.98)(2.7nF)} = 2067\ Hz$$

$$BW^{min} = \frac{1}{2\pi R_2 C} = \frac{1}{2\pi(1.01)(294k\Omega)(1.02)(2.7nF)} = 195\ Hz$$

$$BW^{max} = \frac{1}{2\pi R_2 C} = \frac{1}{2\pi(0.99)(294k\Omega)(0.98)(2.7nF)} = 207\ Hz$$

$$A_{BP}^{min} = -\frac{R_2}{R_1} = -\frac{294k\Omega(1.01)}{14.7k\Omega(0.99)} = -20.4 \quad A_{BP}^{max} = -\frac{R_2}{R_1} = -\frac{294k\Omega(0.99)}{14.7k\Omega(1.01)} = -19.6$$

The W/C results are similar if R and C are not the same for example where $\omega_o = \frac{1}{\sqrt{R_A R_B C_A C_B}}$.

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(i)-(a) $R_1 = R_2 = 5(2.26k\Omega) = 11.3\ k\Omega \quad C_1 = \frac{0.02\mu F}{5} = 0.004\ \mu F \quad C_2 = \frac{0.01\mu F}{5} = 0.002\ \mu F$

$$f_o = \frac{1}{2\pi\sqrt{(11.3k\Omega)(11.3k\Omega)(0.004\mu F)(0.002\mu F)}} = 4980\ Hz$$

$$Q = \sqrt{\frac{11.3k\Omega}{11.3k\Omega}}\frac{\sqrt{(0.004\mu F)(0.002\mu F)}}{0.004\mu F + 0.002\mu F} = 0.471$$

(b) $R_1 = R_2 = 0.885(2.26k\Omega) = 2.00\ k\Omega \quad C_1 = \frac{0.02\mu F}{0.885} = 0.0226\ \mu F \quad C_2 = \frac{0.01\mu F}{0.885} = 0.0113\ \mu F$

$$f_o = \frac{1}{2\pi\sqrt{(2.00k\Omega)(2.00k\Omega)(0.0226\mu F)(0.0113\mu F)}} = 4980\ Hz$$

$$Q = \sqrt{\frac{2.00k\Omega}{2.00k\Omega}}\frac{\sqrt{(0.0226\mu F)(0.0113\mu F)}}{0.0226\mu F + 0.0113\mu F} = 0.471$$

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$(ii)\ f_o = \dfrac{1}{2\pi\sqrt{(1k\Omega)(82k\Omega)(0.02\mu F)(0.02\mu F)}} = 879\ Hz \quad Q = \sqrt{\dfrac{82k\Omega}{1k\Omega}}\dfrac{\sqrt{(0.02\mu F)(0.02\mu F)}}{0.02\mu F + 0.02\mu F} = 4.53$

The values of the resistors are unchanged. $C_1 = C_2 = \dfrac{0.02\mu F}{4} = 0.005\ \mu F$

$f_o = \dfrac{1}{2\pi\sqrt{(1k\Omega)(82k\Omega)(0.005\mu F)(0.005\mu F)}} = 3520\ Hz \quad Q = \sqrt{\dfrac{82k\Omega}{1k\Omega}}\dfrac{\sqrt{(0.005\mu F)(0.005\mu F)}}{0.005\mu F + 0.005\mu F} = 4.53$

Page 585

The diode will conduct and pull the output up to $v_O = v_S = 1.0\ V$. $v_1 = v_O + v_D = 1.0 + 0.6 = 1.6\ V$

For a negative input, there is no path for current through R, so $v_O = 0\ V$. The op-amp sees a -1V input so the output will limit at the negative power supply: $v_O = -10\ V$.

The diode has a 10-V reverse bias across it, so $V_Z > 10\ V$.

Page 587

(i) $v_S = 2\ V$: Diode D_1 conducts, and D_2 is off. The negative input is a virtual ground.

$v_1 = -v_{D2} = -0.6\ V$. The current in R is 0, so $v_O = 0\ V$.

$v_S = -2\ V$: Diode D_2 conducts, and D_1 is off. The negative input is a virtual ground.

$v_O = -\dfrac{R_2}{R_1}v_S = -\dfrac{68k\Omega}{22k\Omega}(-2V) = +6.18\ V \quad v_1 = v_O + v_{D1} = 6.78\ V.$

$v_S = \dfrac{15V}{-3.09} = -4.85\ V \quad v_1 = v_O + v_{D1} = 6.78\ V.$ When $v_O = 15\ V$, $v_{D2} = -15.6\ V$, so $V_Z = 15.6\ V$.

(ii) $v_O = \dfrac{20k\Omega}{20k\Omega}\left(\dfrac{10.2k\Omega}{3.24k\Omega}\right)\dfrac{2V}{\pi} = 2.00\ V$

Page 589

$V_- = -\dfrac{R_1}{R_1 + R_2}V_{EE} = -\dfrac{1k\Omega}{1k\Omega + 9.1k\Omega}10V = -0.990\ V \quad V_+ = \dfrac{1k\Omega}{1k\Omega + 9.1k\Omega}10V = +0.990\ V$

$V_n = 0.990V - (-0.990V) = 1.98\ V$

Page 591

$T = 2(10k\Omega)(0.001\mu F)\ln\left(\dfrac{1+0.5}{1-0.5}\right) = 21.97\mu s \quad f = \dfrac{1}{T} = 45.5\ kHz$

Page 594

$$\beta = -\frac{22k\Omega}{22k\Omega + 18k\Omega} = 0.550 \quad T = (11k\Omega)(0.002\mu F)\ln\left[\frac{1+\frac{0.7}{5}}{1-0.550}\right] = 20.4\ \mu s$$

$$T_r = (11k\Omega)(0.002\mu F)\ln\left[\frac{1+0.55\left(\frac{5V}{5V}\right)}{1-\frac{0.7}{5}}\right] = 13.0\ \mu s$$

CHAPTER 12

Page 612

$(i)\ A_{ideal} = \frac{1}{\beta} = 100 \qquad A_v = \frac{A}{1+A\beta} = \frac{10^5}{1+10^5(0.01)} = 99.90$

$v_o = 99.9(0.1V) = 9.99\ V \qquad v_{id} = \frac{v_o}{A} = \frac{9.99V}{10^5} = 99.9\ \mu V$

(ii) Values taken from OP - 27 specification sheet (www.jaegerblalock.com or www.analog.com)

(iii) Values taken from OP - 27 specification sheet

Page 613

$$A_v = \frac{-R_2}{R_1}\frac{A\beta}{1+A\beta} \qquad FGE = \frac{\left(\frac{-R_2}{R_1}\right) - \left(\frac{-R_2}{R_1}\frac{A\beta}{1+A\beta}\right)}{\left(\frac{-R_2}{R_1}\right)} = 1 - \frac{A\beta}{1+A\beta} = \frac{1}{1+A\beta}$$

Page 614

$$FGE = \frac{1}{1+A\beta} = \frac{1}{1+10^4\left(\frac{1k\Omega}{1k\Omega + 39k\Omega}\right)} = 3.98x10^{-3}\ or\ 0.398\ \% \qquad FGE \cong \frac{1}{A\beta} = 0.40\ \%$$

Page 615

Values taken from OP - 77 specification sheet (www.jaegerblalock.com or www.analog.com)

Page 616

$$A \cong \frac{R_o}{\beta R_{out}} = \frac{50\Omega}{(0.025)(0.1\Omega)} = 20,000$$

Page 617

$(i)\ A_v = \frac{A}{1+A\beta} = \frac{10^4}{1+10^4(0.025)} = +39.8$

$(ii)\ A_v^{max} = \frac{(39k\Omega + 1k\Omega)(1.05)}{1k\Omega(0.95)} = 44.2 \qquad A_v^{max} = \frac{(39k\Omega + 1k\Omega)(0.95)}{1k\Omega(1.05)} = 36.2$

$GE = 44.2 - 40.0 = 4.20 \quad FGE = \frac{4.20}{40} = 10.5\ \% \qquad GE = 36.2 - 40.0 = -3.80 \quad FGE = \frac{-3.80}{40} = -9.5\ \%$

Page 618

$$A \cong \frac{R_o}{\beta R_{out}} = \frac{200\Omega}{(0.01)(0.1\Omega)} = 200,000 \qquad A_{dB} = 20\log\left(2x10^5\right) = 106\ dB$$

Page 619

Values taken from op-amp specification sheets (www.jaegerblalock.com or www.analog.com)

Page 620

$$R_{in} = R_{id}\left(1 + A\beta\right) = 1M\Omega\left[1 + 10^4\left(\frac{10k\Omega}{10k\Omega + 390k\Omega}\right)\right] = 251\ M\Omega$$

$$i_- = -\frac{v_s}{R_{in}} = -\frac{1V}{251\ M\Omega} = -3.98\ nA \quad i_1 = \frac{\beta v_o}{R_1} = \frac{A\beta}{1 + A\beta}\left(\frac{v_s}{R_1}\right) \cong \left(\frac{1V}{10k\Omega}\right) = 100\ \mu A \quad |i_1| >> |i_-|$$

More exactly, $i_1 = \frac{\beta v_o}{R_1} = \frac{A\beta}{1 + A\beta}\left(\frac{v_s}{R_1}\right) = \frac{10^4(0.025)}{1 + 10^4(0.025)}\left(\frac{1V}{10k\Omega}\right) = 99.6\ \mu A$

Page 621

$$R_{in} = R_1 + R_{id}\left\|\frac{R_2}{1 + A}\right. = 1k\Omega + 1M\Omega\left\|\frac{100k\Omega}{1 + 10^5}\right. = 1001\ \Omega \qquad R_{in}^{ideal} = R_1 = 1000\ \Omega \quad 1\ \Omega\ or\ 0.1\ \%$$

Page 622

Values taken from op-amp specification sheets (www.jaegerblalock.com or www.analog.com)

Page 626

$$v_o = A\left(v_{id} + \frac{v_{ic}}{CMRR}\right)$$

$$v_o^{\min} = A\left(v_{id} + \frac{v_{ic}}{CMRR}\right) = 2500\left(0.002 - \frac{5.000}{10^4}\right) = 3.750\ V$$

$$v_o^{\max} = A\left(v_{id} + \frac{v_{ic}}{CMRR}\right) = 2500\left(0.002 + \frac{5.000}{10^4}\right) = 6.250\ V$$

Page 627

$$A_v = \frac{A\left(1 + \frac{1}{2CMRR}\right)}{1 + A\left(1 - \frac{1}{2CMRR}\right)} = \frac{10^4\left(1 + \frac{1}{2x10^4}\right)}{1 + 10^4\left(1 - \frac{1}{2x10^4}\right)} = 1.000 \qquad A_v = \frac{10^3\left(1 + \frac{1}{2x10^3}\right)}{1 + 10^3\left(1 - \frac{1}{2x10^3}\right)} = 1.000$$

Page 628

$GE = FGE\left(A_v\right) \le 5x10^{-5}(1) = 5x10^{-5}$ Worst case occurs for negative CMRR : $GE \cong \frac{1}{A} + \frac{1}{CMRR}$

If both terms make equal contributions: $\text{A} = \text{CMRR} = \frac{1}{2.5x10^{-5}} = 4\text{x}10^4$ or 92 dB

For other cases: $\text{CMRR} = \left(5x10^{-5} - \frac{1}{A}\right)^{-1}$ or $\text{A} = \left(5x10^{-5} - \frac{1}{CMRR}\right)^{-1}$

$\text{A} = 100\text{dB} \quad \text{CMRR} = \left(5x10^{-5} - \frac{1}{10^5}\right)^{-1} = 2.5x10^4$ or 88 dB

$\text{CMRR} = 100\text{dB} \quad \text{A} = \left(5x10^{-5} - \frac{1}{10^5}\right)^{-1} = 2.5x10^4$ or 88 dB

Page 630

Values taken from op-amp specification sheets (www.jaegerblalock.com or www.analog.com)

Page 631

(i) $\left|V_O\right| \le 50(0.002V) \rightarrow -0.100\ V \le V_O \le +0.100\ V$

(ii) Values taken from op-amp specification sheets (www.jaegerblalock.com or www.analog.com)

Page 633

Values taken from op-amp specification sheets (www.jaegerblalock.com or www.analog.com)

Page 634

(i) $R = 39k\Omega \| 1k\Omega = 975\ \Omega$

(ii) $\text{v}_O(t) = V_{OS} + \frac{V_{OS}}{RC}t + \frac{I_{B2}}{C}t \quad 1.5mV + \frac{1.5mV}{10k\Omega(100\,pF)}t + \frac{100nA}{100\,pF}t = 15V \rightarrow t = 6.00\ ms$

Page 636

Values taken from op-amp specification sheets (www.jaegerblalock.com or www.analog.com)

Page 637

Values taken from op-amp specification sheets (www.jaegerblalock.com or www.analog.com)

Page 638

$$R_{EQ} = R_L \| (R_2 + R_1) \geq \frac{20V}{5mA} = 4k\Omega \qquad R_1 + R_2 \geq \left(\frac{1}{4k\Omega} - \frac{1}{5k\Omega}\right)^{-1} = 20k\Omega$$

Including 5% tolerances, $R_1 + R_2 \geq 21k\Omega$ $\quad A_v = 10 \rightarrow R_2 = 9R_1$

A few possibilities: 27 kΩ and 3 kΩ, 270 kΩ and 30 kΩ, 180 kΩ and 20 kΩ, etc.

Page 640

$$(i)\ A_o = 10^{\frac{100}{20}} = 10^5 \quad \omega_B = \frac{\omega_T}{A_o} = \frac{2\pi(5x10^6)}{10^5} = \frac{10^7\pi}{10^5} = 100\pi \ \ f_B = \frac{100\pi}{2\pi} = 50\ Hz \quad A_v(s) = \frac{10^7\pi}{s + 100\pi}$$

$$(ii)\ A_v(s) = \frac{\omega_T}{s + \frac{\omega_T}{A_o}} = \frac{2\pi\, x\, 10^6}{s + \frac{2\pi\, x\, 10^6}{2x10^5}} = \frac{2\pi\, x\, 10^6}{s + 10\pi}$$

Page 643

$$(i)\ A_o = 10^{\frac{90}{20}} = 31600 \quad f_B = \frac{f_T}{A_o} = \frac{5x10^6}{31600} = 158\ Hz \quad A_v(s) = \frac{2\pi(5x10^6)}{s + 2\pi(158)} = \frac{10^7\pi}{s + 316\pi}$$

$$f_H \cong \beta f_T = 0.01(5MHz) = 50\ kHz \qquad A_v(s) = \frac{2\pi(5x10^6)}{s + 2\pi(5x10^4)} = \frac{10^7\pi}{s + 10^5\pi}$$

$$(ii)\ \text{For } \omega_H >> \omega_B:\ A\beta = \frac{\omega_T}{s + \omega_B}\beta \cong \frac{\beta\omega_T}{j\omega_H} = \frac{1}{j} = -j1 \quad \text{since } \omega_H = \beta\omega_T$$

Page 645

$$(i)\ A_o = 10^{\frac{90}{20}} = 31600 \quad f_B = \frac{f_T}{A_o} = \frac{5x10^6}{31600} = 158\ Hz \qquad A_v(s) = \frac{2\pi(5x10^6)}{s + 2\pi(158)} = \frac{10^7\pi}{s + 316\pi}$$

$$f_H \cong \beta f_T = \frac{5MHz}{1 + 10^{\frac{50}{20}}} = 15.8\ kHz \qquad A_v(s) = \frac{2\pi(5x10^6)}{s + 2\pi(15.8x10^3)} = \frac{10^7\pi}{s + 3.16x10^4\pi}$$

$$(ii)\ f_H \cong \beta f_T = 1(5MHz) = 5\ MHz \qquad f_H \cong \beta f_T = \frac{1}{2}(5MHz) = 2.5\ MHz$$

Page 647

$$A_v(0) = 50(25) = 1250 \qquad \left|A_v(\omega_H)\right| = \frac{1250}{\sqrt{2}} = 884$$

$$\left[1 + \frac{\omega_H^2}{(10000\pi)^2}\right]\left[1 + \frac{\omega_H^2}{(20000\pi)^2}\right] = 2 \rightarrow \left(\omega_H^2\right)^2 + 4.935x10^9\omega_H^2 - 3.896x10^{18} = 0$$

$$\omega_H^2 = 6.925x10^8 \rightarrow \omega_H = 26.3x10^3 \rightarrow f_H = \frac{26.3x10^3}{2\pi} = 4190\ Hz$$

Page 648

$$(i) \quad A_v(0) = -100(66.7)(50) = -3.34x10^5 \qquad \left|A_v(\omega_H)\right| = \frac{-3.34x10^5}{\sqrt{2}} = -2.36x10^5$$

$$\left[1 + \frac{\omega_H^2}{(10000\pi)^2}\right]\left[1 + \frac{\omega_H^2}{(15000\pi)^2}\right]\left[1 + \frac{\omega_H^2}{(20000\pi)^2}\right] = 2$$

$$\omega_H^6 + 7.156x10^9\omega_H^4 + 1.486x10^{10}\omega_H^2 - 8.562x10^{27} = 0$$

Using MATLAB, $\omega_H = 21.7x10^3 \rightarrow f_H = \frac{21.7x10^3}{2\pi} = 3450\ Hz$

$$(ii) \quad A_v(0) = (-30)^3 = -2.70x10^4 \qquad f_H = (33.3kHz)\sqrt{2^{\frac{1}{3}} - 1} = 17.0\ \text{k}Hz$$

Page 653

$$V_M \leq \frac{SR}{\omega} = \frac{5x10^5 V/s}{2\pi(20kHz)} = 3.98\ V \qquad f_M = \frac{SR}{2\pi V_{FS}} = \frac{5x10^5 V/s}{2\pi(10V)} = 7.96\ kHz$$

Page 657

$$A_{v1} = 1 + \frac{130k\Omega}{22k\Omega} = 6.909 \qquad v_{O1} = 0.001(6.909) = 6.91\ mV \qquad v_{O2} = 0.001V(6.909)^2 = 47.7\ mV$$

$$v_{O3} = 0.001(6.909)^3 = 330\ mV \qquad v_{O4} = 0.001V(6.909)^4 = 2.28\ V \qquad v_{O5} = 0.001V(6.909)^5 = 15.7\ V$$

$$v_{O5} > 15V \rightarrow v_{O5} = 15\ V \qquad v_{O6} = 15V(6.909) = 104\ V \qquad v_{O6} > 15V \rightarrow v_{O6} = 15\ V$$

CHAPTER 13

Page 671

(i) (a) At the Q-point: $\beta_F = \frac{I_C}{I_B} = \frac{1.5mA}{15\mu A} = 100$ (b) $I_S = \frac{I_C}{\exp\left(\frac{V_{BE}}{V_T}\right)} = \frac{1.5mA}{\exp\left(\frac{0.700V}{0.025V}\right)} = 1.04\ fA$

(c) $R_{in} = \frac{v_{be}}{i_b} = \frac{8mV}{5\mu A} = 1.6\ k\Omega$ (d) With the given applied signal, the smallest value of v_{CE} is

$v_{CE}^{min} = 5V - 0.5mA(3.3k\Omega) = 3.35\ V$ which exceeds $v_{BE} = 0.708\ V$.

(ii) (a) $v_{DS} = 10 - 3300 i_{DS}$

(b) Using the peak-to-peak voltage swings, $A_v = \frac{v_{ds}}{v_{gs}} = \frac{2.7 - 6.7}{4.0 - 3.0}\frac{V}{V} = -4.0.$

Note that there is some distortion in this amplifier since the negative output voltage excursion is larger than the positive output change.

(c) $v_{DS}^{min} = 2.7V$ with $v_{GS} - V_{TN} = 4 - 1 = 3V$, so the transistor has entered the triode region.

(d) Choose two points on the i-v characteristics. For example,

$1.56mA = \frac{K_n}{2}\left(3.5 - V_{TN}\right)^2$ and $1.0mA = \frac{K_n}{2}\left(3.0 - V_{TN}\right)^2$.

Solving for K_n and V_{TN} yields $500\frac{\mu A}{V^2}$ and 1 V respectively.

Page 673

(i) $V_{EQ} = \frac{10k\Omega}{10k\Omega + 30k\Omega}12V = 3.00V$ $R_{EQ} = 10k\Omega \| 30k\Omega = 7.5k\Omega$

$$I_C = \beta_F I_B = \beta_F \frac{V_{EQ} - V_{BE}}{R_{EQ} + (\beta_F + 1)R_4} = 100\frac{3.0V - 0.7V}{7.5k\Omega + (101)(1.5k\Omega)} = 1.45\ mA$$

$$V_{CE} = 12 - 4300 I_C - 1500 I_E = 12 - 4300(1.45mA) - 1500\left(\frac{101}{100}\right)(1.45mA) = 3.57\ V$$

(ii) $v_C(t) = V_C + v_C = (5.8 - 1.1\sin 2000\pi t)\ V$ $v_E(t) = V_E + 0 = 1.45mA(1.5k\Omega) = 2.2\ V$

$|i_c| = \frac{1.1V}{4.3k\Omega} = 0.256mA$ $\angle i_c = 180^o$ $i_c(t) = -0.26\sin 2000\pi t\ mA$

(iii) $X_C = \frac{1}{\omega C} = \frac{1}{2000\pi(500\mu F)} = 0.318\ \Omega$

Page 676

$R_B = 20k\Omega \| 62k\Omega = 15.1\ k\Omega$ $R_L = 8.2k\Omega \| 100k\Omega = 7.58\ k\Omega$

Page 680

$(i)\ r_d = \frac{V_T}{I_D + I_S} \quad r_d = \frac{0.025V}{1fA} = 25.0\ T\Omega \quad r_d = \frac{0.025V}{50\mu A} = 500\ \Omega$

$r_d = \frac{0.025V}{2mA} = 12.5\ \Omega \quad r_d = \frac{0.025V}{3A} = 8.33\ \text{m}\Omega$

$(\text{ii})\ r_d = \frac{0.025V}{1.5mA} = 16.7\ \Omega \quad \frac{kT}{q} = \left(8.62x10^{-5}\frac{V}{K}\right)(373K) = 0.0322\ V \quad r_d = \frac{0.0322V}{1.5mA} = 21.5\ \Omega$

Page 685

$(i)\ g_m = 40I_C = 40(50\mu A) = 2.00\ mS \quad r_\pi = \frac{\beta_o}{g_m} = \frac{75}{2mS} = 37.5\ k\Omega$

$r_o = \frac{V_A + V_{CE}}{I_C} = \frac{60V + 5V}{50\mu A} = 1.30\ M\Omega \quad \mu_f = g_m r_o = 2mS(1.30M\Omega) = 2600$

$(ii)\ g_m = 40I_C = 40(250\mu A) = 10.0\ mS \quad r_\pi = \frac{\beta_o}{g_m} = \frac{50}{10mS} = 5.00\ k\Omega$

$r_o = \frac{V_A + V_{CE}}{I_C} = \frac{75V + 15V}{250\mu A} = 360\ k\Omega \quad \mu_f = g_m r_o = 10mS(360k\Omega) = 3600$

(iii) The slope of the output characteristics is zero, so $V_A = \infty$ and $r_o = \infty$.

$\beta_{FO} = \frac{\beta_F}{1 + \frac{V_{CE}}{V_A}} = \beta_F = \frac{I_C}{I_B} = \frac{1.5mA}{15\mu A} = 100 \quad g_m = \frac{\Delta i_C}{\Delta v_{BE}} = \frac{0.5mA}{8mV} = 62.5\ mS$

$\beta_o = \frac{\Delta i_C}{\Delta i_B} = \frac{500\mu A}{5\mu A} = 100 \quad r_\pi = \frac{\beta_o}{g_m} = \frac{100}{62.5mS} = 1.60\ k\Omega$

Page 692

$A_{vt} = -g_m R_L = -9.80mS(18k\Omega) = -176$

Page 695

Assume the Q - point remains constant.

$(a)\ R_L^{max} = 19.8k\Omega \quad R_L^{min} = 16.2k\Omega \quad R_E^{max} = 3.30k\Omega \quad R_L^{min} = 2.70k\Omega$

$R_{iB}^{max} = 10.2k\Omega + 101(3.3k\Omega) = 344k\Omega \quad R_{iB}^{min} = 10.2k\Omega + 101(2.7k\Omega) = 283k\Omega$

$$A_v^{min} = -\frac{9.80mS(16.2k\Omega)}{1+9.80mS(3.30k\Omega)}\left(\frac{104k\Omega \| 344k\Omega}{1k\Omega + 104k\Omega \| 344k\Omega}\right) = -4.70$$

$$A_v^{max} = -\frac{9.80mS(19.8k\Omega)}{1+9.80mS(2.70k\Omega)}\left(\frac{104k\Omega \| 283k\Omega}{1k\Omega + 104k\Omega \| 283k\Omega}\right) = -6.98$$

$(b)\ r_\pi = \dfrac{125}{9.80mS} = 12.8k\Omega \quad R_{iB} = 12.8k\Omega + 126(3.0k\Omega) = 391k\Omega$

$$A_v = -\frac{9.80mS(18k\Omega)}{1+9.80mS(3.00k\Omega)}\left(\frac{104k\Omega \| 391k\Omega}{1k\Omega + 104k\Omega \| 391k\Omega}\right) = -5.73$$

$(c)\ V_{CE} = 12V - 22k\Omega I_C - 13k\Omega I_E = 12V - 0.275mA\left(22k\Omega + \dfrac{101}{100}13k\Omega\right) = 2.34\ V$

$g_m = 40(0.275mA) = 11.0mS \quad r_\pi = \dfrac{100}{11.0mS} = 9.09k\Omega$

$$R_{iB} = 9.09k\Omega + 101(3.0k\Omega) = 312k\Omega \quad A_v = -\frac{11.0mS(18k\Omega)}{1+11.0mS(3.00k\Omega)}\left(\frac{104k\Omega \| 312k\Omega}{1k\Omega + 104k\Omega \| 312k\Omega}\right) = -5.75$$

Page 697

$(i)\ R_{iB}^{max} = 10.2k\Omega + 101(1k\Omega) = 111k\Omega \quad R_{E2} = 13k\Omega - 1k\Omega = 12\ k\Omega$

$$A_v = -\frac{9.80mS(18k\Omega)}{1+9.80mS(1.00k\Omega)}\left(\frac{104k\Omega \| 111k\Omega}{1k\Omega + 104k\Omega \| 111k\Omega}\right) = -16.0$$

(ii) The reference to C_2 should be C_3. $A_v = -159$ as calculated in the Ex. 13.4.

$$(iii)\ V_T = \left(\frac{1.38x10^{-23}}{1.602x10^{-19}}\frac{V}{K}\right)(273K + 27K) = 25.84mV \quad I_S = \frac{I_C}{\exp\left(\frac{V_{BE}}{V_T}\right)} = \frac{245\mu A}{\exp\left(\frac{0.700V}{0.02584V}\right)} = 0.421fA$$

(iv) From Ex. 13.3, $R_{iB} = 313\ k\Omega$, and $r_\pi = 10.2k\Omega$.

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$$(i)\ R_{iC} = 320k\Omega\left[1 + \frac{100(2k\Omega)}{(1k\Omega \| 104k\Omega) + 10.2k\Omega + 2k\Omega}\right] = 4.85\ M\Omega \qquad \mu_f R_E = 3140(2k\Omega) = 6.28\ M\Omega$$

$$R_{iC} < \mu_f R_E \qquad R_{out} = 4.85M\Omega \| 22k\Omega = 21.9\ k\Omega$$

$$(ii)\ \lim_{R_E \to \infty} R_{iC} = \lim_{R_E \to \infty} r_o\left(1 + \frac{\beta_o R_E}{R_{th} + r_\pi + R_E}\right) = r_o\left(1 + \frac{\beta_o R_E}{R_E}\right) = (\beta_o + 1)r_o$$

Page 704

$$(i)\ (a)\ g_m = \sqrt{2K_n I_D(1 + \lambda V_{DS})} = \sqrt{2(1mA/V^2)(0.25mA)[1 + 0.02(5)]} = 1.73\ mS$$

$$r_o = \frac{\frac{1}{\lambda} + V_{DS}}{I_D} = \frac{50V + 5V}{250\mu A} = 220\ k\Omega \qquad \mu_f = g_m r_o = 0.742mS(220k\Omega) = 163$$

$$g_m = \sqrt{2K_n I_D(1 + \lambda V_{DS})} = \sqrt{2(1mA/V^2)(5mA)[1 + 0.02(10)]} = 3.46\ mS$$

$$r_o = \frac{\frac{1}{\lambda} + V_{DS}}{I_D} = \frac{50V + 10V}{5mA} = 12\ k\Omega \qquad \mu_f = g_m r_o = 3.46mS(12k\Omega) = 41.5$$

(b) The slope of the output characteristics is zero, so $\lambda = 0$ and $r_o = \infty$.

For the positive change in v_{gs}, $g_m = \dfrac{\Delta i_D}{\Delta v_{GS}} \cong \dfrac{\frac{2.1V}{3.3k\Omega}}{0.5V} = 1.3\ mS$

$$(ii)\ |v_{gs}| \le 0.2(V_{GS} - V_{TN}) = 0.2\sqrt{\frac{2I_D}{K_n}} = 0.2\sqrt{\frac{2(25mA)}{2.0mA/V^2}} = 1.00\ V \qquad |v_{be}| \le 0.005\ V$$

Page 705

$$\eta = \frac{\gamma}{2\sqrt{V_{SB} + 2\phi_F}} = \frac{0.75}{2\sqrt{0 + 0.6}} = 0.48 \qquad \eta = \frac{0.75}{2\sqrt{3 + 0.6}} = 0.20$$

Page 713

$(i)\ V_{EQ} = \dfrac{1.5M\Omega}{1.5M\Omega + 2.2M\Omega}12V = 4.87V \quad R_{EQ} = 1.5M\Omega \| 2.2M\Omega = 892k\Omega$

Neglect λ in hand calculations of the Q-point.

$4.87 = V_{GS} + 12000 I_D \quad 4.87 = V_{GS} + 12000\left(\dfrac{5x10^{-4}}{2}\right)(V_{GS} - 1)^2$

$3V_{GS}^2 - 5V_{GS} - 1.87 = 0 \rightarrow V_{GS} = 1.981V \quad I_D = 241\ \mu A$

$V_{DS} = 12 - 22000 I_D - 12000 I_D = 3.81\ V \quad Q\text{-}point: (241\ \mu A,\ 3.81\ V)$

$(ii)\ A_{vdB} = 20\log(4.50) = 13.1\ dB$

Page 714

$V_{DS} \geq V_{GS} - V_{TH} = 1.981V - 1V = 0.981\ V$

Page 717

$V_{GS} - V_{TN} \cong \sqrt{\dfrac{2(241\mu A)}{2x10^{-3}}} = 0.491V \quad A_v^{CS} \cong -\dfrac{12V}{0.491V} = -24.4 \quad M = \dfrac{K_{n2}}{K_{n1}} = \dfrac{2x10^{-3}}{5x10^{-4}} = 4$

Page 720

$R_{in}^{CS} = 680k\Omega \| 1.0M\Omega = 405\ k\Omega \quad V_{EQ} = \dfrac{680k\Omega}{680k\Omega + 1M\Omega}12V = 4.86\ V$

Page 725

The gain is proportional to R_L: $R_L = 10k\Omega \| 220k\Omega = 9.57k\Omega \quad A_v^{CE} = -36.1\left(\dfrac{9.57k\Omega}{9.540k\Omega}\right) = -36.8$

Page 726

$(i)\ \mu_f = g_m r_o = 9.56mS(225k\Omega) = 2150$

$(ii)\ v_{be} = v_i\left(\dfrac{R_{in}^{CE}}{R_I + R_{in}^{CE}}\right)\left(\dfrac{1}{1 + g_m R_E}\right) \quad v_i \leq 5mV\left(\dfrac{0.33k\Omega + 14.2k\Omega}{14.2k\Omega}\right)\left[1 + 9.56mS(0.15k\Omega)\right] = 12.4\ mV$

$v_o \leq 12.4mV(36.1) = 0.450\ V$

$(iv)\ R_{in}^{CE} = 100k\Omega \| 6.8k\Omega = 6.37\ k\Omega \quad R_{out}^{CE} = 10k\Omega \| 225k\Omega = 9.57\ k\Omega$

$A_v^{CE} = -g_m R_L\left(\dfrac{R_{in}^{CE}}{R_I + R_{in}^{CE}}\right) = \text{-9.56mS}(9.57k\Omega \| 220k\Omega)\left(\dfrac{6.37k\Omega}{0.33k\Omega + 6.37k\Omega}\right) = -83.4$

Page 730

(i) The gain is proportional to R_L.

$$R_L = 300k\Omega \| R_{out}^{CS} = 300k\Omega \| 28.4k\Omega = 25.9k\Omega \quad A_v^{CS} = -6.85\left(\frac{25.9k\Omega}{27.3k\Omega}\right) = -6.50$$

The corrected gain agrees more closely with thevalue from SPICE.

$(ii)\ \mu_f = g_m r_o = 0.515mS(258k\Omega) = 133$

$$(iii)\ v_{gs} = v_i\left(\frac{R_{in}^{CS}}{R_I + R_{in}^{CS}}\right)\left(\frac{1}{1+g_m R_S}\right) \qquad v_{gs} \le 0.2(V_{GS} - V_{TN})$$

$$v_i \le 0.2(1V)\left(\frac{10k\Omega + 1M\Omega}{1M\Omega}\right)\left[1 + 0.515mS(2k\Omega)\right] = 410\ mV \qquad v_o \le 410mV(6.85) = 2.81\ V$$

$$(iv)\ A_v^{CS} = -\left(\frac{R_{in}^{CS}}{R_I + R_{in}^{CS}}\right)\left(\frac{g_m R_L}{1+g_m R_S}\right) = -\left(\frac{1M\Omega}{10k\Omega + 1M\Omega}\right)\left[\frac{0.515mS(30k\Omega \| 300k\Omega)}{1 + 0.515mS(32k\Omega)}\right] = -0.796$$

The calculation is slightly larger than the SPICE value since it neglects R_{out}^{CS}.

Page 734

$$(i)\ P_D = I_C V_{CE} + I_B V_{BE} = 239\mu A(3.67V) + \frac{239\mu A}{65}(0.7V) = 0.880\ mW$$

$$P_S = I_C V_{CC} + I_E V_{EE} = 239\mu A(5V) + 239\mu A\left(1 + \frac{1}{65}\right)(5V) = 2.41\ mW$$

$$(i)\ P_D = I_D V_{DS} = 250\mu A(4.5V) = 1.13\ mW$$

$$P_S = I_D V_{DD} + I_S V_{SS} = 250\mu A(10V) + 250\mu A(10V) = 5.00\ mW$$

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$$(a)\ V_M \le \min\left[I_C R_C, (V_{CE} - V_{BE})\right] = \min\left[239\mu A(10k\Omega), (3.67 - 0.7)V\right] = 2.39\ V$$

Limited by the voltage drop across R_C.

$$(b)\ V_M \le \min\left[I_D R_D, (V_{DS} - V_{DSSAT})\right] = \min\left[250\mu A(30k\Omega), (4.50 - 1)V\right] = 3.50\ V$$

Limited by the value of V_{DS}.

CHAPTER 14

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$R_B = 160k\Omega \| 300k\Omega = 104\ k\Omega \quad R_E = 3.00\ k\Omega \quad R_L = 100k\Omega \| 22k\Omega = 18.0\ k\Omega$

$R_G = 1.5M\Omega \| 2.2M\Omega = 892\ k\Omega \quad R_S = 2.00\ k\Omega \quad R_L = 100k\Omega \| 22k\Omega = 18.0\ k\Omega$

Page 761

$(i)\ A_v^{CE} = -\frac{0.838V}{0.150} = -5.59$

$(ii)\ R_{iB} = 10.2k\Omega + 101(1.0k\Omega) = 111k\Omega$

$$A_v^{CE} = -\frac{9.80mS(18k\Omega)}{1 + 9.80mS(1k\Omega)}\left(\frac{104k\Omega \| 111k\Omega}{2k\Omega + 104k\Omega \| 111k\Omega}\right) = -15.8 \quad R_4 = 13k\Omega - 1k\Omega = 12\ k\Omega$$

$$A_v^{CS} = -\frac{0.491mS(18k\Omega)}{1 + 0.491mS(1k\Omega)}\left(\frac{892k\Omega}{2k\Omega + 892k\Omega}\right) = -5.91 \quad R_4 = 12k\Omega - 1k\Omega = 11\ k\Omega$$

$(iii)\ R_{iB} = 10.2k\Omega$

$$A_v^{CE} = -9.80mS(18k\Omega)\left(\frac{104k\Omega \| 10.2k\Omega}{2k\Omega + 104k\Omega \| 10.2k\Omega}\right) = -145$$

$$A_v^{CS} = -0.491mS(18k\Omega)\left(\frac{892k\Omega}{2k\Omega + 892k\Omega}\right) = -8.82$$

$$(iv)\ V_T = \left(\frac{1.38x10^{-23}}{1.602x10^{-19}}\frac{V}{K}\right)(273K + 27K) = 25.84mV \quad I_S = \frac{I_C}{\exp\left(\frac{V_{BE}}{V_T}\right)} = \frac{245\mu A}{\exp\left(\frac{0.700V}{0.02584V}\right)} = 0.421fA$$

$(v)\ g_m R_L = \text{-9.80mS}(18k\Omega) = -176,\ A_v^{CE} \cong -\frac{18k\Omega}{3k\Omega} = -9.00$

$g_m R_L = \text{-0.491mS}(18k\Omega) = -8.84,\ A_v^{CE} \cong -\frac{18k\Omega}{2k\Omega} = -9.00$

(vi) The exercise should refer to Fig. 14.2. $R_{iB} = 10.2k\Omega + 101(3.0k\Omega) = 313k\Omega$

$R_{in}^{CE} = R_B \| R_{iB} = 104k\Omega \| 313k\Omega = 78.1\ k\Omega \qquad R_{in}^{CS} = R_G = 892k\Omega \qquad R_{in}^{CE} > r_\pi$

Page 761

$$(i)\ A_{vt} = \frac{2k\Omega + 892k\Omega}{892k\Omega}0.956 = 0.958 \qquad \frac{(0.491ms)R_L}{1+(0.491ms)R_L} = 0.958 \rightarrow R_L = 46.5k\Omega$$

$$R_6 \| 100k\Omega = 46.5k\Omega \rightarrow R_6 = 86.9k\Omega$$

$$(ii)\ R_{iB} = 10.2k\Omega + 101(13k\Omega) = 1.32\,M\Omega \qquad R_{in}^{CC} = 104k\Omega \| 1.32\,M\Omega = 96.4k\Omega$$

$$A_v^{CE} = -\frac{9.80mS(13k\Omega)}{1+9.80mS(13k\Omega)}\left(\frac{96.4k\Omega}{2k\Omega + 96.4k\Omega}\right) = +0.972$$

$$A_v^{CS} = -\frac{0.491mS(12k\Omega)}{1+0.491mS(12k\Omega)}\left(\frac{892k\Omega}{2k\Omega + 892k\Omega}\right) = +0.853$$

$$(iv)\ \text{BJT}: g_m R_L = 9.80mS(11.5k\Omega) = 113 \quad \text{FET}: g_m R_L = 0.491mS(10.7k\Omega) = 5.25$$

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$$v_i \le 0.005V(1+g_m R_L)\frac{R_I + R_B \| R_{iB}}{R_B \| R_{iB}} = 0.005V\left[1+9.8mS(11.5k\Omega)\right]\frac{2k\Omega + 95.4k\Omega}{95.4k\Omega} = 0.580\ V$$

$$v_i \le 0.2(V_{GS} - V_{TN})(1+g_m R_L)\frac{R_I + R_G}{R_G} = 0.2(0.982)\left[1+0.491mS(10.7k\Omega)\right]\frac{2k\Omega + 892k\Omega}{892k\Omega} = 1.23\ V$$

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$$R_{out}^{CD} = R_6 \left\| \frac{1}{g_m} \right. \qquad 12\text{k}\Omega \left\| \frac{1}{g_m} \right. = 120\Omega \rightarrow g_m = 8.25mS \qquad 8.25mS = \sqrt{2\left(500\mu A/V^2\right)I_D} \rightarrow I_D = 68.1\ mA$$

$$g_m = \frac{2I_D}{V_{GS} - V_{TN}} \qquad V_{GS} - V_{TN} = \frac{2(68.1\text{mA})}{8.25\text{mS}} = 16.5\text{ V}$$

If one neglects R_6, $I_D = 69.4\ mA$ and $V_{GS} - V_{TN} = 16.8$ V

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$$\text{BJT}: v_i \le 0.005V(1+g_m R_I)\frac{R_I + R_6}{R_6} = 0.005V\left[1+9.8mS(2k\Omega)\right]\left(\frac{2k\Omega + 13k\Omega}{13k\Omega}\right) = 119\text{ m}V$$

$$\text{Neglecting } R_6,\ v_i \le 0.005V(1+g_m R_I) = 0.005V\left[1+9.8mS(2k\Omega)\right] = 103\ mV$$

$$\text{FET}: v_i \le 0.2(V_{GS} - V_{TN})(1+g_m R_I)\frac{R_I + R_6}{R_6} = 0.2(0.982)\left[1+0.491mS(2k\Omega)\right]\frac{2k\Omega + 12k\Omega}{12k\Omega} = 454\text{ m}V$$

$$\text{Neglecting } R_6,\ v_i \le 0.2(V_{GS} - V_{TN})(1+g_m R_I) = 0.2(0.982)\left[1+0.491mS(2k\Omega)\right] = 389\text{ m}V$$

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$$R_{iC} = r_o\left[1 + \frac{\beta_o R_{th}}{R_{th} + r_\pi}\right] = 219k\Omega\left[1 + \frac{100(1.73k\Omega)}{1.73k\Omega + 10.2k\Omega}\right] = 3.40\ M\Omega$$

Or more approximately, $R_{iC} = r_o\left[1 + g_m R_{th}\right] = 219k\Omega\left[1 + 9.8mS(1.73k\Omega)\right] = 3.93\ M\Omega$

$$R_{iD} = r_o\left[1 + g_m R_{th}\right] = 223k\Omega\left[1 + 0.491(1.71k\Omega)\right] = 4.10\ M\Omega$$

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$$(i)\ A_v^{CB} = g_m R_L \frac{\dfrac{R_6\left(\dfrac{1}{g_m}\right)}{R_6 + \dfrac{1}{g_m}}}{R_I + \dfrac{R_6\left(\dfrac{1}{g_m}\right)}{R_6 + \dfrac{1}{g_m}}} = g_m R_L \frac{\dfrac{R_6}{R_6 + \dfrac{1}{g_m}}}{g_m R_I + \dfrac{R_6}{R_6 + \dfrac{1}{g_m}}} = g_m R_L \frac{R_6}{R_6\left(1 + g_m R_I\right) + R_I}$$

$$A_v^{CB} = g_m R_L \frac{R_6}{R_6 + R_I}\frac{1}{1 + \dfrac{g_m R_I R_6}{R_6 + R_I}} = \frac{g_m R_L}{1 + g_m R_{th}}\left(\frac{R_6}{R_6 + R_I}\right)$$

(ii) The voltage gains are proportional to the load resistance

$$A_v^{CE} = +8.48\left(\frac{22k\Omega}{18k\Omega}\right) = +10.4 \qquad A_v^{CG} = +4.12\left(\frac{22k\Omega}{18k\Omega}\right) = +5.02$$

$$(iii)\ \text{CB}: A_v^{CB} \le g_m R_L = 176 \quad A_v^{CB} \cong \frac{R_L}{R_{th}} = \frac{R_L}{R_I \| R_6} = \frac{18k\Omega}{1.73k\Omega} = 10.4 \qquad 8.48 < 10.4 << 176$$

$$\text{CG}: A_v^{CG} \le g_m R_L = 8.84 \quad A_v^{CB} \cong \frac{R_L}{R_{th}} = \frac{R_L}{R_I \| R_6} = \frac{18k\Omega}{1.71k\Omega} = 10.5 \quad 4.11 < 8.84 < 10.5$$

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(i) Since we need high gain, the emitter should be bypassed, and $R_{in}^{CE} = R_B \| r_\pi = 250k\Omega$.

If we choose $R_B \cong r_\pi$, $I_C = \dfrac{\beta_o}{40 r_\pi} \cong \dfrac{100}{40(500k\Omega)} = 5\ \mu\text{A}$

(ii) $R_{in}^{CG} \cong \dfrac{1}{g_m} \qquad I_C \cong \dfrac{1}{40(2k\Omega)} = 12.5\ \mu A$

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(i) Common – Emitter :

$$C_1 >> \frac{1}{2\pi(250Hz)(1k\Omega + 77.9k\Omega)} = 8.07nF \quad \text{Choose } C_1 = 82\ nF = 0.082\ \mu F$$

$$C_2 >> \frac{1}{2\pi(250Hz)\left[10k\Omega \| \left(3k\Omega + \frac{1}{9.80mS}\right)\right]} = 0.269\mu F \quad \text{Choose } C_2 = 2.7\ \mu F$$

$$C_3 >> \frac{1}{2\pi(250Hz)(21.9k\Omega + 82k\Omega)} = 6.13nF \quad \text{Choose } C_{31} = 68\ nF = 0.068\ \mu F$$

Common – Source :

$$C_1 >> \frac{1}{2\pi(250Hz)(1k\Omega + 892k\Omega)} = 713\,pF \quad \text{Choose } C_1 = 8200\ pF$$

$$C_2 >> \frac{1}{2\pi(250Hz)\left[10k\Omega \| \left(2k\Omega + \frac{1}{0.491mS}\right)\right]} = 0.221\mu F \quad \text{Choose } C_2 = 2.2\ \mu F$$

$$C_3 >> \frac{1}{2\pi(250Hz)(21.5k\Omega + 82k\Omega)} = 6.15nF \quad \text{Choose } C_3 = 68\ nF = 0.068\ \mu F$$

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Common – Collector :

$$C_1 >> \frac{1}{2\pi(250Hz)(1k\Omega + 95.5k\Omega)} = 6.60nF \quad \text{Choose } C_1 = 68\ nF = 0.068\ \mu F$$

$$C_3 >> \frac{1}{2\pi(250Hz)(120\Omega + 82k\Omega)} = 7.75nF \quad \text{Choose } C_3 = 82\ nF = 0.082\ \mu F$$

Common – Drain :

$$C_1 >> \frac{1}{2\pi(250Hz)(1k\Omega + 892k\Omega)} = 713\,pF \quad \text{Choose } C_1 = 8200\ pF$$

$$C_3 >> \frac{1}{2\pi(250Hz)(1.74k\Omega + 82k\Omega)} = 7.60nF \quad \text{Choose } C_3 = 82\ nF = 0.082\ \mu F$$

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Common – Base:

$$C_1 >> \frac{1}{2\pi(250Hz)(1k\Omega + 0.1k\Omega)} = 0.579\mu F \quad \text{Choose } C_1 = 6.8\ \mu F$$

$$C_2 >> \frac{1}{2\pi(250Hz)\left(160k\Omega \| 300k\Omega \| \left[10.2k\Omega + 101(13k\Omega \| 1k\Omega)\right]\right)} = 12.2nF \quad \text{Choose } C_2 = 0.12\ \mu F$$

$$C_3 >> \frac{1}{2\pi(250Hz)(21.9k\Omega + 82k\Omega)} = 6.13nF \quad \text{Choose } C_3 = 0.068\ \mu F$$

Common – Gate:

$$C_1 >> \frac{1}{2\pi(250Hz)(1k\Omega + 1.74k\Omega)} = 0.232\mu F \quad \text{Choose } C_1 = 2.2\ \mu F$$

$$C_2 >> \frac{1}{2\pi(250Hz)(1.5M\Omega \| 2.2M\Omega)} = 714pF \quad \text{Choose } C_2 = 8200\ pF$$

$$C_3 >> \frac{1}{2\pi(250Hz)(20.9k\Omega + 82k\Omega)} = 6.19nF \quad \text{Choose } C_3 = 0.068\ \mu F$$

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(a) Common – Source:

$$C_2 = \frac{1}{2\pi(1000Hz)\left[10k\Omega \| \left(2k\Omega + \frac{1}{0.491mS}\right)\right]} = 55.3nF \quad \text{Choose } C_2 = 0.056\ \mu F$$

(b) Common – Collector:

$$C_3 >> \frac{1}{2\pi(2000Hz)(120\Omega + 100k\Omega)} = 795pF \quad \text{Choose } C_3 = 820\ pF$$

(c) Common – Gate:

$$C_1 >> \frac{1}{2\pi(1000Hz)(2k\Omega + 1.74k\Omega)} = 42.6nF \quad \text{Choose } C_1 = 0.042\ \mu F$$

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$(i)\ 20V = V_{GS} + 3600 I_D \quad 20 = V_{GS} + 3600\frac{0.020}{2}\left(V_{GS} - 1.5\right)^2 \rightarrow V_{GS} = 2.203V \quad I_D = 4.94\ mA$

$V_{DS} = 5 - \left(-V_{GS}\right) = 7.20\ V \quad \text{Q-point: (4.94 mA, 7.20 V)} \quad R_{\text{in}} = R_G = 22\ M\Omega$

$A_v^{CD} = \frac{g_m R_L}{1 + g_m R_L} \quad g_m = \frac{2(4.94mA)}{(2.20 - 1.50)V} = 14.2mS \quad R_L = 3600\Omega \| 3000\Omega = 1630\Omega \quad A_v^{CD} = 0.959$

$(ii)\ R_{\text{out}}^{\text{CD}} = 3.6k\Omega \left\| \frac{1}{g_m} \right. = 3.6k\Omega \left\| \frac{1}{0.0142} \right. = 69.1\ \Omega \quad v_{gs} \le 0.2(2.20 - 1.50)\left[1 + 0.0142(1630)\right] = 3.38\ V$

$(iii)\ r_o = \frac{\frac{1}{\lambda} + V_{DS}}{I_D} = \frac{\frac{1}{0.015} + 5 + 2.21}{0.005} = 14.8k\Omega \quad R_L = 3600\Omega \| 3000\Omega \| 14.8k\Omega = 1470\Omega \quad A_v^{CD} = 0.954$

$(iv)\ \frac{W}{L} = \frac{K_n}{K_n^{'}} = \frac{2x10^{-2}}{5x10^{-5}} = \frac{400}{1}$

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$A = \frac{g_m R_S}{1 + g_m R_S} \quad g_m = \frac{2(4.94mA)}{(2.20 - 1.50)V} = 14.2mS \quad R_S = 3600\Omega \quad A_v^{CD} = 0.981 \quad R_{\text{in}} = R_G = 22\ M\Omega$

$R_{\text{out}}^{\text{CD}} = 3.6k\Omega \left\| \frac{1}{g_m} \right. = 3.6k\Omega \left\| \frac{1}{0.0142} \right. = 69.1\ \Omega \quad A_v^{CD} = A\frac{3000\Omega}{69.1\Omega + 3000\Omega} = 0.959$

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(i) Reverse the direction of the arrow on the ermitter of the transistor as well as the values of V_{EE} and V_{CC}.

$(ii)\ R_{out}^{CD} = R_E \left\| \frac{1}{g_m} \right. = 13k\Omega \left\| \frac{1}{40(331\mu A)} \right. = 75.1\ \Omega \quad A_V^{CB} = \frac{75.1\Omega}{75\Omega + 75.1\Omega}(13.2mS)(7.58k\Omega) = 50.1$

(iii) For $v_{CB} \ge 0$, we require $v_C \ge 0$. $\quad V_C = 5 - I_C R_C = 2.29\ V \quad \therefore \left|v_c\right| \le 2.29\ V$

$v_o \le 5mV(g_m R_L) = 5mV(13.2mS)(7580\Omega) = 0.500\ V$

$(iv)\ R_E = 75\Omega\left[1 + 40(7.5 - 0.7)\right] = 20.5\ k\Omega$ (a standard 1% value) $\quad I_C \cong \frac{6.8V}{20.5k\Omega} = 332\ \mu A$

$50 = 40(332\mu A) R_L \frac{75}{75 + 75} \rightarrow R_L = 7.53k\Omega \rightarrow R_C = 8.14\ k\Omega \rightarrow 8.06\ k\Omega$ (a standard 1% value)

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(i) 5% tolerances $I_C^{\max} \cong \dfrac{V_{EE}^{\max} - 0.7V}{R_E^{\min}} = \dfrac{5(1.05) - 0.7V}{13k\Omega(0.95)} = 368\mu A$

$V_C^{\min} = V_{CC}^{\min} - I_C^{\max} R_C^{\max} = 5V(0.95) - 368\mu A(8.2k\Omega)(1.05) = 1.58\ V \quad 1.58 \geq 0,$ so active region is ok.

10% tolerances $I_C^{\max} \cong \dfrac{V_{EE}^{\max} - 0.7V}{R_E^{\min}} = \dfrac{5(1.1) - 0.7V}{13k\Omega(0.9)} = 410\mu A$

$V_C^{\min} = V_{CC}^{\min} - I_C^{\max} R_C^{\max} = 5V(0.90) - 410\mu A(8.2k\Omega)(1.1) = 0.802\ V \quad 0.802 \geq 0,$ so active region is ok.

$(ii)\ A = g_m R_C = (13.2mS)(8200\Omega) = 108 \quad R_{\text{out}}^{\text{CB}} = 8.2k\Omega \quad R_{\text{in}}^{\text{CB}} = 75\ \Omega$

$$A_v^{CG} = \frac{R_{\text{in}}^{\text{CB}}}{75\Omega + R_{\text{in}}^{\text{CB}}} A \frac{100k\Omega}{R_{\text{out}}^{\text{CB}} + 100k\Omega} = \frac{75\Omega}{75\Omega + 75\Omega}(108)\left(\frac{100k\Omega}{8200 + 100k\Omega}\right) = 49.9$$

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$(ii)\ r_o \cong r_o = \dfrac{1}{\lambda I_D} = \dfrac{1}{0.015(2x10^{-4})} = 333k\Omega$

or more exactly $V_{DS} = 25 - 10^5 I_D - 9.1x10^3 I_D = 25 - 1.09x10^5(0.2mA) = 3.18\ V$

$$r_o = \frac{\frac{1}{\lambda} + V_{DS}}{I_D} = \frac{\frac{1}{0.015} + 3.18}{2x10^{-4}} = 349k\Omega \qquad R_L = 100k\Omega \| 100k\Omega \| 349k\Omega = 43.7k\Omega$$

$$A_v^{CS} = -(g_m R_L)\frac{R_{in}}{R_I + R_{in}} = -\frac{2(0.2mA)}{0.2V}(43.7k\Omega)\left(\frac{75\Omega}{75\Omega + 75\Omega}\right) = -43.7$$

$(iii)\ I_D = \dfrac{0.01}{2}(0.25)^2 = 0.3125mA \quad V_{GS} - V_{TN} = 0.25V \quad V_{GS} = 0.25V - 2 = -1.75V$

$$R_S = \frac{-V_{GS}}{I_D} = \frac{1.75V}{0.3125mA} = 5.60k\Omega \to 5.6\ k\Omega \qquad R_L = 2\frac{A_v}{g_m} = \frac{50(0.25V)}{0.3125mA} = 40\ k\Omega \quad R_D \| 100k\Omega = 40k\Omega$$

$R_D = 66.7k\Omega \to 68\ k\Omega \quad C_1$ remains unchanged.

$$C_2 >> \frac{1}{10^6\pi\left(5.6k\Omega \middle\| \frac{1}{2.5mS}\right)} = 0.853nF \to \text{Choose } C_2 = 8200\ pF$$

$$C_3 >> \frac{1}{10^6\pi(68k\Omega + 100k\Omega)} = 1.90\,pF \to \text{Choose } C_3 = 20\ pF$$

$(iv)\ A = -g_m R_D = -(2mS)(100k\Omega) = -200 \quad R_{\text{out}} = 100k\Omega \quad R_{\text{in}} = 75\ \Omega$

$$A_v^{CG} = \frac{R_{\text{in}}}{75\Omega + R_{\text{in}}} A \frac{100k\Omega}{R_{\text{out}} + 100k\Omega} = \frac{75\Omega}{75\Omega + 75\Omega}(-200)\left(\frac{100k\Omega}{100k\Omega + 100k\Omega}\right) = -50.0$$

Page 813

(i) $M_1: \ I_D = \frac{K_n}{2}\left(V_{GS} - V_{TN}\right)^2 \quad V_{GS} = -R_{S1}I_D \quad I_D = \frac{0.01}{2}\left(-200I_D + 2\right)^2 \rightarrow I_D = 5.00mA$

$V_{DS} = 15 - 5mA\left(820\Omega\right) = 10.9\ V$

$g_m = \sqrt{2K_nI_D} = \sqrt{2\left(0.01\right)\left(0.005\right)} = 10.0\ mS \quad r_o = \frac{1+\lambda V_{DS}}{\lambda I_D} = \frac{1+0.02\left(10.9\right)}{0.02\left(5mA\right)} = 12.2\ k\Omega$

$Q_2: \ V_{EQ} = \frac{22k\Omega}{22k\Omega + 78k\Omega}\left(15V\right) = 3.30\ V \quad R_{EQ} = 22k\Omega \| 78k\Omega = 17.2k\Omega$

$I_C = 150\frac{3.30 - 0.7}{17.2k\Omega + 151\left(1.6k\Omega\right)} = 1.52\ mA \quad V_{CE} = 15 - 1.52mA\left(4.7k\Omega + \frac{151}{150}1.6k\Omega\right) = 5.41\ V$

$g_m = 40\left(1.52mA\right) = 60.8\ mS \quad r_\pi = \frac{150}{60.8mS} = 2.47\ k\Omega \quad r_o = \frac{80+5.41}{1.52mA} = 56.2\ k\Omega$

$Q_3: \ V_{EQ} = \frac{120k\Omega}{120k\Omega + 91k\Omega}\left(15V\right) = 8.53\ V \quad R_{EQ} = 120k\Omega \| 91k\Omega = 51.8k\Omega$

$I_C = 80\frac{8.53 - 0.7}{51.8k\Omega + 81\left(3.3k\Omega\right)} = 1.96\ mA \quad V_{CE} = 15 - 1.96mA\left(\frac{81}{80}3.3k\Omega\right) = 8.45\ V$

$g_m = 40\left(1.96mA\right) = 78.4\ mS \quad r_\pi = \frac{80}{78.4mS} = 1.02\ k\Omega \quad r_o = \frac{60+8.45}{1.96mA} = 34.9\ k\Omega$

(ii) A typical op-amp gain is at least 10,000 which exceeds the amplification factor of a single transistor.

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(i) $R_{L1} = 478\Omega \| 12.2k\Omega = 460\Omega \quad R_{L2} = 3.53k\Omega \| 54.2k\Omega = 3.31k\Omega \quad R_{L3} = 232\Omega \| 34.4k\Omega = 230\Omega$

$$A_v = -10mS\left(460\Omega\right)\left(-62.8mS\right)\left(3.31k\Omega\right)\left[\frac{79.6mS\left(230\Omega\right)}{1+79.6mS\left(230\Omega\right)}\right]\left(\frac{1M\Omega}{10k\Omega + 1M\Omega}\right) = 898 \quad 20\log\left(898\right) = 59.1\ dB$$

(ii) $A_v \cong \left(-\frac{V_{DD}}{V_{GS} - V_{TN}}\right)\left(-10V_{CC}\right)\left(1\right) = -\frac{15}{1}\left(-10\right)\left(15\right)\left(1\right) = 2250$

(iii) $A_v = -10mS\left(2.39k\Omega\right)\left(-62.8mS\right)\left(19.8k\Omega\right)\left(0.95\right)\left(0.99\right) = 28000$

Page 820

(i) $R_{out} = 3300 \| \left(\frac{1}{0.0796S} + \frac{3990}{90.1}\right) = 55.9\ \Omega$

(ii) Note that these are obtained from SPICE.

(iii) $A_{v1} = -g_mR_{L1} = -\sqrt{2\left(0.01\right)\left(0.001\right)}\left(3k\Omega \| 17.2k\Omega \| 2.39k\Omega\right) = 5.52$

$A_v = -5.52\left(-222\right)\left(3.31k\Omega\right)\left(0.95\right)\left(0.99\right) = 1150$

CHAPTER 15

Page 842

$$(i)\ I_C = \alpha_F I_E = \frac{60}{61}\left[\frac{15-0.7}{2\left(75k\Omega\right)}\right] = 93.8\ \mu A \qquad V_{CE} = 15 - 93.8\mu A\left(75k\Omega\right) - \left(-0.7V\right) = 8.67\ V$$

$$(ii)\ I_C = \alpha_F I_E = \frac{60}{61}\left[\frac{15-V_{BE}}{2\left(75k\Omega\right)}\right] \quad \text{and} \quad V_{BE} = 0.025V\ \ln\left(\frac{I_C}{0.5x10^{-15}\ A}\right) \rightarrow I_C = 94.7\ \mu A$$

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$$v_{id} = v_1 - v_2 = 1.01 - 0.990 = 0.020\ V \qquad v_{ic} = \frac{v_1 + v_2}{2} = \frac{1.01+0.99}{2} = 01.00\ V$$

$$v_{id} = v_1 - v_2 = 4.995 - 5.005 = -0.010\ V \qquad v_{ic} = \frac{v_1 + v_2}{2} = \frac{4.995+5.005}{2} = 5.00\ V$$

$$v_{od} = A_{dd}v_{id} + A_{cd}v_{ic} \qquad v_{oc} = A_{dc}v_{id} + A_{cc}v_{ic}$$

$$\begin{bmatrix}2.20\\0\end{bmatrix} = \begin{bmatrix}A_{dd} & A_{cd}\end{bmatrix}\begin{bmatrix}0.02 & 1.00\\-0.01 & 5.00\end{bmatrix} \rightarrow \begin{bmatrix}A_{dd} & A_{cd}\end{bmatrix} = \begin{bmatrix}100 & 0.20\end{bmatrix}$$

$$\begin{bmatrix}1.002\\5.001\end{bmatrix} = \begin{bmatrix}A_{dc} & A_{cc}\end{bmatrix}\begin{bmatrix}0.02 & 1.00\\-0.01 & 5.00\end{bmatrix} \rightarrow \begin{bmatrix}A_{dc} & A_{cc}\end{bmatrix} = \begin{bmatrix}0.100 & 1.00\end{bmatrix}$$

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$$\text{Differential output: } A_{dm} = A_{dd} = -20V_{CC} = -300 \qquad A_{cm} = 0 \qquad \text{CMRR} = \infty$$

$$\text{Single-ended output: } A_{dm} = \frac{A_{dd}}{2} = +10V_{CC} = 150 \qquad CMRR = 20V_{EE} = 300 \qquad A_{cm} = -\frac{150}{300} = -0.5$$

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$$V_{IC} = 15V\left[\frac{1 - \frac{100}{101}\left(\frac{R_C}{2R_C}\right)\frac{15-0.7}{15}}{1 + \frac{100}{101}\left(\frac{R_C}{2R_C}\right)}\right] = 5.30\ V$$

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$$I_{DC} = I_{SS} - \frac{V_O}{R_{SS}} = 100\mu A - \frac{15V}{750k\Omega} = 80\ \mu A$$

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$$I_D = \frac{I_{SS}}{2} = 100\ \mu A \qquad V_{DS} = 12 - I_D R_D + V_{GS} = 12 - 100\mu A(62k\Omega) + V_{GS} = 5.8V + V_{GS}$$

$$V_{GS} = V_{TN} + \sqrt{\frac{2I_D}{K_n}} = V_{TN} + 0.2V \qquad V_{TN} = 1 + 0.75\left(\sqrt{V_{SB} + 0.6} - \sqrt{0.6}\right) \qquad V_{SB} = -V_{GS} - (-12V)$$

$$V_{SB} = 11.8 - V_{TN} \qquad V_{TN} = 1 + 0.75\left(\sqrt{12.4 - V_{TN}} - \sqrt{0.6}\right) \rightarrow V_{TN} = 2.75V \qquad V_{DS} = 8.75\ V$$

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$$R_{od} = 2r_o \cong 2\frac{V_A}{I_C} = 2\frac{60V}{37.5\mu A} = 3.20\ M\Omega \qquad R_{oc} \cong 2\mu_f R_{EE} = 2(40)(60)(1M\Omega) = 4.80\ G\Omega$$

$$i_{dm} = g_m v_{dm} = 40(37.5\mu A)v_{dm} = 1.5x10^{-3} v_{dm} \qquad i_{cm} \cong \frac{v_{cm}}{2R_{EE}} = \frac{v_{cm}}{2M\Omega} = 5.00x10^{-7} v_{cm}$$

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$$I_{C1} = I_{C2} = \frac{100}{101}\left(\frac{150\mu A}{2}\right) = 74.3\ \mu A \qquad I_{C3} = \frac{15V}{20k\Omega} = 750\ \mu A \qquad V_{CE3} = 15 - 0 = 0\ V$$

$$V_{CE1} = 15 - 74.3\mu A(10k\Omega) - (-0.7) = 15.0\ \text{V} \qquad V_{CE2} = 15 - (74.3\mu A - 7.5\mu A)(10k\Omega) - (-0.7) = 15.0\ V$$

$$V_{EB3} = (74.3\mu A - 7.5\mu A)(10k\Omega) = 0.668\ V \qquad I_{S3} = \frac{750\mu A}{\exp\left(\frac{0.668\text{V}}{0.025}\right)} = 1.87x10^{-15}\ A$$

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$$(i)\ A_{dm}^{\max} = 560\ (15) = 8400$$

$$(ii)\ I_{C1} \le 50(1\mu A) = 50\ \mu A \qquad A_{dm} = \frac{8400}{1 + \frac{28}{100}\left(\frac{500\mu A}{50\mu A}\right)} = 2210$$

$$(iii)\ I_{C1} \le 50(1\mu A) = 50\ \mu A \qquad A_{dm} = \frac{8400}{1 + \frac{28}{100}\left(\frac{5mA}{50\mu A}\right)} = 290$$

$$(iv)\ A_{dm}^{\max} = 560\ (1.5) = 840$$

$$(v)\ R_{in} = 2r_\pi = 2\frac{50}{40(50\mu A)} = 50\ k\Omega \qquad R_{out} \cong \frac{15V}{0.5mA} = 30\ k\Omega$$

$$R_{in} = 2r_\pi = 2\frac{50}{40(50\mu A)} = 50\ k\Omega \qquad R_{out} \cong \frac{15V}{5mA} = 3.0\ k\Omega$$

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$$CMRR \cong g_{m2}R_1 = 40\ (50\mu A)(750k\Omega) = 1500 \qquad CMRR_{dB} = 20\log(1500) = 63.5\ dB$$

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$$(i)\ \ A_{dm} = \frac{g_{m2}}{2}\left(\frac{R_C r_{\pi 3}}{R_C + r_{\pi 3}}\right)(g_{m3}r_{o3}) = \frac{40}{2}\left(\frac{I_{C2}R_C r_{\pi 3}}{R_C + r_{\pi 3}}\right)(40I_{C3}r_{o3}) \cong 800\left(\frac{0.7r_{\pi 3}}{R_C + r_{\pi 3}}\right)(V_{A3}) = \frac{560V_{A3}}{1+\frac{R_C}{r_{\pi 3}}}$$

$$A_{dm} = \frac{560V_{A3}}{1+\frac{40I_{C3}R_C}{\beta_{o3}}} = \frac{560V_{A3}}{1+\frac{40I_{C2}R_C}{\beta_{o3}}\left(\frac{I_{C3}}{I_{C2}}\right)} = \frac{560V_{A3}}{1+\frac{40(0.7)}{\beta_{o3}}\left(\frac{I_{C3}}{I_{C2}}\right)} = \frac{560V_{A3}}{1+\frac{28}{\beta_{o3}}\left(\frac{I_{C3}}{I_{C2}}\right)}$$

$$(ii)\ \ A_{dm}^{\max} = 560\ (75) = 42000 \qquad I_{C1} \le 50(1\mu A) = 50\ \mu A$$

$$A_{dm} = \frac{42000}{1+\frac{28}{100}\left(\frac{500\mu A}{50\mu A}\right)} = 11000 \qquad A_{dm} = \frac{42000}{1+\frac{28}{100}\left(\frac{5mA}{50\mu A}\right)} = 1450$$

$$(iii)\ \ R_{in} = 2r_\pi = 2\frac{50}{40(50\mu A)} = 50\ k\Omega \qquad R_{out} \cong r_{o3} = \frac{75V + 15V}{0.5mA} = 180\ k\Omega$$

$$R_{in} = 2r_\pi = 2\frac{50}{40(50\mu A)} = 50\ k\Omega \qquad R_{out} \cong \frac{90V}{5mA} = 18.0\ k\Omega$$

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$$A_{vt1} = -3.50 \qquad A_{vt2} = -22mS(150k\Omega \| 162k\Omega \| 203k\Omega) = -1238$$

$$A_{vt3} = \frac{0.198S(2k\Omega \| 18k\Omega)}{1+0.198S(2k\Omega \| 18k\Omega)} = 0.9971 \quad A_{dm} = -3.50(-1238)(0.9971) = 4320$$

$$R_{in} = 2r_\pi = 2\frac{100}{40(49.5\mu A)} = 101\ k\Omega \qquad R_{out} \cong \frac{1}{g_{m4}} + \frac{r_{o3}\|R_2}{\beta_{o4}+1} = \frac{1}{40(4.95mA)} + \frac{162k\Omega \| 150k\Omega}{101} = 776\ \Omega$$

$$P \cong (I_1 + I_2 + I_3)(V_{CC} + V_{EE}) = (100 + 500 + 5000)\mu A(30V) = 168\ mW$$

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$(i)\ I_C = 50\mu A\left(\frac{150}{151}\right) = 49.7\mu A \quad I_{C3} = 500\mu A + \frac{5mA}{151} = 533\ \mu A \quad R_C = \frac{0.7V}{\left(49.7 - \frac{533}{150}\right)\mu A} = 15.2k\Omega$

$r_{\pi 3} = \frac{150}{40(533\mu A)} = 7.04\ k\Omega \quad A_{vt2} = -20(49.7\mu A)(15.2k\Omega \| 7.04k\Omega) = -4.68$

$I_{C4} = \frac{150}{151}5mA = 4.97mA \quad r_{\pi 4} = \frac{150}{40(4.97mA)} = 755\ \Omega \quad r_{o3} = \frac{75 + 14.3}{533\mu A} = 168\ k\Omega$

$A_{vt2} = -40(533\mu A)\left[168k\Omega \| 755 + 151(2k\Omega)\right] = -2304$

$g_{m4} = 40(4.97mA) = 0.199S \quad A_{vt3} = \frac{0.199S(2k\Omega)}{1 + 0.199S(2k\Omega)} = 0.998$

$A_{dm} = -4.78(-2304)(0.998) = 11000$

$R_{id} = 2r_{\pi 1} = 2\frac{150}{40(49.7\mu A)} = 151\ k\Omega \quad R_{out} \cong \frac{1}{g_{m4}} + \frac{r_{o3} \| R_2}{\beta_{o4} + 1} = \frac{1}{40(4.95mA)} + \frac{168k\Omega}{151} = 1.12\ k\Omega$

CMRR is set by the input stage and doesn't change since the bias current is the same.

$(ii)\ A_{vt2} = -22mS(117k\Omega \| 203k\Omega) = -1630 \quad r_{o3} = \frac{50 + 14.3}{550\mu A} = 117\ k\Omega$

$A_{dm} = -3.50(-1630)(0.998) = 5700 \quad R_{out} \cong \frac{1}{g_{m4}} + \frac{r_{o3} \| R_2}{\beta_{o4} + 1} = \frac{1}{40(4.95mA)} + \frac{117k\Omega}{101} = 1.16\ k\Omega$

CMRR and input resistance are set by the input stage and don't change.

$(iii)\ A_v = \frac{A_{dm}}{1 + A_{dm}} = \frac{6920}{6921} = 0.99986 \quad R_{out} = \frac{R_o}{1 + A_{dm}} = \frac{1.62k\Omega}{1 + 6920} = 0.234\ \Omega$

$R_{in} = R_{id}(1 + A_{dm}) = 101k\Omega(6921) = 699\ \mathrm{M\Omega}$

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$$(i)\ V_{GS3} = 1 + \sqrt{\frac{2(500\mu A)}{2.5mA}} = 1.63\ V \qquad R_D = \frac{1.63V}{100\mu A} = 16.3\ k\Omega$$

$$A_{vt1} = -\frac{1}{2}\sqrt{2(0.005)(100\mu A)}(16.3k\Omega) = -8.16$$

$$A_{vt2} = -g_{m3}r_{o3} = -\sqrt{2(0.0025)(0.0005)}\left(\frac{1}{0.01(0.5mA)}\right) = -316$$

$$g_{m4} = \sqrt{2(0.005mA)(0.005mA)} = 7.07mS \qquad A_{vt3} = \frac{7.07mS(2k\Omega)}{1 + 7.07mS(2k\Omega)} = 0.934$$

$$A_{dm} = -8.16(-316)(0.934) = 2410 \qquad R_{id} = \infty \qquad R_o = \frac{1}{g_{m4}} = \frac{1}{7.07mS} = 141\ \Omega$$

$$CMRR = g_{m1}R_1 = 1.00mS(375k\Omega) = 375 \quad or \quad 51.5\ dB$$

$$(ii)\ P \cong (I_1 + I_2 + I_3)(V_{DD} + V_{SS}) = (5.7mA)(24V) = 137\ mW$$

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$(i)\ V_{GS1} + V_{SG2} = 0.5mA(4.4k\Omega) = 2.2\ V$ Since the device parameters are the same,

$$V_{GS1} = V_{SG2} = 1.1\ V \qquad I_D = \frac{0.025}{2}(1.1-1)^2 = 125\ \mu A$$

(ii) Since the device parameters are the same, $V_{BE1} = V_{EB2} = \dfrac{0.5mA(2.4k\Omega)}{2} = 0.6\ V$

$$I_C = (10^{-14}\ A)\ \exp\left(\frac{0.6}{0.025}\right) = 265\ \mu A$$

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$$A_{v1} = \frac{v_d}{v_g} = -g_m n^2 R_L = -(50mA/V^2)(2V - 1V)(10)^2(8\Omega) = -40.0$$

$$A_{vo} = A_{v1}\frac{1}{n} = -\frac{40.0}{10} = -4.00 \qquad |v_g| \le 0.2(2-1)V = 0.200\ V \qquad |v_d| \le 0.2V(40) = 8.00\ V$$

$$|v_o| \le \frac{8V}{10} = 0.800\ V$$

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$$(i)\ R_{bb} \to 0 \quad R_{out} = 432k\Omega\left[1 + \frac{150(18.4k\Omega)}{18.8k\Omega + 18.4k\Omega}\right] = 32.5\ M\Omega$$

$$(ii)\ V_{EQ} = -15V\frac{270k\Omega}{110k\Omega + 270k\Omega} = -10.66\ V \quad R_{EQ} = 110k\Omega \| 270k\Omega = 78.2\ k\Omega$$

$$I_C = 150\frac{-10.66 - 0.7 - (-15)}{78.2k\Omega + 151(18k\Omega)} = 195\ \mu A \quad r_o = \frac{(75 + 11.5)V}{195\mu A} = 446\ k\Omega \quad r_\pi = \frac{150}{40(195\mu A)} = 19.3\ k\Omega$$

$$R_{out} = 446k\Omega\left[1 + \frac{150(18k\Omega)}{78.2k\Omega + 19.3k\Omega + 18k\Omega}\right] = 10.9\ M\Omega$$

$(iii)\ R_1 + R_2 \cong \frac{15V}{20\mu A} = 750k\Omega$ Using a spreadsheet with $I_o = 200\ \mu A$ yields $V_{BB} = 9V$.

$$R_1 = 750k\Omega\left(\frac{9V}{15V}\right) = 450\ k\Omega \quad R_1 = 300\ k\Omega \quad R_E = \frac{150}{151}\left[\frac{9 - 0.7 - 1.33\mu A(180k\Omega)}{200\mu A}\right] = 40.0\ k\Omega$$

$$R_{out} = \left(\frac{75 + 15 - 8.3}{2x10^{-4}}\right)\left[1 + \frac{150(40.0k\Omega)}{180k\Omega + 18.75k\Omega + 40.0k\Omega}\right] = 10.7\ M\Omega$$

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$$(i)\ V_{DS} \geq V_{GS} - V_{TN} = 1 + \sqrt{\frac{2(0.2mA)}{2.49mA/V^2}} = 1.40\ V \quad V_D = V_S + 1.40 = -15 + 0.2mA(18.2k\Omega) + 1.40 = -9.96V$$

$$(ii)\ \frac{W}{L} = \frac{K_n}{K_n'} = \frac{2.49mA/V^2}{25\mu A/V^2} = \frac{99.6}{1}$$

$$(iii)\ P_{R_S} = (0.2mA)^2 18.2k\Omega = 0.728\ mW \quad I_{BIAS} = \frac{15V}{499k\Omega + 249k\Omega} = 20.1\ \mu A$$

$$P_{R_4} = (20.1\mu A)^2 499k\Omega = 0.202\ mW \quad P_{R_3} = (20.1\mu A)^2 249k\Omega = 0.101\ mW$$

$$V_{GG} = -15V\frac{510k\Omega}{510k\Omega + 240k\Omega} = -10.2V \quad -10.2 - V_{GS} - 18000I_D = -15V$$

$$4.8 - V_{GS} - 18000\frac{2.49mA}{2}(V_{GS} - 1)^2 = 0 \quad V_{GS} = 1.390\ V \quad I_D = 189\ \mu A$$

$$R_{out} \cong \mu_f R_S \cong \frac{1}{0.01}\sqrt{\frac{2(2.49x10^{-3})}{189x10^{-6}}}\left[1 + 0.01(11.6)\right](18k\Omega) = 10.3\ M\Omega$$

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$$R_{avg} = 10k\Omega(1 + 0.2) = 12\ k\Omega \quad 12k\Omega(1 - 0.01) \leq R \leq 12k\Omega(1 + 0.01) \quad 11.88\ k\Omega \leq R \leq 12.12\ k\Omega$$

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$$(i)\ V_{DS1} = V_{TN} + \sqrt{\frac{2I_{REF}}{K_n(1+\lambda V_{DS1})}} \qquad V_{DS1} = 1 + \sqrt{\frac{2(150\mu A)}{250\mu A/V^2[1+0.0133V_{DS1}]}} \rightarrow V_{DS1} = 2.08\ V$$

$$I_O = 150\mu A\frac{1+0.0133(10)}{1+0.0133(2.08)} = 165\ \mu A$$

$$(ii)\ \ V_{DS} \geq V_{GS} - V_{TN} \qquad V_D - (-10V) \geq \sqrt{\frac{2I_D}{K_n}} \qquad V_D \geq -10V + \sqrt{\frac{2(150\mu A)}{250\mu A/V^2}} = -8.91\ V$$

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$$MR = \frac{25/1}{3/1} = 8.33 \qquad V_{DS1} = 1V + \sqrt{\frac{2(50\mu A)}{3(25\mu A/V^2)}} = 2.16\ V \qquad MR = 8.33\frac{1+0.02(15)}{1+0.02(2.16)} = 10.4$$

$$MR = \frac{2/1}{5/1} = 0.400 \qquad V_{DS1} = 1V + \sqrt{\frac{2(50\mu A)}{5(25\mu A/V^2)}} = 1.89\ V \qquad MR = 8.33\frac{1+0.02(10)}{1+0.02(1.89)} = 0.463$$

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$$I_{REF} = I_S \exp\left(\frac{V_{BE1}}{V_T}\right)\left(1+\frac{V_{BE1}}{V_{A1}}+\frac{2}{\beta_{FO}}\right) \qquad 100\mu\text{A} = (0.1fA)\exp(40V_{BE1})\left(1+\frac{V_{BE1}}{50V}+\frac{2}{100}\right) \rightarrow V_{BE1} = 0.690$$

$$V_{CE} \geq V_{BE} \rightarrow V_C \geq -V_{EE} + 0.690\ V$$

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$$MR = \frac{0.5A}{A} = 0.5 \qquad MR = \frac{0.5}{1+\frac{1.5}{75}} = 0.490 \qquad MR = 0.5\frac{1+\frac{15}{60}}{1+\frac{0.7}{60}+\frac{1.5}{75}} = 0.606$$

$$MR = \frac{5A}{2A} = 2.50 \qquad MR = \frac{2.50}{1+\frac{3.5}{75}} = 2.39 \qquad MR = 2.5\frac{1+\frac{15}{60}}{1+\frac{0.7}{60}+\frac{3.5}{75}} = 2.95$$

Page 901

$$(i)\ I_{O2} = 100\mu A\left(\frac{10/1}{5/1}\right) = 200\ \mu A \quad I_{O3} = 100\mu A\left(\frac{20/1}{5/1}\right) = 400\ \mu A$$

$$I_{O4} = 100\mu A\left(\frac{40/1}{5/1}\right) = 800\ \mu A \quad I_{O5} = 100\mu A\left(\frac{2.5/1}{5/1}\right) = 50\ \mu A$$

$$(ii)\ I_{O2} = 200\mu A\frac{1+0.02(10)}{1+0.02(2)} = 231\ \mu A \quad I_{O3} = 400\mu A\frac{1+0.02(5)}{1+0.02(2)} = 423\ \mu A$$

$$I_{O4} = 800\mu A\frac{1+0.02(12)}{1+0.02(2)} = 954\ \mu A \quad I_{O5} = 50\mu A\frac{1+0.02(8)}{1+0.02(2)} = 55.8\ \mu A$$

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$$(i)\ I_{O2} = 10\mu A\frac{1}{1+\frac{17}{50}} = 7.46\ \mu A \quad I_{O3} = 5(7.46\mu A) = 37.3\ \mu A \quad I_{O4} = 10(7.46\mu A) = 74.6\ \mu A$$

$$I_{O2} = 10\mu A\frac{1+\frac{10}{50}}{1+\frac{0.7}{50}+\frac{17}{50}} = 8.86\ \mu A \quad I_{O3} = 50\mu A\frac{1+\frac{10}{50}}{1+\frac{0.7}{50}+\frac{17}{50}} = 44.3\ \mu A$$

$$I_{O4} = 100\mu A\frac{1+\frac{10}{50}}{1+\frac{0.7}{50}+\frac{17}{50}} = 88.6\ \mu A$$

$$(ii)\ MR = \frac{10}{1+\frac{11}{50(51)}} = 9.957 \quad FE = \frac{10-9.957}{10} = 4.3x10^{-3} \quad V_{CE2} = V_{BE1} + V_{BE3} = 1.4\ V$$

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$$\text{MOS}:\ I_{O2} = 200\mu A\frac{1+0.02(10)}{1+0.02(2)} = 231\ \mu A \quad R_{out2} = \frac{50V+10V}{231\mu A} = 260\ k\Omega$$

$$I_{O3} = 400\mu A\frac{1+0.02(5)}{1+0.02(2)} = 423\ \mu A \quad R_{out3} = \frac{50V+5V}{423\mu A} = 130\ k\Omega$$

$$\text{BJT}:\ I_{O2} = 10\mu A\frac{1+\frac{10}{50}}{1+\frac{0.7}{50}+\frac{17}{100}} = 10.1\ \mu A \quad R_{out2} = \frac{50V+10V}{10.1\mu A} = 5.94\ M\Omega$$

$$I_{O3} = 50\mu A\frac{1+\frac{10}{50}}{1+\frac{0.7}{50}+\frac{17}{100}} = 50.7\ \mu A \quad R_{out3} = \frac{50V+10V}{50.7\mu A} = 1.19\ M\Omega$$

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$$I_{C1} = 100\mu A \frac{1+\frac{0.7V}{50V}}{1+\frac{0.7V}{50V}+\frac{6}{50V}} = 89.4\mu A \quad I_{C2} = 500\mu A \frac{1+\frac{10V}{50V}}{1+\frac{0.7V}{50V}+\frac{6}{50V}} 529\mu A$$

$$R_{in} \cong \frac{1}{g_{m1}} = \frac{1}{40(89.4\mu A)} = 280\ \Omega \quad \beta = \frac{529\mu A}{89.4\mu A} = 5.92 \quad R_{out} = \frac{50V+10V}{529\mu A} = 113\ k\Omega$$

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$$V_{DS1} = V_{GS1} = 0.75V + \sqrt{\frac{2(100\mu A)}{1mA/V^2}} = 1.20\ V \quad I_{D2} = 100\mu A \frac{1+\frac{10V}{50V}}{1+\frac{1.2}{50V}} = 117\ \mu A$$

$$R_{in} \cong \frac{1}{g_{m1}} = \frac{1}{\sqrt{2(10^{-3})(10^{-4})}} = 2.24\ \text{k}\Omega \quad \beta = \frac{117\mu A}{100\mu A} = 1.17 \quad R_{out} = \frac{50V+10V}{117\mu A} = 513\ k\Omega$$

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$$(i) \quad R = \frac{V_T}{I_O}\ln\left(\frac{I_{REF}}{I_O}\frac{A_{E2}}{A_{E1}}\right) = \frac{0.025V}{25\mu A}\ln\left(\frac{100\mu A}{25\mu A}5\right) = 3000\ \Omega$$

$$K = 1+\ln\left(\frac{100\mu A}{25\mu A}5\right) = 4.00 \quad R_{out} = 4\left(\frac{75V}{25\mu A}\right) = 12.0\ M\Omega$$

$$(ii) \quad I_O = \frac{V_T}{R}\ln\left(\frac{I_{REF}}{I_O}\frac{A_{E2}}{A_{E1}}\right) \quad I_O = \frac{0.025V}{100\Omega}\ln\left(\frac{1000\mu A}{I_O}\right) \rightarrow I_O = 300.54\ \mu A$$

$$K = 1+\ln\left(\frac{100\mu A}{300.54\mu A}10\right) = 2.202 \quad R_{out} = 2.202\left(\frac{75V}{300.54\mu A}\right) = 550\ k\Omega$$

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$$I_O = \frac{1}{R}\sqrt{\frac{2I_{REF}}{K_{n1}}}\left(1-\sqrt{\frac{I_O}{I_{REF}}\frac{(W/L)_1}{(W/L)_2}}\right) \quad I_O = \frac{1}{2k\Omega}\sqrt{\frac{2(200\mu A)}{25\mu A/V^2}}\left(1-\sqrt{\frac{I_O}{200\mu A}\frac{1}{10}}\right)$$

$$I_O = 2.00mA\left(1-\sqrt{\frac{I_O}{2.00mA}}\right) \rightarrow I_O = 764\ \mu A$$

$$R_{out} = \frac{50V+10V}{764\mu A}\left(1+2000\sqrt{2(2.5x10^{-4})(7.64x10^{-4})}\right) = 176\ k\Omega$$

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$$R_{out} \cong \frac{\beta_o r_o}{2} = \frac{150}{2}\left(\frac{50V+15V}{50\mu A}\right) = 97.5\ M\Omega \quad R_{out} = r_o = \frac{50V+15V}{50\mu A} = 1.30\ M\Omega$$

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$$V_{DS2} = V_{GS2} = 0.8V + \sqrt{\frac{2\left(5x10^{-5}\right)}{2.5x10^{-4}}} = 1.43\ V \quad V_{DS4} = 15 - 1.43 = 13.6\ V$$

$$R_{out} \cong \mu_{f4} r_{o2} = \sqrt{2\left(2.5x10^{-4}\right)\left(5x10^{-5}\right)\left[1+0.015\left(13.6\right)\right]}\left(\frac{\frac{1}{0.015}V + 13.6V}{50\mu A}\right)\left(\frac{\frac{1}{0.015}V + 1.43V}{50\mu A}\right) = 379\ M\Omega$$

$$R_{out} = r_o = \frac{66.7V + 15V}{50\mu A} = 1.63\ M\Omega$$

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$$R_{out} \cong \frac{\beta_o r_o}{2} = \frac{100}{2}\left(\frac{67V + 14.3V}{50\mu A}\right) = 81.3\ M\Omega \quad R_{out} = r_o = \frac{67V + 15V}{50\mu A} = 164\ k\Omega$$

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$$(i)\ I_O = 25.015\mu A + \frac{10V - 20V}{1.66G\Omega} = 25.009\ \mu A$$

$$(ii)\ V_{DS4} \geq V_{GS4} - V_{TN} = 0.2\ V \quad V_{D4} \geq V_{S4} + 0.2 \quad V_{D4} \geq 0.95 + 0.2 = 1.15\ V$$

$$(iii)\ I_O = 50\mu A \pm 0.1\% \quad \Delta I_O \leq 50nA \quad R_{out} \geq \frac{20V}{50nA} = 400\,M\Omega \quad \text{Choose } R_{out} = 1\ G\Omega.$$

$$r_o \cong \frac{50V}{50\mu A} = 1\ M\Omega \rightarrow \mu_f = 1000 \quad \mu_f \cong \frac{1}{\lambda}\sqrt{\frac{2K_n}{I_D}} \quad K_n = \left[\frac{0.01}{V}\left(1000\right)\right]^2 \frac{50\mu A}{2} = 2.5\frac{mA}{V^2}$$

$$\left(W/L\right)_2 = \left(W/L\right)_4 = \frac{2.5x10^{-3}}{5x10^{-5}} = \frac{50}{1} \quad \left(W/L\right)_3 = \left(W/L\right)_1 = \frac{1}{2}\left(\frac{50}{1}\right) = \frac{25}{1}$$

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$$(i)\ I_{REF} = \frac{5V - 0.7V}{43k\Omega} = 100\ \mu A \quad I_{REF} = \frac{7.5V - 0.7V}{43k\Omega} = 158\ \mu A$$

(ii) Since the transistors have the same parameters, $V_{GS1} = \dfrac{V_{DD} - \left(-V_{SS}\right)}{3}$

$$I_{D2} = I_{D1} = \frac{4x10^{-4}}{2}\left(1.667 - 1\right)^2 = 89.0\ \mu A \quad I_{D2} = I_{D1} = \frac{4x10^{-4}}{2}\left(2.5 - 1\right)^2 = 450\ \mu A$$

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$$I_O \cong \frac{0.025V}{6.8k\Omega}\ln\frac{5 - 1.4}{10^{-16}\left(39k\Omega\right)} = 101\ \mu A \quad I_O \cong \frac{0.025V}{6.8k\Omega}\ln\frac{7.5 - 1.4}{10^{-16}\left(39k\Omega\right)} = 103\ \mu A$$

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$$(i)\ I_O = \frac{V_T}{R}\ln\left(\frac{I_{C1}}{I_{C2}}\frac{A_{E2}}{A_{E1}}\right) \quad I_O = \frac{0.025V}{1000\Omega}\ln\left[10(10)\right] = 115\ \mu A$$

$$(\text{ii})\ V_{CC} + V_{EE} \geq V_{BE1} + V_{BE4} \cong 1.4\ V$$

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$$R = \sqrt{\frac{2}{5\left(25x10^{-6}\right)\left(10^{-4}\right)}}\left(1 - \sqrt{\frac{5}{50}}\right) = 8.65\ k\Omega$$

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$$(ii)\quad R = \frac{V_T}{I_O}\ln\left(\frac{I_{C1}}{I_{C2}}\frac{A_{E2}}{A_{E1}}\right) = \frac{0.02588V}{45\mu A}\ln\left(\frac{25}{5}\right) = 926\ \Omega$$

$$A_{E1} = A \quad A_{E2} = 25A_{E1} = 25\ A \quad A_{E3} = A \quad A_{E4} = 5.58A_{E3} = 5.58\ A$$

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$$I_{D3} = I_{D4} = I_{D1} = I_{D2} = \frac{250\mu A}{2} = 125\ \mu A \quad V_{GS1} = 0.75V + \sqrt{\frac{2(125\mu A)}{250\mu A/V^2}} = 1.75\ V$$

$$V_{GS3} = -0.75V - \sqrt{\frac{2(125\mu A)}{200\mu A/V^2}} = -1.87\ V$$

$$V_{DS1} = V_{D1} - V_{S1} = (5 - 1.87) - (-1.75) = 4.88\ V \quad V_{SD3} = V_{SG3} = 1.87\ V$$

$$M_1 \text{ and } M_2 : (125\mu A, 4.88V) \quad M_3 \text{ and } M_4 : (125\mu A, 1.87V)$$

$$G_m = g_{m1} = \sqrt{2\left(2.5x10^{-4}\right)\left(1.25x10^{-4}\right)} = 250\ \mu S$$

$$R_o = r_{o2}\|r_{o4} = \frac{75.2V + 4.88V}{125\mu A}\Bigg\|\frac{75.2V + 1.87V}{125\mu A} = 314\ k\Omega$$

$$A_v = G_m R_o = 78.5$$

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$$CMRR \cong \mu_{f3} g_{m2} R_{SS} = \left(\frac{1}{\lambda}\sqrt{\frac{2K_{n3}}{I_{D3}}}\right)\left(\sqrt{2K_{n2}I_{D2}}\right)R_{SS} = \left(\frac{1}{\lambda}\sqrt{\frac{2K_{n3}}{I_{D3}}}\right)\left(\sqrt{2K_{n2}I_{D2}}\right)R_{SS}$$

$$K_{n3} = K_{n2} \quad I_{D2} = I_{D3} \quad CMRR = \frac{1}{0.0167}2(0.005)10^7 = 5.99x10^6 \quad \text{or} \quad 136\ dB$$

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For the buffered current mirror, $V_{EC4} = V_{EB3} + V_{EB11} + \frac{2V_A}{\beta_{FO4}(\beta_{FO11}+1)}$

$$I_{C11} \cong \frac{2I_{C4}}{\beta_{FO4}} = \frac{2I_{C4}}{50} = \frac{I_{C4}}{25} \quad \Delta V_{EB} = 0.025\ln\left(\frac{I_{C4}}{I_{C4}/25}\right) = 80.5\ mV$$

$$V_{EC4} = 0.7 + (0.7 - 0.081) + \frac{2(60)}{50(51)} = 1.37\ V \quad \Delta V_{EC} = \frac{2(60V)}{50(51)} = 47.1mV \quad V_{OS} = \frac{47mV}{100} = 0.47\ mV$$

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$$A_{dm} \cong A_{v1}A_{v2}A_{v3} \quad A_{v1} \cong \left(\beta_{o5}\frac{I_{C2}}{I_{C5}}\right) = \frac{150}{3} = 50 \quad A_{v2} \cong \mu_{f5} \cong 40(75) = 3000 \quad A_{v3} \cong 1$$

$A_{dm} \cong 50(3000)(1) = 150000$ Note that this assumes $R_L = \infty$.

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$$CMRR = \frac{2}{100}\left[\frac{1}{100(40)(75)} - \frac{1}{2(40)(10^{-4})(10^{7})}\right]^{-1} = 5.45x10^{6} \rightarrow 135\ dB$$

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$$(i)\ I_{REF} = \frac{22+22-1.4}{39k\Omega} = 1.09\ mA \quad I_1 = \frac{0.025V}{5k\Omega}\ln\left(\frac{1.09mA}{I_1}\right) \rightarrow I_1 = 20.0\ \mu A$$

$$I_2 = 0.75(1.09mA)\frac{1+\frac{23.4V}{60V}}{1+\frac{0.7V}{60V}+\frac{2}{50}} = 1.08\ mA \quad I_2 = 0.25(1.09mA)\frac{1+\frac{21.3V}{60V}}{1+\frac{0.7V}{60V}+\frac{2}{50}} = 351\ \mu A$$

$$(ii)\ R_o = r_{o21}\left[1+\ln\frac{I_{C20}}{I_{C21}}\frac{A_{E20}}{A_{E21}}\right] = \frac{60V+13.5V}{18.4\mu A}\left[1+\ln\left(\frac{733\mu A}{18.4\mu A}1\right)\right] = 18.7\ M\Omega$$

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$$(ii)\ V_{CE6} = V_{CE5} + \frac{2V_{A6}}{\beta_{FO6}} = 0.7 + \frac{2(60V)}{100} = 1.90\ V$$

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$$R_{th} = 2r_{o4} \| 1.3r_{o6} = 2\left(\frac{60+13}{7.25\mu A}\right) \Big\| 1.3\left(\frac{60+1.3}{7.16\mu A}\right) = 20.1M\Omega \| 11.1M\Omega = 7.15\ M\Omega$$

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$$A_{v1} = -1.46x10^{-4}\left(6.54M\Omega \| R_{in11}\right) = -1.46x10^{-4}\left(6.54M\Omega \| 20.7k\Omega\right) = -3.01$$

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$$(i)\ \ R_{eq2} = r_{\pi 16} + \left(\beta_{o16} + 1\right)R_L = \frac{50\left(0.025\right)}{2mA} + 51\left(2k\Omega\right) = 103\ k\Omega$$

$$R_{eq1} = r_{d14} + \left(r_{d13} + R_3\right)\left\|R_{eq2} = \frac{0.025V}{0.216mA} + \left[\frac{0.025V}{0.216mA} + 344k\Omega\right]\right\|103k\Omega = 79.4\ k\Omega$$

$$R_{in12} = \frac{50\left(0.025V\right)}{0.216mA} + 51\left(79.4k\Omega\right) = 4.06\ M\Omega$$

$$R_{eq3} = \left(r_{d13} + R_3\right)\left\|\left(r_{d14} + \frac{r_{\pi 12} + y_{22}^{-1}}{\beta_{o12} + 1}\right) = \left(\frac{0.025V}{0.216mA} + 344k\Omega\right)\right\|\left(\frac{0.025V}{0.216mA} + \frac{5.79k\Omega + 89.1k\Omega}{51}\right) = 1.97\ k\Omega$$

$$r_{\pi 16} = 50\frac{0.025}{2mA} = 625\Omega \quad R_{out} = \frac{625 + 1970}{51} + 22 = 75.9\ \Omega$$

$$(ii)\ \ I_{SC+} \cong \frac{0.7V}{27\Omega} = 25.9\ mA \quad I_{SC-} \cong -\frac{0.7V}{22\Omega} = -31.8\ mA$$

CHAPTER 16

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$$f_L \cong \frac{1}{2\pi}\sqrt{10^2 + 1000^2 - 2(50)^2 - 2(0)^2} = 159\ Hz \quad f_L \cong \frac{1}{2\pi}\sqrt{100^2 + 1000^2 - 2(500)^2 - 2(0)^2} = 114\ Hz$$

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$$\left|\frac{200s}{(s+1000)}\right| \ge 0.9\left|\frac{200s(s+100)}{(s+10)(s+1000)}\right| \qquad 1 \ge 0.9\frac{\sqrt{\omega^2+100^2}}{\sqrt{\omega^2+10^2}} \rightarrow 0.81 \le \frac{\omega^2+10^2}{\omega^2+100^2} \rightarrow \omega \ge 205 \text{ rad/s}$$

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(i) The value of C_2 does not change A_{mid}, ω_{P1}, ω_{P3}, ω_{z1}, or ω_{Z3}.

$$\omega_{P2} = -\frac{1}{2\mu F\left(1.3k\Omega \middle\| \frac{1}{1.23mS}\right)} = -1000 \text{ rad/s} \qquad \omega_{Z3} = -\frac{1}{2\mu F(1.3k\Omega)} = -385 \text{ rad/s}$$

$$f_L = \frac{1}{2\pi}\sqrt{41.0^2 + 95.9^2 + 1000^2 - 2\left(0^2 + 0^2 + 385^2\right)} = 135\ Hz$$

$$(ii)\quad A_{mid} = 10^{\frac{13.5}{20}} = 4.732 \qquad 4.3k\Omega \| 100k\Omega \| r_o = \frac{4.732}{1.23mS} \rightarrow r_o = 57.5k\Omega$$

Note that the SPICE value of g_m probably differs from 1.23mS as well.

$$(iii)\quad \omega_{P2} = -\frac{1}{10\mu F\left(1.3k\Omega \middle\| \frac{1}{1.23mS} \middle\| 57.5k\Omega\right)} = -202 \text{ rad/s}$$

$$f_L = \frac{1}{2\pi}\sqrt{41.0^2 + 95.9^2 + 202^2 - 2\left(0^2 + 0^2 + 76.9^2\right)} = 31.8\ Hz$$

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$$(ii)\quad r_\pi = \frac{140(0.025V)}{175\mu A} = 20.0\ k\Omega \quad R_{1S}C_1 = \left(1k\Omega + 75k\Omega \| 20.0k\Omega\right)2\mu F = 33.6\ ms \quad R_{th} = 75k\Omega \| 1k\Omega = 987\ \Omega$$

$$R_{2S}C_2 = \left(13k\Omega \middle\| \frac{20.0k\Omega + 987\Omega}{141}\right)10\mu F = 1.47\ ms \qquad R_{3S}C_3 = \left(43k\Omega + 100k\Omega\right)0.1\mu F = 14.3\ ms$$

$$f_L \cong \frac{1}{2\pi}\left(\frac{1}{33.6ms} + \frac{1}{1.47ms} + \frac{1}{14.3ms}\right) = 124\ Hz$$

Page 1001

$$(i)\ \ A_v = -\frac{R_{in}}{R_I + R_{in}}\left(\frac{\beta_o}{r_\pi}R_L\right) \cong -\left(\frac{1260}{2260}\right)\left(\frac{100}{1.51k\Omega}\right)\left(4.3k\Omega \| 100k\Omega\right) = -157$$

$$A_v = -\frac{R_{in}}{R_I + R_{in}}\left(\frac{\beta_o}{r_\pi}R_L\right) \cong -\left(\frac{1260}{2260}\right)\left(\frac{100}{1.51k\Omega}\right)\left(4.3k\Omega \| 100k\Omega \| 46.8k\Omega\right) = -140$$

r_o is responsible for most of the discrepancy. r_π and β_o will also be differ from our hand calculations. Note that 45% of the gain is lost because of the amplifier's low input resistance.

$$(ii)\ \ g_m = \frac{2(1.5mA)}{0.5V} = 6.00\ mS \qquad R_{1S}C_1 = (1k\Omega + 243k\Omega)0.1\mu F = 24.4\ ms$$

$$R_{2S}C_2 = \left(1.3k\Omega \Big\| \frac{1}{6.00mS}\right)10\mu F = 1.48\ ms \qquad R_{3S}C_3 = (4.3k\Omega + 100k\Omega)0.1\mu F = 10.4\ ms$$

$$f_L \cong \frac{1}{2\pi}\left(\frac{1}{24.4ms} + \frac{1}{1.48ms} + \frac{1}{10.4ms}\right) = 129\ Hz$$

Page 1003

$$(i)\ \ g_m = 40(0.1mA) = 4.00\ mS \qquad R_{1S}C_1 = \left(100\Omega + 43k\Omega \Big\| \frac{1}{4.00mS}\right)4.7\mu F = 1.64\ ms$$

$$R_{2S}C_2 = (22k\Omega + 75k\Omega)1\mu F = 97.0\ ms \qquad f_L \cong \frac{1}{2\pi}\left(\frac{1}{1.64ms} + \frac{1}{97.0ms}\right) = 98.7\ Hz$$

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$$g_m = \frac{2(1.5mA)}{0.5V} = 6.00\ mS \qquad R_{1S}C_1 = \left(100\Omega + 1.3k\Omega \Big\| \frac{1}{6.00mS}\right)1\mu F = 0.248\ ms$$

$$R_{2S}C_2 = (4.3k\Omega + 75k\Omega)0.1\mu F = 7.93\ ms \qquad f_L \cong \frac{1}{2\pi}\left(\frac{1}{0.248ms} + \frac{1}{7.93ms}\right) = 662\ Hz$$

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$$(i)\ \ g_m = 40(1mA) = 40.0\ mS \quad r_\pi = \frac{100}{.04S} = 2.50\ k\Omega$$

$$R_{1S}C_1 = \left(1k\Omega + 100k\Omega \| \left[2.5k\Omega + 101(3k\Omega\|47k\Omega)\right]\right)0.1\mu F = 7.52\ ms$$

$$R_{2S}C_2 = \left(47k\Omega + 3k\Omega \left\| \frac{2.5k\Omega + (100k\Omega\|1k\Omega)}{101}\right.\right)100\mu F = 4.70\ s \quad f_L \cong \frac{1}{2\pi}\left(\frac{1}{7.52ms} + \frac{1}{4.7s}\right) = 21.2\ Hz$$

$$A_{mid} \cong \frac{(\beta_o + 1)R_L}{R_{th} + r_\pi + (\beta_o + 1)R_L}\left(\frac{R_I}{R_I + R_B}\right) = \frac{101(3k\Omega\|47k\Omega)}{990\Omega + 2.5k\Omega + 101(3k\Omega\|47k\Omega)}\left(\frac{100k\Omega}{1k\Omega + 100k\Omega}\right) = +0.978$$

$$(ii)\quad R_{1S}C_1 = (1k\Omega + 243k\Omega)0.1\mu F = 24.4\ ms$$

$$R_{2S}C_2 = \left(24k\Omega + 1.3k\Omega \left\| \frac{1}{1mS}\right.\right)47\mu F = 1.15\ s \quad f_L \cong \frac{1}{2\pi}\left(\frac{1}{24.4ms} + \frac{1}{1.15s}\right) = 6.66\ Hz$$

$$A_{mid} = +\left(\frac{R_G}{R_I + R_G}\right)\frac{g_m R_L}{1 + g_m R_L} = +\left(\frac{243k\Omega}{244k\Omega}\right)\frac{1mS(1.3k\Omega\|24k\Omega)}{1 + (1.3k\Omega\|24k\Omega)} = +0.550$$

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$$C_\pi = \frac{g_m}{\omega_T} - C_\mu \quad C_\mu = \frac{C_{\mu o}}{\sqrt{1 + \frac{V_{CB}}{\varphi_{jc}}}}$$

$$(100\mu A, 8V):\quad C_\mu = \frac{2\,pF}{\sqrt{1 + \frac{7.3V}{0.6V}}} = 0.551\,pF \quad C_\pi = \frac{40(10^{-4})}{2\pi(500\,MHz)} - 0.551x10^{-12} = 0.722\ pF$$

$$(2mA, 5V):\quad C_\mu = \frac{2\,pF}{\sqrt{1 + \frac{4.3V}{0.6V}}} = 0.700\ pF \quad C_\pi = \frac{40(2x10^{-3})}{2\pi(500\,MHz)} - 0.700x10^{-12} = 24.8\ pF$$

$$(50mA, 8V):\quad C_\mu = \frac{2\,pF}{\sqrt{1 + \frac{7.3V}{0.6V}}} = 0.551\,pF \quad C_\pi = \frac{40(5x10^{-2})}{2\pi(500\,MHz)} - 0.551x10^{-12} = 636\ pF$$

Page 1012

$$(i)\ \ C_{GS} = C_{GD} = \frac{1}{2}C_{ISS} = 0.5\ pF$$

$$(ii)\ \ C_{GS} + C_{GD} = \frac{g_m}{\omega_T} \qquad 5C_{GD} + C_{GD} = \frac{\sqrt{2(0.01)(0.01)}}{2\pi(200\,MHz)} = 11.3\ pF \qquad C_{GD} = 1.88\ pF \quad C_{GS} = 9.38\ pF$$

$$(iii)\ C_\mu = \frac{C_{\mu o}}{\sqrt{1+\frac{V_{CB}}{\varphi_{jc}}}} = \frac{2\,pF}{\sqrt{1+\frac{7.3V}{0.6V}}} = 0.551\,pF \quad C_\pi = \frac{g_m}{\omega_T} - C_\mu = \frac{40(20\mu A)}{2\pi(500\,MHz)} - 0.551pF = -0.296\ pF$$

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$$A_v = -\frac{R_{in}}{R_I + R_{in}}\left(\frac{\beta_o}{r_x + r_\pi}R_L\right) \qquad R_{in} = 7.5k\Omega \| (1.51k\Omega + 250\Omega) = 1.43k\Omega$$

$$\cong -\left(\frac{1430}{2430}\right)\left(\frac{100}{1.76k\Omega}\right)(4.3k\Omega \| 100k\Omega) = -139$$

$$A_v = -\frac{R_{in}}{R_I + R_{in}}\left(\frac{\beta_o}{r_\pi}R_L\right) \cong -\left(\frac{1260}{2260}\right)\left(\frac{100}{1.51k\Omega}\right)(4.3k\Omega \| 100k\Omega) = -157$$

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(ii) The term $C_L\frac{R_L}{r_{\pi o}}$ is added to the value of C_T.

$$C_L\frac{R_L}{r_{\pi o}} = 3pF\left(\frac{4120}{656}\right) = 18.8\ pF \quad f_{P1} = \frac{1}{2\pi(656\Omega)(156+18.8)pF} = 1.39\ MHz$$

$$f_{P2} = \frac{g_m}{2\pi(C_\pi + C_L)} = \frac{0.064S}{2\pi(19.9+3)pF} = 445\ MHz$$

$$(iii)\ \ C_\pi = \frac{0.064}{2\pi(500\,MHz)} - 10^{-12} = 19.4\ pF$$

$$C_T = 19.4 + 1\left[1 + 0.064(4120) + \frac{4120}{656}\right] = 290\ pF \quad f_{P1} = \frac{1}{2\pi(656\Omega)290\,pF} = 837\ kHz$$

$$f_{P2} = \frac{g_m}{2\pi C_\pi} = \frac{0.064S}{2\pi(19.4\,pF)} = 525\ MHz \qquad f_Z = \frac{g_m}{2\pi C_\mu} = \frac{0.064S}{2\pi(1pF)} = 10.2\ GHz$$

$A_{mid} = -135$ is not affected by the value of f_T.

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$$C_T = 10 + 2\left[1 + 1.23mS(4.12k\Omega) + \frac{4120}{996}\right] = 30.4\ pF \quad f_{P1} = \frac{1}{2\pi(996\Omega)30.4\,pF} = 5.26\ MHz$$

$$f_{P2} = \frac{g_m}{2\pi C_{GS}} = \frac{1.23mS}{2\pi(10\,pF)} = 19.6\ MHz \quad f_Z = \frac{g_m}{2\pi C_{GD}} = \frac{1.23mS}{2\pi(2\,pF)} = 97.9\ MHz$$

$$f_T = \frac{g_m}{2\pi(C_{GS} + C_D)} = \frac{1.23mS}{2\pi(12\,pF)} = 16.3\ MHz$$

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$$(ii)\ \ 1 + g_m R_E = 1 + 0.064(100) = 7.40 \qquad R_{iB} = 250 + 1560 + 101(100) = 11.9\ k\Omega$$

$$r_{\pi 0} = 11.9k\Omega \| (882 + 250) = 1030\ \Omega$$

$$A_i = \frac{10k\Omega \| 30k\Omega \| 11.9k\Omega}{1k\Omega + 10k\Omega \| 30k\Omega \| 11.9k\Omega} = 0.821 \qquad A_{mid} = -0.821\left(\frac{264}{7.4}\right) = -29.3$$

$$f_H = \frac{1}{2\pi(1.03k\Omega)\left[\frac{19.9\,pF}{7.4} + 0.5\,pF\left(1 + \frac{264}{7.4} + \frac{4120}{1030}\right)\right]} = 6.70\ MHz \quad GBW = 196\ MHz$$

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$$(i)\ A_{mid} \cong \frac{g_m^{'} R_L}{1 + g_m^{'} R_E} \quad g_m^{'} = \frac{\beta_o}{r_x + r_\pi} = \frac{100}{250 + \frac{100}{40(0.1mA)}} = 3.96\ mS \quad A_{mid} \cong \frac{3.96mS(17.0k\Omega)}{1 + 3.96mS(100\Omega)} = +48.2$$

$$f_H \cong \frac{1}{2\pi(17.0k\Omega)(0.5\,pF)} = 18.7\ MHz \qquad GBW = 903\ MHz$$

$$(ii)\ R_{iS} = R_4 \left\| \frac{1}{g_m} \right. = 1.3k\Omega \left\| \frac{1}{3mS} \right. = 265\ \Omega \qquad A_i = \frac{265}{100 + 265} = 0.726$$

$$A_{mid} = 0.726(g_m R_L) = 0.726(3mS)(4.12k\Omega) = 8.98 \qquad f_H \cong \frac{1}{2\pi(4.12k\Omega)(4\,pF)} = 9.66\ MHz$$

$$f_T \cong \frac{3mS}{2\pi(11\,pF)} = 43.4\ MHz \qquad GBW = 86.7\ MHz$$

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$$g_m = 40(1.5mA) = 60\ mS \quad r_\pi = \frac{100}{60mS} = 1.67\ k\Omega \quad R_L = 3k\Omega \| 47k\Omega = 2.82k\Omega$$

$$A_i = \frac{100k\Omega \| [150 + 1670 + 101(2820)]}{1k\Omega + 100k\Omega \| [150 + 1670 + 101(2820)]} = 0.987 \quad A_{mid} = 0.987 \frac{60mS(2.82k\Omega)}{1 + 60mS(2.82k\Omega)} = 0.980$$

$$C_\pi = \frac{60mS}{2\pi(500\,MHz)} - 0.5pF = 18.6\ pF \quad f_H \cong \frac{1}{2\pi} \frac{1}{((990 + 150)\|286k\Omega)\left(0.5pF + \frac{18.6pF}{1 + 169}\right)} = 230\ MHz$$

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$$R_L = 1.3k\Omega \| 24k\Omega = 1.23k\Omega \quad A_i = \frac{430k\Omega}{1k\Omega + 430k\Omega} = 0.998$$

$$A_{mid} = 0.998 \frac{3mS(1.23k\Omega)}{1 + 3mS(1.23k\Omega)} = 0.785 \quad f_H \cong \frac{1}{2\pi} \frac{1}{(1k\Omega \| 430k\Omega)\left(1pF + \frac{10pF}{1 + 3.69}\right)} = 50.9\ MHz$$

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$$f_Z = \frac{1}{2\pi(25M\Omega)1pF} = 6.37\ kHz \quad f_P = \frac{1}{2\pi(50.25k\Omega)0.5pF} = 6.33\ MHz$$

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$$\text{Differential Pair}: A_{dm} = -g_m R_C = -40(99.0\mu A)(50k\Omega) = -198$$

$$C_\pi = \frac{40(99.0\mu A)}{2\pi(500\,MHz)} - 0.5pF = 0.761\,pF \quad r_\pi = \frac{100}{40(99.0\mu A)} = 25.3\ k\Omega$$

$$f_H = \frac{1}{2\pi(250\Omega)\left[0.761pf + 0.5pF\left(1 + 198 + \frac{50k\Omega}{250\Omega}\right)\right]} = 3.18\ MHz$$

$$\text{CC} - \text{CB Cascade}: A_v = \frac{g_{m1}\left(\frac{1}{g_{m2}}\right)}{1 + g_{m1}\left(\frac{1}{g_{m2}}\right)}(g_m R_C) = +\frac{198}{2} = +99 \quad f_H \cong \frac{1}{2\pi(50k\Omega)(0.5pF)} = 6.37\ MHz$$

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$$g_m = 40(1.6mA) = 64.0\ mS \quad r_\pi = \frac{100}{64mS} = 1.56\ k\Omega \quad C_\pi = \frac{64.0mS}{2\pi(500\,MHz)} - 0.5\,pF = 19.9\ pF$$

$$A_{mid} = \frac{r_\pi}{R_I + r_x + r_\pi}(-g_m R_L) = \frac{1.56\ k\Omega}{882\Omega + 250\Omega + 1.56\ k\Omega}(-64.0mS)(4.12k\Omega) = -153$$

$$f_{P1} \cong \frac{1}{2\pi\, r_{\pi 0}(C_\pi + 2C_\mu)} = \frac{1}{2\pi\,(656\Omega)(19.9+1)pF} = 11.6\ MHz$$

$$f_{P2} \cong \frac{1}{2\pi\, R_L(C_\mu + C_L)} = \frac{1}{2\pi\,(4120\Omega)(0.5+5)pF} = 7.02\ MHz$$

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$$f_{P1} \cong \frac{1}{4\pi\, C_{GGD} r_{o2}} = \frac{0.02(100\mu A)}{4\pi\,(1\text{pF})} = 159\ kHz \quad f_{P1} \cong \frac{1}{4\pi\, C_{GGD} r_{o2}} = \frac{0.02(25\mu A)}{4\pi\,(1\text{pF})} = 39.8\ kHz$$

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$$(i)\ X_C = \frac{1}{2\pi(530\,Hz)39\,pF} = 7.69\ M\Omega >> 2.39\ k\Omega$$

$$X_C = \frac{1}{2\pi(530\,Hz)1\,pF} = 300\ M\Omega >> 51.8k\Omega \| 19.8k\Omega = 14.3\ k\Omega$$

$$(ii)\ X_1 = \frac{1}{2\pi(667\,kHz)0.01\mu F} = 23.9\ \Omega << 1.01\ M\Omega$$

$$X_2 = \frac{1}{2\pi(667\,kHz)47\mu F} = 5.07\ \text{m}\Omega << 66.7\ \Omega$$

$$X_3 = \frac{1}{2\pi(667\,kHz)1\mu F} = 239\ \text{m}\Omega << 2.69\ k\Omega$$

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$$Z_C = \frac{1}{2\pi j(5\,MHz)0.01\mu F} = -j3.18\ \Omega$$

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$(i)\ f_o = \dfrac{1}{2\pi\sqrt{(10\mu H)(100\,pF + 20\,pF)}} = 4.59\ MHz \qquad r_o = \dfrac{50V + 15V - 1.6V}{3.2mA} = 19.8k\Omega$

$$Q = \frac{100k\Omega \| 100k\Omega \| r_o}{2\pi(4.59\ MHz)(10\mu H)} = 49.2 \qquad BW = \frac{4.59\,MHz}{49.2} = 93.3\text{ kHz}$$

$$A_{mid} = -g_m(100k\Omega \| 100k\Omega \| r_o) = -\sqrt{2(0.005)(0.0032)}(100k\Omega \| 100k\Omega \| 19.8k\Omega) = -80.2$$

$(ii)\ f_o$ is unchanged

CHAPTER 17

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$(i)\ A_v = \frac{A}{1+A\beta} \quad \beta = \frac{10k\Omega}{10k\Omega + 91k\Omega} = 0.0990 \quad A_v = \frac{10^4}{1+10^4(0.0990)} = 10.1$

$R_{in} = R_{id}(1+A\beta) = 25k\Omega\left[1+10^4(0.0990)\right] = 24.8\ M\Omega \quad R_{out} = \frac{R_o}{1+A\beta} = \frac{10^3}{1+10^4(0.0990)} = 1.01\ \Omega$

$(ii)\ A = 4730\frac{1k\Omega + 25k\Omega + 9.01k\Omega}{25k\Omega + 9.01k\Omega} = 4870 \quad A_v = \frac{4870}{1+4870(0.0990)} = 10.1$

$R_{in} = R_{id}(1+A\beta) = 34.0k\Omega\left[1+4870(0.0990)\right] = 16.4\ M\Omega \quad R_{out} = \frac{R_o}{1+A\beta} = \frac{662\Omega}{1+4870(0.0990)} = 1.37\ \Omega$

$(iii)\ h_{12}^A = 0$ (No reverse gain through the amplifier.)

$h_{21}^A = \left.\frac{i_2}{i_1}\right|_{v_2=0} = -\frac{25000(10^4)}{1000} = -2.5x10^5 \quad h_{21}^F = \left.\frac{i_2}{i_1}\right|_{v_2=0} = -\frac{10k\Omega}{10k\Omega + 91k\Omega} = -0.0990$

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$(i)\ y_{21}^A = \left.\frac{i_2}{v_1}\right|_{v_2=0} = +g_m = +39.1\ mS \quad y_{21}^F = \left.\frac{i_2}{v_1}\right|_{v_2=0} = -\frac{1}{R_F} = -10^{-5}S$

$y_{12}^A = 0$ (No reverse gain through the amplifier.)

$(ii)\ A = -\frac{4.76k\Omega}{4.76k\Omega + 3.84k\Omega}(150)(10k\Omega \| 100k\Omega \| 5k\Omega \| 52.6k\Omega) = -252\ k\Omega$

$\beta = -\frac{1}{R_F} = -10^{-5}S = -0.01\ mS \quad A_{tr} = \frac{-252k\Omega}{1-252k\Omega(-0.01mS)} = -71.6\ k\Omega$

$R_{in} = \frac{R_{in}^A}{1+A\beta} = \frac{2.13k\Omega}{1+2.52} = 605\ \Omega \quad R_{out} = \frac{R_o}{1+A\beta} = \frac{10k\Omega \| 100k\Omega \| 5k\Omega \| 52.6k\Omega}{1+2.52} = 863\ \Omega$

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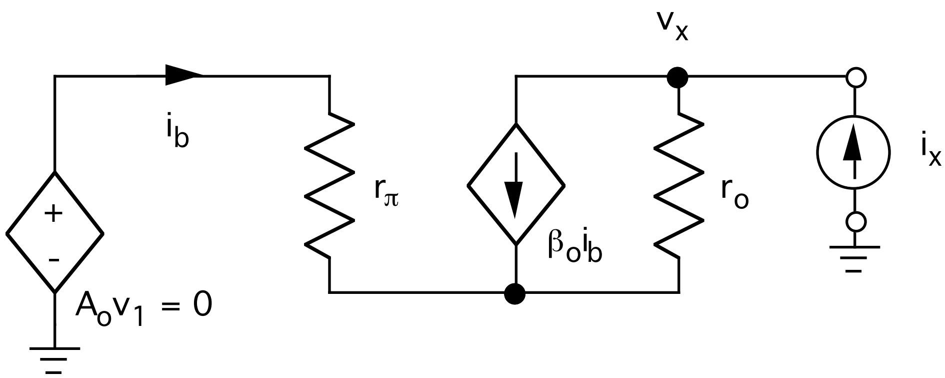

$$v_x = (i_x - \beta_o i_b) r_o + i_x r_\pi \qquad i_b = -i_x \qquad v_x = (i_x - \beta_o i_x) r_o + i_x r_\pi = i_x r_o\left(\beta_o + 1 + \frac{\beta_o}{\mu_f}\right)$$

$$R_{out} = \frac{v_x}{i_x} = r_o\left(\beta_o + 1 + \frac{\beta_o}{\mu_f}\right) \cong \beta_o r_o \quad \text{for } \beta_o >> 1 \quad \text{and} \quad \mu_f >> \beta_o$$

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R_E is now connected between the emitter and collector of Q_2 in the upper half of Fig. 17.36. However, when the A - circuit is constructed, y_{22}^F is connected in parallel with R_E, so the resistance at the output of the A - circuit is still 901 Ω. The value of y_{11}^F is unchanged, so overall the A - circuit is unchanged. Likewise, β is unchanged, and so A_{tr} is the same.

Page 1102

(i) Using voltage division: $v_+ - v_- = -v_{P1}\dfrac{R_1\|R_{id}}{R_2 + (R_1\|R_{id})}$ $\quad \mathrm{v_o} = A(v_+ - v_-) \quad T = -\dfrac{v_o}{v_{P1}} = A\dfrac{R_1\|R_{id}}{R_2 + (R_1\|R_{id})}$

(ii) $T = A\dfrac{R_1}{R_1 + R_2}\dfrac{R_{id}}{R_{id} + R_3} = A\dfrac{R_1}{R_1 + R_2}\dfrac{R_{id}}{R_{id} + \dfrac{R_1 R_2}{R_1 + R_2}} = A\dfrac{R_1 R_{id}}{R_{id}(R_1 + R_2) + R_1 R_2}$

$$T = A\frac{R_1 R_{id}}{R_1 R_{id} + (R_1 + R_{id})R_2} = A\frac{\dfrac{R_1 R_{id}}{R_1 + R_{id}}}{\dfrac{R_1 R_{id}}{R_1 + R_{id}} + R_2} = A\frac{R_1\|R_{id}}{R_2 + R_1\|R_{id}}$$

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$$R_D = 50k\Omega\left[1 + \frac{100\left(5k\Omega\|25k\Omega\right)}{5k\Omega + 2.5k\Omega + \left(5k\Omega\|25k\Omega\right)}\right] = 1.84\ M\Omega$$

$$\left|T_{SC}\right| = 10^4\frac{101\left(3.85k\Omega\right)}{5k\Omega + 2.5k\Omega + 101\left(3.85k\Omega\right)} = 9810 \qquad \left|T_{OC}\right| = 10^4\frac{\left(5k\Omega\|25k\Omega\right)}{5k\Omega + 2.5k\Omega + \left(5k\Omega\|25k\Omega\right)} = 3570$$

$$R_{out} = 1.84M\Omega\left(\frac{1+9810}{1+3570}\right) = 5.06\ M\Omega$$

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The analysis is the same with r_π and $\beta_o \rightarrow \infty$.

$$R_D = r_{o3}\left(1 + \frac{\beta_{o3}}{\mu_{f2} + \beta_{o3} + 1}\right) \rightarrow 2r_{o3} \qquad \left|T_{OC}\right| = \frac{1}{1 + \dfrac{\beta_o + 1}{\mu_f}} \rightarrow 0 \qquad \left|T_{SC}\right| = \frac{\beta_o + 1}{1 + \dfrac{2\beta_o + 1}{\mu_f}} \rightarrow \frac{\mu_f}{2}$$

$$R_{out} = 2r_{o3}\frac{1 + \dfrac{\mu_f}{2}}{1 + 0} \cong \mu_f r_{o3}$$

Page 1116

$$f_B = \frac{f_T}{A_o} = \frac{10^7\ Hz}{10^5} = 100\ Hz \qquad f_H = \beta f_T = \frac{10^7\ Hz}{10^3} = 10\ \text{k}Hz$$

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$$\angle T\left(j\omega\right) = -3\tan^{-1}\left(\omega\right) = -\pi \rightarrow \omega = 1.732 \qquad \left|T\left(j\omega\right)\right| = \frac{5}{\left(\sqrt{\omega^2 + 1}\right)^3} = 0.625$$

$$GM = 20\log\left(\frac{1}{0.625}\right) = 4.08\ dB$$

Page 1122

From the Bode plot, the phase shift at the unity gain frequency (10 MHz) is -130^o.
The phase margin is 180^o - 130^o = 50^o.

Page 1124

$$G_m = g_{m2} = \sqrt{2\left(10^{-3}\right)\left(5x10^{-5}\right)} = 0.316\ mS \qquad R_O = r_{o4} \| r_{o2} \cong \frac{1}{2\lambda I_D} = \frac{1}{2\left(0.02\right)5x10^{-5}} = 500\ \text{k}\Omega$$

$$f_T = \frac{1}{2\pi}\left(\frac{G_m}{C_C}\right) = \frac{1}{2\pi}\left(\frac{0.316mS}{20\text{pF}}\right) = 2.51\ MHz$$

$$f_B = \frac{1}{2\pi}\left[\frac{1}{R_O C_C\left(1 + A_{v2}\right)}\right] = \frac{1}{2\pi}\left[\frac{1}{R_O C_C\left(1 + \mu_{f2}\right)}\right] \cong \frac{1}{2\pi}\left[\frac{1}{500k\Omega\left(20\text{pF}\right)\left[1 + \frac{1}{0.02}\sqrt{\frac{2\left(0.001\right)}{5x10^{-4}}}\right]}\right] = 158\ Hz$$

Page 1126

$$f_z \cong \frac{1}{2\pi}\frac{g_{m5}}{C_C} = \frac{1}{2\pi}\frac{\sqrt{2\left(0.001\right)5x10^{-4}}}{20x10^{-12}} = 7.96\ MHz \qquad R = \frac{1}{g_{m5}} = \frac{1}{\sqrt{2\left(0.001\right)5x10^{-4}}} = 1.00\ k\Omega$$

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$$G_m = g_{m2} = 40\left(5x10^{-5}\right) = 2.00\ mS \qquad R_O = r_{\pi 5} \cong \frac{100V}{40\left(5.5x10^{-4}\ A\right)} = 4.54\ k\Omega$$

$$f_T = \frac{1}{2\pi}\left(\frac{G_m}{C_C}\right) = \frac{1}{2\pi}\left(\frac{2.00mS}{30\text{pF}}\right) = 10.6\ MHz \qquad f_Z = \frac{1}{2\pi}\left(\frac{g_{m5}}{C_C}\right) = \frac{1}{2\pi}\left[\frac{40\left(5x10^{-4}\right)}{3x10^{-11}}\right] = 106\ MHz$$

$$f_B = \frac{1}{2\pi}\left[\frac{1}{r_{\pi 5} C_C\left(1 + \mu_{f2}\right)}\right] \cong \frac{1}{2\pi}\left[\frac{1}{4.54k\Omega\left(30\text{pF}\right)\left[1 + 40\left(50\right)\right]}\right] = 584\ Hz$$

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$$\left(ii\right)\ SR = \frac{100\mu A}{20\,pF} = 5.00x10^6\frac{V}{s} = 5.00\frac{V}{\mu s}$$

Page 1129

$$SR = \frac{100\mu A}{20\,pF} = 5.00x10^6\frac{V}{s} = 5.00\frac{V}{\mu s}$$

Page 1132

$$G_m = g_{m2} = 40\left(2.5x10^{-4}\right) = 10.0\ mS \qquad f_T = \frac{1}{2\pi}\left(\frac{G_m/2}{C_C + C_{\mu 3}}\right) = \frac{1}{4\pi}\left(\frac{10.0mS}{50.8\text{pF}}\right) = 15.7\ MHz$$

$$\phi_{\text{M}} = 90 - \tan^{-1}\left(\frac{15.7\,MHz}{142\,MHz}\right) + \tan^{-1}\left(\frac{15.7\,MHz}{173\,MHz}\right) + \tan^{-1}\left(\frac{15.7\,MHz}{192\,MHz}\right) + \tan^{-1}\left(\frac{15.7\,MHz}{206\,MHz}\right) = 69.5^o$$

Page 1137

$$(i)\ \ SR \cong \frac{I_1}{C_C + C_{GD5}} = \frac{1mA}{65pF} = 15.4x10^6\frac{V}{s} = 15.4\frac{V}{\mu s}$$

$$(ii)\ \ 30^o = \tan^{-1}\left(\frac{f_T}{49.2MHz}\right) + \tan^{-1}\left(\frac{f_T}{82.1MHz}\right) + \tan^{-1}\left(\frac{f_T}{100MHz}\right) \rightarrow f_T = 16.6\ MHz$$

$$C_C = 65pF\left(\frac{8.5MHz}{16.6MHz}\right) - 2pF = 31.3\ pF$$

Page 1144

$$f_o = \frac{1}{2\pi(10k\Omega)(1nF)} = 15.9kHz \qquad |v_o| = \frac{3(0.6V)}{\left(2 - \frac{10k\Omega}{10k\Omega}\right)\left(1 + \frac{24k\Omega}{12k\Omega}\right) - \frac{24k\Omega}{10k\Omega}} = 3.00\ V$$

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$$f_P = \frac{1}{2\pi\sqrt{31.8mH\left[\frac{31.8fF(7pF)}{7.0318pF}\right]}} = 5.016\ MHz \qquad f_P = \frac{1}{2\pi\sqrt{31.8mH\left[\frac{31.8fF(25pF)}{25.0318pF}\right]}} = 5.008\ MHz$$
