Microelectronic Circuit Design
Fourth Edition - Part III
Solutions to Exercises
Updated - 09/25/10

CHAPTER 10

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$(a)\ A_P = |A_v||A_i| = 4x10^4(2.75x10^8) = 1.10x10^{13}$

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

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

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

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

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

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

$R_{out} = g_{22} = \left[\frac{1}{50k\Omega} + \frac{1}{20k\Omega} + \frac{75}{20k\Omega}\right]^{-1} = 262\ \Omega \ |\ g_{12} = -\frac{g_{22}}{(20k\Omega)} = -\frac{262\Omega}{(20k\Omega)} = -0.0131$

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

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(a) The constant slope region spanning a maximum input range is between $-0.5\text{ V} \le v_{ID} \le 1.5\ V$,

and the bias voltage V_{ID} should be centered in this range: $V_{ID} = \dfrac{1.5 + (-0.5)}{2} V = +0.5\ V$.

$v_{ID} = V_{ID} + v_{id}$ | $-0.5\text{V} \le 0.5V + v_{id} \rightarrow v_{id} \ge -1\ V$ and $0.5V + v_{id} \le 1.5 \rightarrow v_{id} \le +1\ V$

$\therefore -1\ V \le v_{id} \le +1\ V$ or $|v_{id}| \le 1\ V$ and $|v_o| \le 10\ V$

(b) For $V_{ID} = -1\ V$, the slope of the voltage transfer characteristics is zero, so $A = 0$.

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$v_O = 10(v_{ID} - 0.5V) = 10(-0.5 + 0.25 + 0.75\sin 1000\pi t) = (-2.5 + 7.5\sin 1000\pi t)\ V$ | $V_O = -2.5\ V$

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$$v_{id} = \frac{10V}{100} = 0.100V = 100\ mV \quad | \quad v_{id} = \frac{10V}{10^4} = 0.001\ V = 1.00\ mV$$

$$v_{id} = \frac{10V}{10^6} = 1.00x10^{-5}V = 10.0\ \mu V$$

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$$A_v = -\frac{360k\Omega}{68k\Omega} = -5.29 \quad | \quad v_o = -5.29(0.5V) = -2.65\ V$$

$$i_i = \frac{0.5V}{68k\Omega} = 7.35\ \mu A \quad | \quad i_o = -i_2 = -i_i = -7.35\ \mu A$$

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$$I_I = \frac{2V}{4.7k\Omega} = 426\ \mu A \quad | \quad I_2 = I_I = 426\ \mu A \quad | \quad I_O = -I_2 = -426\ \mu A$$

$$A_v = -\frac{24k\Omega}{4.7k\Omega} = -5.11 \quad | \quad V_O = -5.11(2V) = -10.2\ V$$

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$$A_{tr} = -R_2 = -\frac{5V}{25\mu A} = -0.2\ M\Omega \quad | \quad R_2 = 200\ k\Omega$$

$$v_o = -R_2 i_i = -2x10^5\left(5x10^{-5}\sin 2000\pi t\right) = -10\sin 2000\pi t\ \ V$$

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

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

$$v_o = 40.0(0.25V) = 10.0\ V \quad | \quad i_o = \frac{10.0V}{39k\Omega + 1k\Omega} = 0.250\ mA$$

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$$A_v = 10^{\frac{54}{20}} = 501 \qquad 1 + \frac{R_2}{R_1} = 501 \qquad \frac{R_2}{R_1} = 500 \qquad i_o = \frac{v_o}{R_2 + R_1} \qquad \frac{10}{R_2 + R_1} \le 0.1\ mA$$

$R_1 + R_2 \ge 100k\Omega \quad 501R_1 \ge 100k\Omega \rightarrow R_1 \ge 200\ \Omega$ 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: $A_v = -\frac{30k\Omega}{1.5k\Omega} = -20.0 \quad | \quad R_{in} = R_1 = 1.5\ \text{k}\Omega$

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

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

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

– – –

Add resistor R_3 in parallel with the op amp input as in the schemeatic on page 560 with $R_3 = 2\ k\Omega$.

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

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

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

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Since $i_+ = 0,\ I_2 = \frac{3V}{10k\Omega + 100k\Omega} = 27.3\ \mu A$

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

$V_+ = V_2 \frac{R_4}{R_3 + R_4} = 5\frac{100k\Omega}{10k\Omega + 100k\Omega} = 4.545V$

$I_O = \frac{20.0 - 4.545}{100k\Omega} = +155\ \mu A$ | $I_2 = \frac{5V}{10k\Omega + 100k\Omega} = 45.5\ \mu A$

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

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

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

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

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

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

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

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$$A_v(j1) = 50\frac{-1+4}{-1+2+j2} = \frac{150}{1+j2} \quad | \quad \left|A_v(j1)\right| = \frac{150}{\sqrt{(1)^2+(2)^2}} = 67.08$$

$$\mathrm{A_{vdB}} = 20\log(67.08) = 36.5\ dB \quad | \quad \angle A_v(j1) = \angle(50) + \angle(3) - \tan^{-1}\left[\frac{2}{1}\right] = 0 + 0 - 63.4^o = -63.4^o$$

$$A_v(j5) = 50\frac{-25+4}{-25+2+j10} = \frac{1050}{23-j10} \quad | \quad \left|A_v(j5)\right| = \frac{1050}{\sqrt{(-23)^2+(10)^2}} = 41.87$$

$$A_{vdB} = 20\log(41.87) = 32.4\ dB \quad | \quad \angle A_v(j5) = \angle(1050) + -\tan^{-1}\left[\frac{10}{-23}\right] = 0 - \left(-23.5^o\right) = +23.5^o$$

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$$\mathrm{A_v}(j\omega) = \frac{20}{1 + j\dfrac{0.1\omega}{1-\omega^2}} \quad | \quad \left|A_v(j0.95)\right| = \frac{20}{\sqrt{1^2 + \dfrac{(0.1)^2(0.95^2)}{(1-0.95^2)^2}}} = 14.3$$

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

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

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

– – –

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

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

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$$A_v(s) = -\frac{2x10^7 s}{(s+100)(s+50000)} = \frac{-400}{\left(1+\frac{100}{s}\right)\left(1+\frac{s}{50000}\right)}$$

$$\angle A_v(j\omega) = -180 + 90^o - \tan^{-1}\left(\frac{\omega}{100}\right) - \tan^{-1}\left(\frac{\omega}{50000}\right) = -90^o - \tan^{-1}\left(\frac{100}{100}\right) - \tan^{-1}\left(\frac{100}{50000}\right)$$

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

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

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

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

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

$$R_2 = 20R_1 = 200\ k\Omega \quad | \quad C = \frac{1}{2\pi(3kHz)(200k\Omega)} = 265\ pF$$

Closest values: $R_1 = 10\ k\Omega$ | $R_2 = 200\ k\Omega$ | $C = 270\ pF$

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$$A_v = -\frac{R_2}{R_1} = -10^{\frac{20}{20}} = -10.0 \quad | \quad R_1 = R_{in} = 18\ k\Omega$$

$$R_2 = 10R_1 = 180\ k\Omega \quad | \quad C = \frac{1}{\omega_L R_1} = \frac{1}{2\pi(5kHz)(18k\Omega)} = 1.77\ nF = 1770\ pF$$

Closest values: $R_1 = 10\ k\Omega$ | $R_2 = 180\ k\Omega$ | $C = 1800\ pF$

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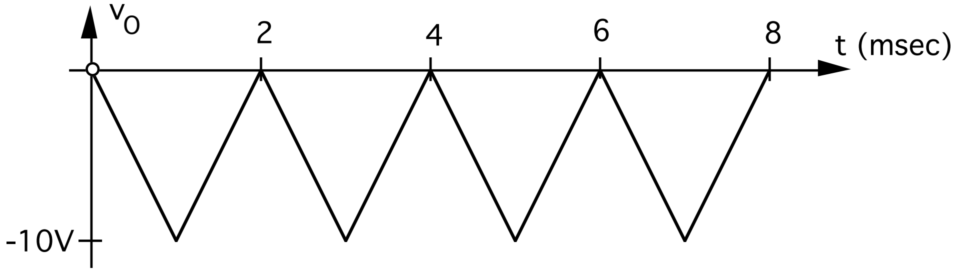
$$R_{in} = R_1 = 10\ k\Omega \quad | \quad \Delta V = -\frac{I}{C}\Delta T \quad | \quad \mathrm{C} = \frac{(10V/2)}{10k\Omega}\left(\frac{1}{10V}\right)(1ms) = 0.05\ \mu F$$



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

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CHAPTER 11

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$A_v^{Ideal} = \frac{1}{\beta} = 100 \quad | \quad T = A\beta = \frac{10^5}{100} = 1000 \quad | \quad A_v = A_v^{Ideal}\frac{T}{1+T} = 100\frac{1000}{1001} = 99.90$

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

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$A_v^{Ideal} = -\frac{R_2}{R_1} \quad | \quad \frac{1}{\beta} = 1 + \frac{R_2}{R_1} \rightarrow \frac{R_2}{R_1} = 99 \quad | \quad A_v^{Ideal} = -99 \quad | \quad T = A\beta = \frac{10^5}{100} = 1000$

$A_v = A_v^{Ideal}\frac{T}{1+T} = -99\frac{1000}{1001} = -98.90$

$v_o = A_v v_i = -98.9(0.1V) = -9.89\ V \quad | \quad v_{id} = \frac{v_o}{A} = \frac{-9.89V}{10^5} = -98.9\ \mu V$

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

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

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$A_v^{Ideal} = \frac{1}{\beta} = 1 + \frac{R_2}{R_1} = 1 + \frac{39k\Omega}{1k\Omega} = +40.0 \quad | \quad T = A\beta = \frac{10^4}{40} = 250 \quad | \quad A_v = A_v^{Ideal}\frac{T}{1+T} = 40\frac{250}{251} = 39.8$

$FGE = \frac{1}{1+T} = 0.00398 \text{ or } 0.398\ \% \quad | \quad FGE \cong \frac{1}{T} = 0.40\ \%$

– – –

$A_v^{Ideal} = -\frac{R_2}{R_1} = -\frac{39k\Omega}{1k\Omega} = -39.0 \quad | \quad \beta = \frac{1}{1+\frac{R_2}{R_1}} = \frac{1}{40} \quad | \quad T = A\beta = \frac{10^4}{40} = 250 \quad |$

$A_v = A_v^{Ideal}\frac{T}{1+T} = -39\frac{250}{251} = -38.8 \quad | \quad FGE = \frac{1}{1+T} = 0.00398 \text{ or } 0.398\ \% \quad | \quad FGE \cong \frac{1}{T} = 0.40\ \%$

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

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$$1+T=\frac{R_o}{R_{out}} \rightarrow T=\frac{50\Omega}{0.1\Omega}-1=499 \quad | \quad A=T\left(\frac{1}{\beta}\right)=499(40)=2.00x10^4$$

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$$A_v = A_v^{Ideal}\frac{T}{1+T} \quad | \quad A_v^{Ideal}=1+\frac{R_2}{R_1}=1+\frac{39k\Omega}{1k\Omega}=+40.0$$

$$T = A\beta = 10^4\frac{1k\Omega}{0.05k\Omega+39k\Omega+1k\Omega}=249.7 \quad | \quad A_v = A_v^{Ideal}\frac{T}{1+T}=40\frac{249.7}{250.7}=39.8$$

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$$A_v^{\max}=1+\frac{39k\Omega(1.05)}{1k\Omega(0.95)}=44.1 \quad | \quad GE=44.2-40.0=4.20 \quad | \quad FGE=\frac{4.20}{40}=10.5\ \%$$

$$A_v^{\min}=1+\frac{39k\Omega(0.95)}{1k\Omega(1.05)}=36.3 \quad | \quad GE=36.3-40.0=-3.70 \quad \text{F}GE=\frac{-3.70}{40}=-9.3\ \%$$

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$$1+T=\frac{R_o}{R_{out}} \rightarrow T=\frac{200\Omega}{0.1\Omega}-1=1999 \quad | \quad A=T\left(\frac{1}{\beta}\right)=1999(100)=2.00x10^5 \text{ or } 106 \text{ dB}$$

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

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$$R_{in} = R_{id}\left(1+T\right) \ | \ T = A\beta = 10^4\left(\frac{10k\Omega \| 1M\Omega}{10k\Omega \| 1M\Omega + 390k\Omega}\right) = \frac{10^4}{40.39} = 248 \ | \ R_{in} = 1M\Omega\left[1+248\right] = 249\ M\Omega$$

$$i_- = -\frac{v_i}{R_{in}} = -\frac{1V}{249M\Omega} = -4.02\ nA \ | \ i_1 = \frac{\beta v_o}{R_1} \ | \ v_o = A_v^{Ideal}\frac{T}{1+T}v_i = 40\frac{248}{249}v_i = 39.8v_i$$

$$i_1 = \frac{\beta v_o}{R_1} = \frac{39.8}{40.4}\left(\frac{1V}{10k\Omega}\right) = 98.5\ \mu A \ | \ \text{Yes,}\ \ |i_1| >> |i_-|$$

If we assume $1M\Omega >> 10k\Omega$, $T = A\beta = 10^4\left(\frac{10k\Omega}{10k\Omega + 390k\Omega}\right) = \frac{10^4}{40} = 250 \ | \ R_{in} = 1M\Omega\left[1+250\right] = 251\ M\Omega$

$$i_- = -\frac{v_i}{R_{in}} = -\frac{1V}{251M\Omega} = -3.98\ nA \ | \ i_1 = \frac{\beta v_o}{R_1} \ | \ v_o = A_v^{Ideal}\frac{T}{1+T}v_i = 40\frac{250}{251}v_i = 39.8v_i$$

$$i_1 = \frac{\beta v_o}{R_1} = \frac{39.8}{40}\left(\frac{1V}{10k\Omega}\right) = 99.5\ \mu A \ | \ \text{Yes,}\ \ |i_1| >> |i_-|$$

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

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$$A_v^{Ideal} = 1 + \frac{R_2}{R_1} = 1 + \frac{91k\Omega}{10k\Omega} = 10.1$$

$$R_{in}^D = R_{id} + R_1 \| (R_2 + R_o) = 25k\Omega + 10k\Omega \| (91k\Omega + 1k\Omega) = 34.0\ k\Omega$$

$$R_{out}^D = R_o \| [R_2 + R_1 \| R_{id}] = 1k\Omega \| [91k\Omega + 10k\Omega \| 25k\Omega] = 990\ \Omega$$

$$T = A_o \frac{R_1 \| R_{id}}{R_o + R_2 + R_1 \| R_{id}} = 10^4 \frac{10k\Omega \| 25k\Omega}{1k\Omega + 91k\Omega + 10k\Omega \| 25k\Omega} = 720$$

$$A_v = A_v^{Ideal} \frac{T}{1+T} = 10.1 \frac{720}{1+720} = 10.1$$

$$R_{in} = R_{in}^D (1+T) = 34.0k\Omega(1+720) = 24.5\ M\Omega$$

$$R_{out} = \frac{R_{out}^D}{1+T} = \frac{990\Omega}{1+720} = 1.37\ \Omega$$

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$$A_v^{Ideal} = 1 + \frac{R_2}{R_1} = 1 + \frac{91k\Omega}{10k\Omega} = 10.1$$

$$R_{in}^D = R_I + R_{id} + R_1 \| (R_2 + R_o \| R_L) = 2k\Omega + 25k\Omega + 10k\Omega \| (91k\Omega + 1k\Omega \| 5k\Omega) = 36.0\ k\Omega$$

$$R_{out}^D = R_L \| R_o \| [R_2 + R_1 \| (R_{id} + R_I)] = 5k\Omega \| 1k\Omega \| [91k\Omega + 10k\Omega \| (25k\Omega + 2k\Omega)] = 826\ \Omega$$

$$v_{th} = \left(A_o \frac{R_L}{R_o + R_L} v_{id} \right) \frac{R_1}{R_L \| R_o + R_2 + R_1} = 10^4 \frac{5k\Omega}{1k\Omega + 5k\Omega} v_{id} \frac{10k\Omega}{1k\Omega \| 5k\Omega + 91k\Omega + 10k\Omega} = 818 v_{id}$$

$$R_{th} = R_1 \| (R_2 + R_L \| R_o) = 10k\Omega \| (91k\Omega + 1k\Omega \| 5k\Omega) = 9.02\ k\Omega$$

$$T = -\left(\frac{v_{th}}{v_{id}} \right) \frac{R_{id}}{R_{th} + R_{id} + R_I} = -818 \frac{25k\Omega}{9.02k\Omega + 25k\Omega + 2k\Omega} = -568$$

$$A_v = A_v^{Ideal} \frac{T}{1+T} = 10.1 \frac{568}{1+568} = 10.1$$

$$R_{in} = R_{in}^D (1+T) = 36.0k\Omega(1+568) = 20.5\ M\Omega$$

$$R_{out} = \frac{R_{out}^D}{1+T} = \frac{826\Omega}{1+568} = 1.45\ \Omega$$

– – –

Continued on next page.

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$$A_v^{Ideal} = 1 + \frac{R_2}{R_1} = 1 + \frac{91k\Omega}{10k\Omega} = 10.1$$

$$R_{in}^D = R_{id} = 25k\Omega \quad | \quad R_{out}^D = R_o = 1\text{ k}\Omega$$

$$T = A_o \frac{R_1}{R_1 + R_2} = 10^4 \frac{10k\Omega}{10k\Omega + 91k\Omega} = 990$$

$$A_v = A_v^{Ideal} \frac{T}{1+T} = 10.1 \frac{990}{1+990} = 10.1$$

$$R_{in} = R_{in}^D \left(1+T\right) = 25.0k\Omega\left(1+990\right) = 24.8\ M\Omega$$

$$R_{out} = \frac{R_{out}^D}{1+T} = \frac{1k\Omega}{1+990} = 1.01\ \Omega$$

– – –

$$A_v^{Ideal} = 1 + \frac{R_2}{R_1} = 1 + \frac{91k\Omega}{10k\Omega} = 10.1$$

$$R_{in}^D = R_I + R_{id} + R_1 \| \left(R_2 + R_o\right) = 5k\Omega + 25k\Omega + 10k\Omega \| \left(91k\Omega + 1k\Omega\right) = 39.0\ k\Omega$$

$$R_{out}^D = R_o \| \left[R_2 + R_1 \| \left(R_{id} + R_I\right)\right] = 1k\Omega \| \left[91k\Omega + 10k\Omega \| \left(25k\Omega + 5k\Omega\right)\right] = 990\ \Omega$$

$$v_{th} = A_o v_{id} \frac{R_1}{R_o + R_2 + R_1} = 10^4 v_{id} \frac{10k\Omega}{1k\Omega + 91k\Omega + 10k\Omega} = 980 v_{id}$$

$$R_{th} = R_1 \| \left(R_2 + R_o\right) = 10k\Omega \| \left(91k\Omega + 1k\Omega\right) = 9.02\ k\Omega$$

$$T = \frac{v_{th}}{v_{id}} \frac{R_{id}}{R_{th} + R_{id} + R_I} = 980 \frac{25k\Omega}{9.02k\Omega + 25k\Omega + 5k\Omega} = 628$$

$$A_v = A_v^{Ideal} \frac{T}{1+T} = 10.1 \frac{628}{1+628} = 10.1$$

$$R_{in} = R_{in}^D \left(1+T\right) = 39.0k\Omega\left(1+628\right) = 24.5\ M\Omega$$

$$R_{out} = \frac{R_{out}^D}{1+T} = \frac{990\Omega}{1+628} = 1.57\ \Omega$$

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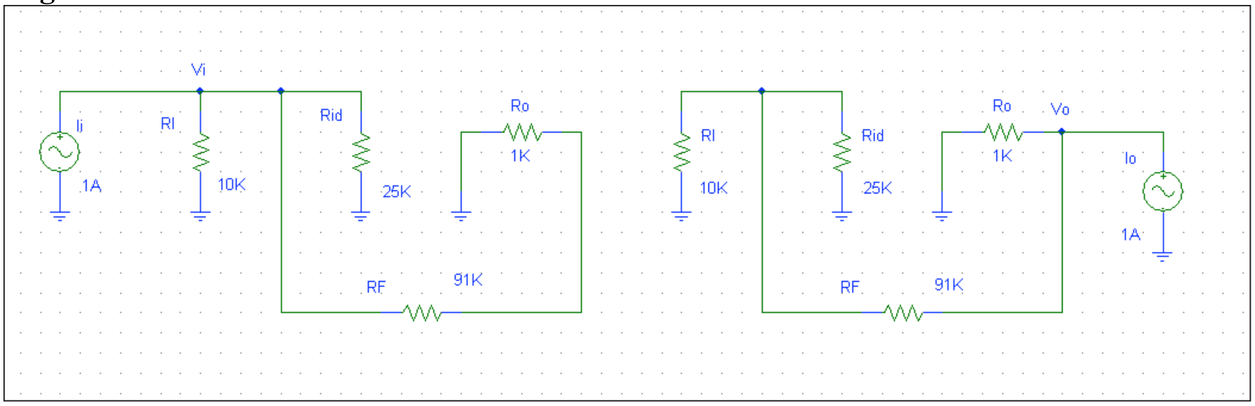

$$R_{in}^D = \frac{v_i}{i_i} = R_I \| R_{id} \| (R_F + R_o) \quad | \quad R_{out}^D = \frac{v_o}{i_o} = R_o \| (R_F + R_{id} \| R_I)$$

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$$A_{tr}^{Ideal} = -R_F = -91k\Omega$$

$$R_{in}^D = R_I \| (R_F + R_o) = 10k\Omega \| (91k\Omega + 1k\Omega) = 9.02\ k\Omega$$

$$R_{out}^D = R_o \| (R_F + R_I) = 1k\Omega \| (91k\Omega + 10k\Omega) = 990\ \Omega$$

$$T = A_o \frac{R_I}{R_o + R_F + R_I} = 10^4 \frac{10k\Omega}{1k\Omega + 91k\Omega + 10k\Omega} = 980$$

$$A_{tr} = A_{tr}^{Ideal} \frac{T}{1+T} = -91k\Omega \frac{980}{1+980} = -90.9\ k\Omega$$

$$R_{in} = \frac{R_{in}^D}{1+T} = \frac{9.02k\Omega}{1+980} = 9.19\ \Omega \qquad R_{out} = \frac{R_{out}^D}{1+T} = \frac{990\Omega}{1+980} = 1.01\ \Omega$$

– – –

$$A_{tr}^{Ideal} = -R_F = -91k\Omega$$

$$R_{in}^D = R_{id} \| (R_F + R_o) = 25k\Omega \| (91k\Omega + 1k\Omega) = 19.7\ k\Omega$$

$$R_{out}^D = R_o \| (R_F + R_{id}) = 1k\Omega \| (91k\Omega + 25k\Omega) = 991\ \Omega$$

$$T = A_o \frac{R_{id}}{R_o + R_F + R_{id}} = 10^4 \frac{25k\Omega}{1k\Omega + 91k\Omega + 25k\Omega} = 2137$$

$$A_{tr} = A_{tr}^{Ideal} \frac{T}{1+T} = -91k\Omega \frac{2137}{1+2137} = -91.0\ k\Omega$$

$$R_{in} = \frac{R_{in}^D}{1+T} = \frac{19.7k\Omega}{1+2137} = 9.21\ \Omega \qquad R_{out} = \frac{R_{out}^D}{1+T} = \frac{991\Omega}{1+2317} = 0.464\ \Omega$$

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$$A_{tc}^{Ideal} = -\frac{1}{R} = -\frac{1}{10k\Omega} = -10^{-4}\,S$$

$$R_{in}^{D} = R_{id} + R\|R_o = 25k\Omega + 10k\Omega\|1k\Omega = 25.9\ k\Omega$$

$$R_{out}^{D} = R_o + R\|R_{id} = 1k\Omega + 10k\Omega\|25k\Omega = 8.14\ k\Omega$$

$$T = -\left(\frac{v_{th}}{v_{id}}\right)\frac{R_{id}}{R_{th} + R_{id}} = 9090\frac{25k\Omega}{0.909k\Omega + 25k\Omega} = 8770$$

$$A_{tc} = -\frac{1}{R}\left(\frac{T}{1+T}\right) = -\frac{1}{10k\Omega}\left(\frac{8770}{1+8770}\right) = -0.100\ mS$$

$$R_{in} = R_{in}^{D}\left(1+T\right) = 25.9k\Omega\left(1+8770\right) = 227\ M\Omega$$

$$R_{out} = R_{out}^{D}\left(1+T\right) = 8.14k\Omega\left(1+8770\right) = 71.4\ M\Omega$$

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$$A_i^{Ideal} = 1 + \frac{R_2}{R_1} = 1 + \frac{27k\Omega}{3k\Omega} = +10$$

$$R_{in}^{D} = R_{id}\|\left(R_2 + R_1\|R_o\right) = 25k\Omega\|\left(27k\Omega + 3k\Omega\|1k\Omega\right) = 13.2\ k\Omega$$

$$R_{out}^{D} = R_o + R_1\|\left(R_2 + R_{id}\right) = 1k\Omega + 3k\Omega\|\left(27k\Omega + 25k\Omega\right) = 3.84\ k\Omega$$

$$T = A_o\frac{\left[R_1\|\left(R_2 + R_{id}\right)\right]}{R_1\|\left(R_2 + R_{id}\right) + R_o}\left(\frac{R_{id}}{R_2 + R_{id}}\right)$$

$$T = 10^4\frac{3k\Omega\|\left(27k\Omega + 25k\Omega\right)}{1k\Omega + 3k\Omega\|\left(27k\Omega + 25k\Omega\right)}\left(\frac{25k\Omega}{27k\Omega + 25k\Omega}\right) = 3555$$

$$A_i = +10\left(\frac{T}{1+T}\right) = +10\left(\frac{3555}{1+3555}\right) = +10.0$$

$$R_{in} = \frac{R_{in}^{D}}{\left(1+T\right)} = \frac{13.2k\Omega}{1+3555} = 3.71\ \Omega$$

$$R_{out} = R_{out}^{D}\left(1+T\right) = 3.84k\Omega\left(1+3555\right) = 13.7\ M\Omega$$

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$$R_{id}^{'} = R_I \| R_{id} = 10k\Omega \| 25k\Omega = 7.14\ k\Omega$$

$$A_i^{Ideal} = 1 + \frac{R_2}{R_1} = 1 + \frac{270k\Omega}{30k\Omega} = +10$$

$$R_{in}^{D} = R_{id}^{'} \| \left(R_2 + R_1 \| R_o\right) = 7.14k\Omega \| \left(270k\Omega + 30k\Omega \| 1k\Omega\right) = 6.96\ k\Omega$$

$$R_{out}^{D} = R_o + R_1 \| \left(R_2 + R_{id}^{'}\right) = 1k\Omega + 30k\Omega \| \left(270k\Omega + 7.14k\Omega\right) = 28.1\ k\Omega$$

$$T = A_o \frac{\left[R_1 \| \left(R_2 + R_{id}^{'}\right)\right]}{R_1 \| \left(R_2 + R_{id}^{'}\right) + R_o} \left(\frac{R_{id}^{'}}{R_2 + R_{id}^{'}}\right)$$

$$T = 10^4 \frac{30k\Omega \| \left(270k\Omega + 7.14k\Omega\right)}{30k\Omega \| \left(270k\Omega + 7.14k\Omega\right) + 1k\Omega} \left(\frac{7.14\ k\Omega}{270k\Omega + 7.14k\Omega}\right) = 248.5$$

$$A_i = +10\left(\frac{T}{1+T}\right) = +10\left(\frac{248.5}{1+248.5}\right) = +9.96$$

$$R_{in} = \frac{R_{in}^{D}}{\left(1+T\right)} = \frac{6.96k\Omega}{1+248.5} = 27.9\ \Omega$$

$$R_{out} = R_{out}^{D}\left(1+T\right) = 28.1k\Omega\left(1+248.5\right) = 7.01\ M\Omega$$

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

– – –

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

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

– – –

$$R = 39k\Omega \| 1k\Omega = 975\ \Omega$$

$R = 1\ k\Omega$ is the closest 5% value, or one could use 39 $k\Omega$ and 1 $k\Omega$ resistors in parallel.

– – –

$$v_O\left(t\right) = V_{OS} + \frac{V_{OS}}{RC}t + \frac{I_{B2}}{C}t \quad | \quad 1.5mV + \frac{1.5mV}{10k\Omega\left(100\,pF\right)}t + \frac{100nA}{100\,pF}t = 15V \rightarrow t = 6.00\ ms$$

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

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

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

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

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

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

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

$$v_o^{\max} = A\left(v_{id} + \frac{v_{ic}}{CMRR}\right) = 2500\left(0.002 + \frac{5.000}{10^4}\right) = 6.250\ V \quad | \quad 3.750\ V \leq \mathrm{v_O} \leq 6.250\ V$$

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

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

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

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

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

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

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

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$$A_o = 10^{\frac{100}{20}} = 10^5 \quad | \quad \omega_B = \frac{\omega_T}{A_o} = \frac{2\pi\left(5x10^6\right)}{10^5} = \frac{10^7\pi}{10^5} = 100\pi \quad | \quad f_B = \frac{100\pi}{2\pi} = 50\ Hz$$

$$A(s) = \frac{\omega_T}{s+\omega_B} = \frac{10^7\pi}{s+100\pi}$$

– – –

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

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$$A_o = 10^{\frac{90}{20}} = 31600 \quad | \quad f_B = \frac{f_T}{A_o} = \frac{5x10^6}{31600} = 158\ Hz \quad | \quad f_H \cong \beta f_T = 0.01\left(5\,MHz\right) = 50\ kHz$$

$$A(s) = \frac{\omega_T}{s+\omega_B} = \frac{2\pi\left(5x10^6\right)}{s+2\pi(158)} = \frac{10^7\pi}{s+316\pi} \quad | \quad A_v(s) = \frac{2\pi\left(5x10^6\right)}{s+2\pi\left(5x10^4\right)} = \frac{10^7\pi}{s+10^5\pi}$$

– – –

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

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$$A_o = 10^{\frac{90}{20}} = 31600 \quad | \quad f_B = \frac{f_T}{A_o} = \frac{5x10^6}{31600} = 158\ Hz \quad | \quad f_H \cong \beta f_T = \frac{5\,MHz}{1+10^{\frac{50}{20}}} = 15.8\ kHz$$

$$A(s) = \frac{2\pi\left(5x10^6\right)}{s+2\pi(158)} = \frac{10^7\pi}{s+316\pi} \quad | \quad A_v(s) = \frac{2\pi\left(5x10^6\right)}{s+2\pi\left(15.8x10^3\right)} = \frac{10^7\pi}{s+3.16x10^4\pi}$$

– – –

$$f_H \cong \beta f_T = 1\left(10\,MHz\right) = 10\ MHz \quad | \quad f_H \cong \beta f_T = \frac{1}{2}\left(10\,MHz\right) = 5\ MHz$$

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$$A_o = 10^{\frac{100}{20}} = 10^5 \quad | \quad f_B = \frac{f_T}{A_o} = \frac{10x10^6}{10^5} = 100\ Hz \quad | \quad f_H \cong \beta f_T = \frac{10\,MHz}{10^{\frac{60}{20}}} = \frac{10\,MHz}{1000} = 10\ kHz$$

$$A(s) = \frac{\omega_T}{s+\omega_B} = \frac{2\pi\left(10^7\right)}{s+2\pi(100)} = \frac{2\pi x10^7}{s+200\pi} \quad | \quad A_v(s) = \frac{2\pi\left(10^7\right)}{s+2\pi\left(10^4\right)} = \frac{2x10^7\pi}{s+2x10^4\pi}$$

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

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

$$A_o = 1.8x10^6 \quad | \quad f_T = 8\ MHz \quad | \quad \omega_B = \frac{\omega_T}{A_o} = \frac{2\pi(8\,MHz)}{1.8x10^6} = 8.89\pi \quad | \quad RC = \frac{1}{\omega_B} = \frac{}{8.89\pi}\ s$$

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$$0.01 = \exp\left(-\frac{\pi\zeta}{\sqrt{1-\zeta^2}}\right) \quad | \quad \text{Let } \kappa = \left(\frac{\ln 100}{\pi}\right)^2 \quad | \quad \zeta = \sqrt{\frac{\kappa}{1+\kappa}} = 0.826$$

$$\phi_M = \tan^{-1}\frac{2\zeta}{\left(\sqrt{4\zeta^4+1} - 2\zeta^2\right)^{0.5}} = 70.9^o$$

$$\cos(45^o) = \sqrt{4\zeta^4+1} - 2\zeta^2 \rightarrow \zeta = 0.420 \quad | \quad \text{Overshoot} = 100\%\ \exp\left(-\frac{\pi\zeta}{\sqrt{1-\zeta^2}}\right) = 23.4\ \%$$

− − −

Settling within the 10% error bars requires $\omega_n t \ge 13$. $\therefore \omega_n \ge \frac{13}{10^{-5}s} = 1.3\text{x}10^6 rad/s$

$$\omega_n = \sqrt{\omega_B\omega_2(1+A_o\beta)} \cong \sqrt{\omega_B\omega_2 A_o\beta} = \sqrt{\beta\omega_T\omega_2} \quad | \quad f_2 = \frac{f_n^2}{\beta f_T} \ge \frac{\left(1.3\text{x}10^6/2\pi\right)^2}{0.1(10^6)} = 428\ kHz$$

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$$\angle T(j\omega_1) = -180^o \rightarrow 3\tan^{-1}\frac{\omega_1}{1} = 180 \rightarrow \omega_1 = \sqrt{3}$$

$$\left|T(j\omega_{180})\right| = \frac{5}{\left(\sqrt{\omega_1^2+1}\right)^3} = \frac{5}{\left(\sqrt{3+1}\right)^3} = \frac{5}{8} \quad | \quad \text{GM} = \frac{8}{5} = 1.60 \text{ or } 4.08\ dB$$

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From the upper graph, the final value of the first step is 5 mV, and the peak of the response is approximately $4mV + 2mV\left(\frac{9.5mm}{11mm}\right) = 5.7\ mV$. Overshoot $= 100\% \frac{5.7mV - 5mV}{5mV} = 14\ \%$

$$0.14 = \exp\left(-\frac{\pi\zeta}{\sqrt{1-\zeta^2}}\right) \quad | \quad \text{Let } \kappa = \left(\frac{-\ln 0.14}{\pi}\right)^2 = 0.3917 \quad | \quad \zeta = \sqrt{\frac{\kappa}{1+\kappa}} = 0.5305$$

$$\phi_M = \tan^{-1}\frac{2\zeta}{\left(\sqrt{4\zeta^4+1} - 2\zeta^2\right)^{0.5}} = 54.2^o$$

– – –

From the lower graph, the final value of the first step is 5 mV, and the peak of the response is approximately $5mV + 5mV\left(\frac{10mm}{12mm}\right) = 9.2\ mV$. Overshoot $= 100\% \frac{9.2mV - 5mV}{5mV} = 84\ \%$

$$0.84 = \exp\left(-\frac{\pi\zeta}{\sqrt{1-\zeta^2}}\right) \quad | \quad \text{Let } \kappa = \left(\frac{-\ln 0.84}{\pi}\right)^2 = 0.3080 \quad | \quad \zeta = \sqrt{\frac{\kappa}{1+\kappa}} = 0.05541$$

$$\phi_M = \tan^{-1}\frac{2\zeta}{\left(\sqrt{4\zeta^4+1} - 2\zeta^2\right)^{0.5}} = 6.34^o$$

– – –

The μA741 curves will be distorted by slew rate limiting.

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CHAPTER 12

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$$A_{vA} = A_{vB} = A_{vC} = -\frac{R_2}{R_1} = -\frac{68k\Omega}{2.7k\Omega} = -25.2 \quad | \quad R_{inA} = R_{inB} = R_{inC} = R_1 = 2.7\ k\Omega$$

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

– – –

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

– – –

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

$$\frac{2.7k\Omega}{R_{out} + 2.7k\Omega} \ge 0.9950 \quad \rightarrow \quad R_{out} \ge 13.6\ \Omega$$

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

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

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

– – –

$$A_v(0) = -100(66.7)(50) = -3.33x10^5 \qquad |A_v(\omega_H)| = \frac{-3.34x10^5}{\sqrt{2}} = -2.36x10^5$$

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

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

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

– – –

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

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

$$v_{O3} = 0.001(6.909)^3 = 330\ mV \quad | \quad v_{O4} = 0.001V(6.909)^4 = 2.28\ V$$

$$v_{O5} = 0.001V(6.909)^5 = 15.7\ V > 15\ V. \quad \therefore v_{O5} = V_O^{\max} = 15\ V$$

$$v_{O6} = 15V(6.909) = 104\ V > 15\ V. \quad \therefore v_{O6} = V_O^{\max} = 15\ V$$

Page 714

$$V_A = V_1 + IR_2 \quad | \quad V_B = V_2 - IR_2 \quad | \quad I = \frac{V_A - V_B}{2R_1} = \frac{5.001V - 4.999V}{2k\Omega} = 1.00\ \mu A$$

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

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

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

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$$A_{LP}(s) = \frac{\omega_o^2}{s^2 + s\frac{\omega_o}{Q} + \omega_o^2} \quad | \quad A_{LP}(0) = \frac{\omega_o^2}{\omega_o^2} = 1 \text{ or } 0 \text{ dB}$$

For $Q = \frac{1}{\sqrt{2}}$: $A_{LP}(j\omega) = \frac{\omega_o^2}{-\omega^2 + j\omega\sqrt{2}\omega_o + \omega_o^2} \quad | \quad \left|A_{LP}(j\omega_H)\right|^2 = \frac{\omega_o^4}{\left(\omega_o^2 - \omega_H^2\right)^2 + 2\omega_o^2\omega_H^2} = \left(\frac{1}{\sqrt{2}}\right)^2$

$$2\omega_o^4 = \omega_o^4 + \omega_H^4 \rightarrow \omega_H = \omega_o$$

– – –

To increase the cutoff frequency from 5 kHz to 10 kHz while maintaining the resistances the same, we must decrease the capacitances by a factor of $\frac{10\text{kHz}}{5\text{kHz}} = 2$

$$\therefore \quad C_1 = \frac{0.02\mu F}{2} = 0.01\ \mu F \quad | \quad C_2 = \frac{0.01\mu F}{2} = 0.005\ \mu F$$

– – –

$$A_{LP}(j\omega) = \frac{\omega_o^2}{-\omega^2 + j\omega\frac{\omega_o}{Q} + \omega_o^2} \quad | \quad A_{LP}(j\omega_o) = \frac{\omega_o^2}{-\omega_o^2 + j\frac{\omega_o^2}{Q} + \omega_o^2} = -jQ \quad | \quad \left|A_{LP}(j\omega_o)\right| = Q$$

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

$$Q = \sqrt{\frac{2C}{C}}\frac{\sqrt{R^2}}{2R} = \frac{\sqrt{2}}{2} = \frac{1}{\sqrt{2}} \quad | \quad \text{Q is unchanged.}$$

– – –

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

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

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$$\left|A_{HP}(j\omega_o)\right| = K\left|\frac{-\omega_o^2}{-\omega_o^2 + j(3-K)\omega_o^2 + \omega_o^2}\right| = \frac{K}{3-K} \quad | \quad A_{HP}(j\omega_o) = \frac{K}{3-K}\angle 90^o$$

– – –

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

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

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

$$Q = \frac{1}{3-K} \rightarrow KQ = 3Q - 1 \quad S_K^Q = 3Q - 1 = \frac{3}{\sqrt{2}} - 1 = 1.12$$

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

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The lower gain results in a larger gain error and center frequency shift.

– – –

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

– – –

$$R = \frac{1}{\omega_o C} = \frac{1}{2\pi(2000)(2000\,pF)} = 39.8\ k\Omega \quad | \quad R_2 = QR = 10(39.8k\Omega) = 398\ k\Omega$$

$$R_1 = \frac{R_2}{\left|A_{BP}\left(j\omega_o\right)\right|} = \frac{398k\Omega}{20} = 19.9\ k\Omega \quad | \quad R_3 \text{ can remain the same.} \quad |$$

The nearest 1% values are $R = 40.2\ k\Omega$, $R_2 = 402\ k\Omega$, $R_1 = 20.0\ k\Omega$, $R_3 = 49.9\ k\Omega$

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

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

– – –

Blindly using the equations at the top of page 580 yields

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

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

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

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

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

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

$$S_{R_2}^{Q} = \frac{R_2}{Q}\frac{dQ}{dR_2} \quad | \quad R_1 = R_2 \rightarrow Q = \frac{1}{2}\sqrt{\frac{C_1}{C_2}} \rightarrow S_{R_2}^{Q} = 0$$

– – –

$$S_R^{\omega_o} = \frac{R}{\omega_o}\frac{d\omega_o}{dR} = \frac{R}{\omega_o}\left(\frac{-1}{R^2C}\right) = -\frac{\omega_o}{\omega_o} = -1 \quad | \quad S_C^{\omega_o} = \frac{C}{\omega_o}\frac{d\omega_o}{dR} = \frac{C}{\omega_o}\left(\frac{-1}{RC^2}\right) = -\frac{\omega_o}{\omega_o} = -1$$

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

– – –

$$S_{R_1}^{\omega_o} = \frac{R_1}{\omega_o}\frac{d\omega_o}{dR_1} = \frac{R_1}{\omega_o}\left(-\frac{\omega_o}{2R_{th}}\right)\frac{dR_{th}}{dR_1} = -\frac{R_1}{2R_{th}}\left(\frac{R_{th}^2}{R_1^2}\right) = -\frac{1}{2}\frac{R_3}{R_1+R_3}$$

$$S_{R_2}^{\omega_o} = \frac{R_2}{\omega_o}\frac{d\omega_o}{dR_2} = \frac{R_2}{\omega_o}\left(-\frac{\omega_o}{2R_2}\right) = -\frac{1}{2}$$

$$S_{R_3}^{\omega_o} = \frac{R_3}{\omega_o}\frac{d\omega_o}{dR_1} = \frac{R_3}{\omega_o}\left(-\frac{\omega_o}{2R_{th}}\right)\frac{dR_{th}}{dR_3} = -\frac{R_3}{2R_{th}}\left(\frac{R_{th}^2}{R_3^2}\right) = -\frac{1}{2}\frac{R_1}{R_1+R_3}$$

$$S_C^{\omega_o} = \frac{C}{\omega_o}\frac{d\omega_o}{dC} = \frac{C}{\omega_o}\left(-\frac{\omega_o}{C}\right) = -1$$

$$S_{R_1}^{Q} = \frac{R_1}{Q}\frac{dQ}{dR_1} = \frac{R_1}{Q}\left(-\frac{Q}{2R_{th}}\right)\frac{dR_{th}}{dR_1} = -\frac{R_1}{2R_{th}}\left(\frac{R_{th}^2}{R_1^2}\right) = -\frac{1}{2}\frac{R_3}{R_1+R_3}$$

$$S_{R_2}^{Q} = \frac{R_2}{Q}\frac{dQ}{dR_2} = \frac{R_2}{Q}\left(\frac{Q}{2R_2}\right) = +\frac{1}{2}$$

$$S_{R_1}^{Q} = \frac{R_3}{Q}\frac{dQ}{dR_3} = \frac{R_3}{Q}\left(-\frac{Q}{2R_{th}}\right)\frac{dR_{th}}{dR_3} = -\frac{R_3}{2R_{th}}\left(\frac{R_{th}^2}{R_3^2}\right) = -\frac{1}{2}\frac{R_1}{R_1+R_3}$$

$$S_C^{Q} = \frac{C}{Q}\frac{dQ}{dC} = \frac{C}{Q}(0) = 0 \quad | \quad S_C^{BW} = \frac{C}{BW}\frac{dBW}{dC} = \frac{C}{BW}\left(-\frac{BW}{C}\right) = -1$$

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

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

$$Q = \sqrt{\frac{11.3k\Omega}{11.3k\Omega}}\frac{\sqrt{(0.004\mu F)(0.002\mu F)}}{0.004\mu F + 0.002\mu F} = \frac{\sqrt{2}}{3} = 0.471$$

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

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

$$Q = \sqrt{\frac{2.00k\Omega}{2.00k\Omega}}\frac{\sqrt{(0.0226\mu F)(0.0113\mu F)}}{0.0226\mu F + 0.0113\mu F} = \frac{\sqrt{2}}{3} = 0.471$$

– – –

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

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

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

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$$\Delta v_O = -\frac{C_1}{C_2}V_I = -\frac{2\,pF}{0.5\,pF}0.1V = -0.4\ V$$

$$v_O(T) = 0 + \Delta v_O = -0.4\ V \ \ | \ \ v_O(5T) = 0 + 5\Delta v_O = -2.0\ V \ \ | \ \ v_O(9T) = 0 + 9\Delta v_O = -3.6\ V$$

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$$f_o = \frac{1}{2\pi}f_C\sqrt{\frac{C_3C_4}{C_1C_2}} = \frac{200kHz}{2\pi}\sqrt{\frac{4\,pF(0.25\,pF)}{3\,pF(3\,pF)}} = 10.6\ kHz$$

$$Q = \sqrt{\frac{C_3}{C_4}}\frac{\sqrt{C_1C_2}}{C_1 + C_2} = \sqrt{\frac{4\,pF}{0.25\,pF}}\frac{\sqrt{3\,pF(3\,pF)}}{3\,pF + 3\,pF} = 2 \ \ | \ \ \text{BW} = \frac{f_o}{Q} = \frac{10.6\ kHz}{2} = 5.30\ kHz$$

$$A_{BP}(j\omega_o) = -\frac{R_2}{2R_1} = -\frac{C_3}{2C_4} = -\frac{4\,pF}{0.5\,pF} = -8.00$$

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$0.01100001_2 = \left(2^{-2} + 2^{-3} + 2^{-8}\right)_{10} = 0.37980625_{10}$ | $0.10001000_2 = \left(2^{-1} + 2^{-5}\right)_{10} = 0.53125_{10}$

– – –

$$V_O = \frac{5.12V}{2^{12}}\left(2^{11} + 2^9 + 2^7 + 2^5 + 2^3 + 2^1\right) = 3.41250\ V$$

$V_{LSB} = \frac{5.12V}{2^{12}} = 1.25\ mV$ | $V_{MSB} = \frac{5.12V}{2} = 2.56\ V$

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$V_{OS} = V_O(000) = 0.100\ V_{FS}$ | $V_{LSB} = \frac{0.8V_{FS} - 0.1V_{FS}}{7} = 0.1\ V_{FS}$

– – –

$2R = 1\ k\Omega$ | $4R = 2\ k\Omega$ | $8R = 4\ k\Omega$ | $16R = 8\ k\Omega$ | $32R = 16\ k\Omega$ | $64R = 32\ k\Omega$
$128R = 64\ k\Omega$ | $256R = 128\ k\Omega$ | $R = 500\ \Omega$

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$R_{Total} = R + 2R + 2R + (n-1)(2R + R) = (3n + 2)R$ | $R_{Total} = (3x8 + 2)(1k\Omega) = 26\ k\Omega$

– – –

$R = 1\ \text{k}\Omega$ | $2R = 2\ k\Omega$ | $4R = 4\ k\Omega$ | $8R = 8\ k\Omega$ | $16R = 16\ k\Omega$ | $32R = 32\ k\Omega$
$64R = 64\ k\Omega$ | $128R = 128\ k\Omega$ | $256R = 256\ k\Omega$ | $R_{Total} = 511\ k\Omega$
In general: $R_{Total} = R\left(2^0 + 2^1 + ... + 2^{n-1} + 2^n\right) = \left(2^{n+1} - 1\right)R$ | $R_{Total} = \left(2^{8+1} - 1\right)1k\Omega = 511\ k\Omega$

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The general case requires 2^n resistors, and the number of switches is
$\left(2^1 + 2^2 + ... + 2^n\right) = 2\left(2^0 + 2^2 + ... + 2^{n-1}\right) = 2\left(2^n - 1\right) = 2^{n+1} - 2$
$2^{10} = 1024$ resistors | $2^{10+1} - 2 = 2046$ switches.

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(a) In general: $C_{Total} = R\left(2^0 + 2^1 + ... + 2^n\right) = \left(2^{n+1} - 1\right)C$ | $C_{Total} = \left(2^{8+1} - 1\right)1pF = 511\ pF$
(b) In general: $R_{Total} = 2C + 2C + (n-1)(2C + C) = 2R + n(3R)$ | $R_{Total} = 2R + 8(3k\Omega) = 26\ k\Omega$

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$V_{LSB} = \frac{5V}{2^8} = 19.53\ mV$ | $1.2V\frac{2^8 LSB}{5V} = 61.44\ LSB$ | The closest code is $61_{10} = 00111101_2$

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$2^n \ge 10^6 \quad | \quad n \ge \dfrac{6\log 10}{\log 2} = 19.93 \rightarrow n \ge 20\ bits$

– – –

The minimum width is 0 corresponding to the missing code 110.

The maximum code width is 2.5 LSB corresponding to output code 101.

$DNL = 2.5 - 1 = 1.5\ LSB$

At code 110, the ADC transfer characteristic is 1 LSB off of the fitted line.

$\therefore INL = 1\ LSB$

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$$T_T^{max} = \frac{2^n}{f_C} = \frac{2^{12}}{2x10^6} = 2.048\ ms \quad | \quad N_{max} = \frac{1}{T_T^{max}} = \frac{1}{2.048ms} = 488\ \frac{\text{conversions}}{\text{second}}$$

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$$T_T = \frac{n}{f_C} = \frac{12}{2x10^6} = 6.00\ \mu s \quad | \quad N_{max} = \frac{1}{T_T} = \frac{1}{6\mu s} = 167{,}000\ \frac{\text{conversions}}{\text{second}}$$

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$$V_{FS} = \frac{1}{RC}\int_0^T V_R(t)dt = \frac{V_R T}{RC} \quad | \quad RC = \frac{V_R}{V_{FS}}T = \frac{V_R}{V_{FS}}\frac{2^n}{f_C} = \frac{2.00V}{5.12V}\left(\frac{2^8}{1MHz}\right) = 0.100\ ms$$

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$$T_T^{max} = \frac{2^{n+1}}{f_C} = \frac{2^{17}}{10^6 Hz} = 0.131\ s \quad | \quad N_{max} = \frac{1}{T_T^{max}} = \frac{1}{0.131s} = 7.63\ \frac{\text{conversions}}{\text{second}}$$

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In general, 2^n resistors and $\left(2^n - 1\right)$ comparators:

$2^{10} = 1024$ resistors and $\left(2^{10} - 1\right) = 1023$ comparators

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

– – –

SPICE Results: 15.90 kHz, 3.33 V

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For $v_I > 0$, the diode will conduct and pull the output up to $v_O = v_I = 1.0\ V$.

$v_1 = v_O + v_D = 1.0 + 0.6 = 1.6\ V$

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: $v_O = -10\ V$.

(Note that the output voltage will actually be determined by the reverse saturation current of the diode: $v_O = -I_S R \cong 0$.)

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

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

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

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

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

The maximum output voltage is $v_O^{\max} = 15V - 0.6V = 14.4\ V$.

$$A_v = -\frac{68k\Omega}{22k\Omega} = -3.09 \quad | \quad v_I = \frac{14.4V}{-3.09} = -4.66\ V$$

When $v_O = 15\ V$, $v_{D2} = -15\ V$, so $V_Z = 15\ V$.

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

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

$$V_{I+} = +\frac{R_1}{R_1 + R_2} V_{CC} = \frac{1k\Omega}{1k\Omega + 9.1k\Omega} 10V = +0.990\ V$$

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

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$$T = 2RC \ln\frac{1+\beta}{1-\beta} \quad | \quad \beta = \frac{R_1}{R_1 + R_2} = \frac{6.8k\Omega}{6.8k\Omega + 6.8k\Omega} = \frac{1}{2}$$

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

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$$\beta = \frac{R_1}{R_1 + R_2} = \frac{22k\Omega}{22k\Omega + 18k\Omega} = 0.550 \quad | \quad T = (11k\Omega)(0.002\mu F)\ln\left[\frac{1+\frac{0.7}{5}}{1-0.550}\right] = 20.4\ \mu s$$

$$T_r = (11k\Omega)(0.002\mu F)\ln\left[\frac{1+0.55\left(\frac{5V}{5V}\right)}{1-\frac{0.7}{5}}\right] = 13.0\ \mu s \quad | \quad T_{min} = 20.4\mu s + 13.0\mu s = 33.4\ \mu s$$

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CHAPTER 13

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

$(c)\ R_{in} = \dfrac{v_{be}}{i_b} = \dfrac{8mV}{5\mu A} = 1.6\ k\Omega$ $\quad (d)$ Yes. 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 $v_{BE} = 0.708\ V$. $(e)\ A_{vdB} = 20\log|-206| = 46.3\ dB$

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(a) No : $v_{DS}^{min} \cong 2.7V$ with $v_{GS} - V_{TN} = 4 - 1 = 3V$, so the transistor has entered the triode region.

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

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

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

$(c)\ A_{vdB} = 20\log|-4.13| = 12.3\ dB$

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

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

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

$$V_B = V_{EQ} - I_B R_{EQ} = 3.00 - \frac{1.45mA}{100}(7.5k\Omega) = 2.89\ V$$

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$v_C(t) = V_C + v_C = (5.8 - 1.1\sin 2000\pi t)\ V$ | $v_E(t) = V_E + 0 = 1.45mA\left(\frac{101}{100}\right)(1.5k\Omega) = 2.20\ V$

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

$V_B = V_{EQ} - I_B R_{EQ} = 3.00 - \frac{1.45mA}{100}(7.5k\Omega) = 2.89\ V$ | $v_B(t) = (2.89 + 0.005\sin\sin 2000\pi)\ V$

– – –

$X_C = \frac{1}{\omega C} = \frac{1}{2000\pi(500\mu F)} = 0.318\ \Omega$ | $X_C << R_{in}$

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

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

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

– – –

$r_d = \frac{0.025V}{1.5mA} = 16.7\ \Omega$ | $\frac{kT}{q} = \left(8.62x10^{-5}\frac{V}{K}\right)(373K) = 0.0322\ V$ | $r_d = \frac{0.0322V}{1.5mA} = 21.4\ \Omega$

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

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

– – –

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

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

- - -

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

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

$\beta_o = \frac{\Delta i_C}{\Delta i_B} = \frac{500\mu A}{5\mu A} = 100$ | $r_\pi = \frac{\beta_o}{g_m} = \frac{100}{62.5mS} = 1.60\ k\Omega$ | $r_\pi = \frac{\Delta v_{BE}}{\Delta i_B} = \frac{8mV}{0.5mA/100} = 1.60\ k\Omega$

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$A_{vt} = -g_m R_L = -9.80mS(18k\Omega) = -176$ | Ten percent of the input signal is being lost by voltage division between source resistance R_I and the amplifier input resistance.

– – –

Assume the Q - point remains constant.

$$(a)\ R_{iB} = r_\pi = \frac{125}{9.80mS} = 12.8\ k\Omega \quad | \quad A_v = -9.80mS(18k\Omega)\left(\frac{104k\Omega\|12.8k\Omega}{1k\Omega + 104k\Omega\|12.8k\Omega}\right) = -162$$

$$(b)\ R_L^{max} = 1.1(18k\Omega) = 19.8\ k\Omega \quad | \quad R_L^{min} = 0.9(18k\Omega) = 16.2\ k\Omega$$

$$A_v^{min} = -9.80mS(16.2k\Omega)\left(\frac{104k\Omega\|10.2k\Omega}{1k\Omega + 104k\Omega\|10.2k\Omega}\right) = -143$$

$$A_v^{max} = A_v^{min}\left(\frac{19.8k\Omega}{16.2k\Omega}\right) = -143\left(\frac{19.8k\Omega}{16.2k\Omega}\right) = -175$$

$$\text{Checking}: A_v^{min} = A_v^{nom}\left(\frac{16.2k\Omega}{18k\Omega}\right) = -159(0.9) = -143 \quad | \quad A_v^{max} = A_v^{nom}\left(\frac{19.8k\Omega}{18k\Omega}\right) = -159(1.1) = -175$$

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

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

$$A_v = -11.0mS(18k\Omega)\left(\frac{104k\Omega\|9.09k\Omega}{1k\Omega + 104k\Omega\|9.09k\Omega}\right) = -177$$

– – –

$$A_v^{CE} \cong -10V_{CC} = -10(20) = -200 \quad | \quad g_m = 40I_C = 40(100\mu A) = 4.00\ mS \quad | \quad R_{iB} = r_\pi = \frac{\beta_o}{g_m} = \frac{100}{4mS} = 25\ k\Omega$$

$$r_o = \frac{V_A + V_{CE}}{I_C} = \frac{50V + 10V}{100\mu A} = 600\ k\Omega \quad | \quad \mu_f = g_m r_o = 4mS(600k\Omega) = 2400$$

$$A_v = -g_m(R_C\|r_o)\frac{R_B\|R_{iB}}{R_I + R_B\|R_{iB}} = -4.00mS(100k\Omega\|600k\Omega)\left(\frac{150k\Omega\|25k\Omega}{5k\Omega + 150k\Omega\|25k\Omega}\right) = -278$$

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$$V_{EQ} = \frac{160k\Omega}{160k\Omega + 300k\Omega}12V = 4.17\ V \quad | \quad R_{EQ} = 160k\Omega \| 300k\Omega = 104\ k\Omega$$

$$I_C = \beta_F I_B = \beta_F \frac{V_{EQ} - V_{BE}}{R_{EQ} + (\beta_F + 1)R_E} = 100\frac{4.17V - 0.7V}{104k\Omega + (101)(13k\Omega)} = 0.245\ mA$$

$$V_{CE} = 12 - 22000I_C - 13000I_E = 12 - 22000(0.245mA) - 13000\left(\frac{101}{100}\right)(0.245mA) = 3.39\ V$$

– – –

$$I_C = I_S \exp\left(\frac{V_{BE}}{V_T}\right)\left(1 + \frac{V_{CB}}{V_A}\right) \quad | \quad V_T = \frac{kT}{q} = \frac{1.38x10^{-23}(300)}{1.6x10^{-19}} = .025875\ V$$

$$I_S = \frac{0.245mA}{\exp\left(\frac{0.7}{0.025875}\right)\left(1 + \frac{3.39 - 0.7}{75}\right)} = 422\ fA$$

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(a) $g_m = \sqrt{2K_n I_D(1 + \lambda V_{DS})} = \sqrt{2(1mA/V^2)(0.25mA)[1 + 0.02(5)]} = 0.742\ mS$

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

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

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

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

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

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

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

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$$g_m = 2\frac{\sqrt{I_{DSS}I_D\left(1+\lambda V_{DS}\right)}}{\left|V_P\right|} = 2\frac{\sqrt{5mA\left(2mA\right)\left[1+0.02\left(5\right)\right]}}{\left|-2\right|} = 3.32\ mS$$

$$r_o = \frac{\frac{1}{\lambda}+V_{DS}}{I_D} = \frac{50V+5V}{2mA} = 27.5\ k\Omega \quad | \quad \mu_f = g_m r_o = 3.32mS\left(27.5k\Omega\right) = 91.3$$

$$V_{GS} = V_P\left(1-\sqrt{\frac{I_D}{I_{DSS}}}\right) = -2V\left(1-\sqrt{\frac{2mA}{5mA}}\right) = -0.735\ V$$

$$\left|v_{gs}\right| \le 0.2\left(V_{GS}-V_P\right) = 0.2\left(-0.735+2\right) = 0.253\ V$$

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$$V_{EQ} = \frac{1.5\,M\Omega}{1.5\,M\Omega+2.2\,M\Omega}12V = 4.87\ V \quad | \quad R_{EQ} = 1.5\,M\Omega\|2.2\,M\Omega = 892\ k\Omega$$

Neglect λ in hand calculations of the Q-point.

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

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

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

– – –

The small-signal model appears in Fig. 13.27(c).

– – –

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

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$$r_\pi = \frac{\beta_o V_T}{I_C} = \frac{100\left(0.025V\right)}{0.725mA} = 3.45\ k\Omega \quad | \quad R_{in}^{CE} = R_B\|r_\pi = 104k\Omega\|3.45k\Omega = 3.34\ k\Omega$$

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$$R_{in}^{CS} = 680k\Omega\|1.0\,M\Omega = 405\ k\Omega \quad | \quad V_{EQnew} = \frac{680k\Omega}{680k\Omega+1M\Omega}V_{DD} = 0.405V_{DD}$$

$$V_{EQold} = \frac{1.5\,M\Omega}{1.5\,Mk\Omega+2.2\,M\Omega}V_{DD} = 0.405V_{DD} \quad | \quad \text{No change. The gate voltages are the same.}$$

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From Ex. 13.6, $\mu_f = 230$ and $A_v = -20.3$. $|A_v| << \mu_f$

– – –

$$V_{GS} = V_P\left(1-\sqrt{\frac{I_D}{I_{DSS}}}\right) = -1V\left(1-\sqrt{\frac{0.25mA}{1mA}}\right) = -0.500\ V$$

$$|v_{gs}| \le 0.2(V_{GS}-V_P) = 0.2(-0.5+1) = 0.100\ V \quad | \quad |v_o| \le 20.3(0.1) = 2.03\ V$$

– – –

SPICE Results:

$\lambda = 0$: Q-point $= (250\ \mu A,\ 4.75\ V)$ | $\lambda = 0.02\ V^{-1}$: Q-point $= (257\ \mu A,\ 4.54\ V)$

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$$I_C = 245\ \mu A \quad | \quad V_{CE} = 3.39\ V \quad | \quad I_E = 245\mu A\left(\frac{66}{65}\right) = 249\ \mu A$$

$$P_D = I_C V_{CE} + I_B V_{BE} = 245\mu A(3.39V) + \frac{245\mu A}{65}(0.7V) = 0.833\ mW$$

$$P_S = V_{CC}(I_C + I_2) \quad | \quad I_2 = \frac{V_{CC}-V_B}{R_2} = \frac{V_{CC}-(V_{BE}+I_E R_E)}{R_2} = \frac{12-0.7-0.249mA(13k\Omega)}{300k\Omega} = 26.9\ \mu A$$

$$P_S = 12V(245\mu A + 26.9\mu A) = 3.26\ mW$$

– – –

$$P_D = I_D V_{DS} = 241\mu A(3.81V) = 0.918\ mW \quad | \quad P_S = V_{DD}(I_D + I_2)$$

$$I_2 = \frac{V_{DD}}{R_1+R_2} = \frac{12V}{1.5M\Omega + 2.2M\Omega} = 3.24\ \mu A \quad | \quad P_S = 12V(241\mu A + 3.24\mu A) = 2.93\ mW$$

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(a) $V_M \le \min\left[I_C R_C, (V_{CE}-V_{BE})\right] = \min\left[245\mu A(22k\Omega), (3.39-0.7)V\right] = 2.69\ V$

V_M is limited by the value of V_{CE}.

(b) $V_M \le \min\left[I_D R_D, (V_{DS}-V_{DSSAT})\right] = \min\left[241\mu A(22k\Omega), (3.81-0.982)V\right] = 2.83\ V$

Limited by the value of V_{DS}.

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CHAPTER 14

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$$V_{EQ} = \frac{160k\Omega}{160k\Omega + 300k\Omega}12V = 4.17\ V \quad | \quad R_{EQ} = 160k\Omega \| 300k\Omega = 104\ k\Omega$$

$$I_C = \beta_F I_B = \beta_F \frac{V_{EQ} - V_{BE}}{R_{EQ} + (\beta_F + 1)R_E} = 100\frac{4.17V - 0.7V}{104k\Omega + (101)(13k\Omega)} = 0.245\ mA$$

$$V_{CE} = 12 - 22000I_C - 13000I_E = 12 - 22000(0.245mA) - 13000\left(\frac{101}{100}\right)(0.245mA) = 3.39\ V$$

$$g_m = 40I_C = 40(0.245mA) = 9.80\ mS \quad | \quad r_\pi = \frac{\beta_o}{g_m} = \frac{100}{9.80mS} = 10.2\ k\Omega$$

$$r_o = \frac{V_A + V_{CE}}{I_C} = \frac{53.4V}{0.245mA} = 218\ k\Omega \quad | \quad \mu_f = g_m r_o = 2140$$

– – –

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

Neglect λ in hand calculations of the Q-point.

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

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

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

$$g_m = \sqrt{2K_n I_D} = \sqrt{2(5x10^{-4})(2.41x10^{-4})} = 0.491\ mS \quad | \quad r_o = \frac{\lambda^{-1} + V_{CE}}{I_C} = \frac{53.8V}{0.241mA} = 223\ k\Omega$$

$$\mu_f = g_m r_o = 110$$

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

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

– – –

$$R_B = 160k\Omega \| 300k\Omega = 104\ k\Omega \quad | \quad R_L = 13k\Omega \| 100k\Omega = 11.5\ k\Omega$$

$$R_G = 1.5M\Omega \| 2.2M\Omega = 892\ k\Omega \quad | \quad R_L = 12k\Omega \| 100k\Omega = 10.7\ k\Omega$$

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$R_I = 2\ k\Omega \quad | \quad R_6 = 13\ k\Omega \quad | \quad R_L = 22k\Omega \| 100k\Omega = 18.0\ k\Omega$

$R_I = 2\ k\Omega \quad | \quad R_6 = 12\ k\Omega \quad | \quad R_L = 22k\Omega \| 100k\Omega = 18.0\ k\Omega$

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$(a)\ I_C \cong \dfrac{V_{EQ} - V_{BE}}{R_E + R_4}$ or $I_C \propto \dfrac{1}{R_E + R_4}$ | $I_C = 0.245mA\dfrac{13k\Omega}{R_E + R_4}$

For large $g_m R_E$, $A_{vt}^{CE} = -\dfrac{g_m R_L}{1 + g_m R_E} \cong -\dfrac{R_L}{R_E} = -\dfrac{R_C \| R_3}{R_E}$

For $A_{vt}^{CE\max}$ make R_C and R_3 large and R_E small. $R_L = 1.1(22k\Omega)\|1.1(100k\Omega) = 19.8\ k\Omega$

$R_E = 0.9(3k\Omega) = 2.7\ k\Omega$ | $I_C = 0.245mA\dfrac{13k\Omega}{12.7k\Omega} = 0.251\ mA$ | $g_m = 40(0.251\ mA) = 10.0\ mS$

$r_\pi = \dfrac{\beta_o}{g_m} = \dfrac{100}{10.0mS} = 10.0\ k\Omega$ | $R_{iB} = 10.0k\Omega + 101(2.7k\Omega) = 283\ k\Omega$

$$A_v^{CE\max} = -\frac{10.0mS(19.8k\Omega)}{1 + 10.0mS(2.7k\Omega)}\left(\frac{104k\Omega\|283k\Omega}{1k\Omega + 104k\Omega\|283k\Omega}\right) = -6.98$$

For $A_{vt}^{CE\min}$ make R_C and R_3 small and R_E large. $R_L = 0.9(22k\Omega)\|0.9(100k\Omega) = 16.2\ k\Omega$

$R_E = 1.1(3k\Omega) = 3.3\ k\Omega$ | $I_C = 0.245mA\dfrac{13k\Omega}{13.3k\Omega} = 0.239\ mA$ | $g_m = 40(0.239\ mA) = 9.56\ mS$

$r_\pi = \dfrac{\beta_o}{g_m} = \dfrac{100}{9.56mS} = 10.5\ k\Omega$ | $R_{iB} = 10.5k\Omega + 101(3.3k\Omega) = 344\ k\Omega$

$$A_v^{CE\min} = -\frac{9.56mS(16.2k\Omega)}{1 + 9.56mS(3.3k\Omega)}\left(\frac{104k\Omega\|344k\Omega}{1k\Omega + 104k\Omega\|344k\Omega}\right) = -4.70$$

(b) Assume the collector current does not change.

$r_\pi = \dfrac{\beta_o}{g_m} = \dfrac{125}{9.8mS} = 12.8\ k\Omega$ | $R_{iB} = 12.8k\Omega + 126(3.0k\Omega) = 391\ k\Omega$

$$A_v^{CE} = -\frac{9.80mS(18k\Omega)}{1 + 9.80mS(3k\Omega)}\left(\frac{104k\Omega\|391k\Omega}{1k\Omega + 104k\Omega\|391k\Omega}\right) = -5.73$$ The gain is essentially unchanged.

$(c)\ V_{CE} = V_{CC} - I_C R_C - I_E(R_E + R_4) = 12V - 0.275mA\left(22k\Omega + \dfrac{101}{100}13k\Omega\right) = 2.34\ V$

$2.34\ V > 0.7\ V$ Therefore the transistor is still in the active region.

$g_m = 40(0.275mA) = 11.0\ mS$ | $r_\pi = \dfrac{\beta_o}{g_m} = \dfrac{100}{11mS} = 9.09\ k\Omega$ | $R_{iB} = 9.09k\Omega + 101(3.0k\Omega) = 312\ k\Omega$

$$A_v^{CE} = -\frac{11.0mS(18k\Omega)}{1 + 11.0mS(3k\Omega)}\left(\frac{104k\Omega\|312k\Omega}{1k\Omega + 104k\Omega\|312k\Omega}\right) = -5.75$$ The gain is essentially unchanged.

Continued on the next page

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$$R_{iC} = 320k\Omega\left[1+\frac{100(2k\Omega)}{(1k\Omega\|104k\Omega)+10.2k\Omega+2k\Omega}\right] = 5.17\ M\Omega \quad | \quad \mu_f R_E = 3140(2k\Omega) = 6.28\ M\Omega$$

$$R_{iC} < \mu_f R_E \quad | \quad R_{out} = 5.17\,M\Omega\|22k\Omega = 21.9\ k\Omega \quad | \quad R_{out} << \mu_f R_E$$

– – –

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

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$$R_{iB} = 10.2k\Omega + 101(1k\Omega) = 111\ k\Omega$$

$$A_v = -\frac{9.80mS(18k\Omega)}{1+9.80mS(1k\Omega)}\left(\frac{104k\Omega\|111k\Omega}{1k\Omega+104k\Omega\|111k\Omega}\right) = -16.0 \quad | \quad R_4 = 13k\Omega - 1k\Omega = 12\ k\Omega.$$

– – –

$$I_C = I_S \exp\left(\frac{V_{BE}}{V_T}\right)\left(1+\frac{V_{CB}}{V_A}\right) \quad | \quad V_T = \frac{kT}{q} = \frac{1.38x10^{-23}(300)}{1.60x10^{-19}} = .025875\ V$$

$$I_S = \frac{0.245mA}{\exp\left(\frac{0.7}{0.025875}\right)\left(1+\frac{3.39-0.7}{100}\right)} = 425\ fA$$

– – –

$$A_v^{CE} \cong -10V_{CC} = -10(20) = -200 \quad | \quad g_m = 40I_C = 40(100\mu A) = 4.00\ mS \quad | \quad R_{iB} = r_\pi = \frac{\beta_o}{g_m} = \frac{100}{4mS} = 25\ k\Omega$$

$$r_o = \frac{V_A + V_{CE}}{I_C} = \frac{50V+10V}{100\mu A} = 600\ k\Omega \quad | \quad \mu_f = g_m r_o = 4mS(600k\Omega) = 2400$$

$$A_v^{CE} = -g_m(R_C\|r_o)\frac{R_B\|R_{iB}}{R_I + R_B\|R_{iB}} = -4.00mS(100k\Omega\|600k\Omega)\left(\frac{150k\Omega\|25k\Omega}{5k\Omega+150k\Omega\|25k\Omega}\right) = -278$$

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$$V_{EQ} = \frac{1.5\,M\Omega}{1.5\,M\Omega + 2.2\,M\Omega}12V = 4.87\ V \quad | \quad R_{EQ} = 1.5\,M\Omega \| 2.2\,M\Omega = 892\ k\Omega$$

Neglect λ in hand calculations of the Q-point.

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

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

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

– – –

$$A_{vdB}^{CS} = 20\log\left|-4.50\right| = -13.1\ dB$$

– – –

$$R_{iB} = 10.2k\Omega + 101\left(1k\Omega\right) = 111k\Omega$$

$$A_v^{CE} = -\frac{9.80mS\left(18k\Omega\right)}{1 + 9.80mS\left(1k\Omega\right)}\left(\frac{104k\Omega \| 111k\Omega}{1k\Omega + 104k\Omega \| 111k\Omega}\right) = -16.0 \quad | \quad R_4 = 13k\Omega - 1k\Omega = 12\ k\Omega$$

$$A_v^{CS} = -\frac{0.503mS\left(18k\Omega\right)}{1 + 0.503mS\left(1k\Omega\right)}\left(\frac{892k\Omega}{1k\Omega + 892k\Omega}\right) = -6.02 \quad | \quad R_4 = 12k\Omega - 1k\Omega = 11\ k\Omega$$

$$(iii)\ \ R_{iB} = 10.2k\Omega + 101\left(13k\Omega\right) = 1.32\ M\Omega$$

$$A_v^{CE} = -\frac{9.80mS\left(18k\Omega\right)}{1 + 9.80mS\left(13k\Omega\right)}\left(\frac{104k\Omega \| 1.32M\Omega}{1k\Omega + 104k\Omega \| 1.32M\Omega}\right) = -1.36 \quad | \quad A_v^{CE} \cong -\frac{R_L}{R_E + R_4} = -\frac{18k\Omega}{13k\Omega} = -1.38$$

$$A_v^{CS} = -\frac{0.503mS\left(18k\Omega\right)}{1 + 0.503mS\left(12k\Omega\right)}\left(\frac{892k\Omega}{1k\Omega + 892k\Omega}\right) = -1.29 \quad | \quad A_v^{CS} \cong -\frac{R_L}{R_S + R_4} = -\frac{18k\Omega}{12k\Omega} = -1.50$$

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$$V_T = \left(\frac{1.381x10^{-23}}{1.602x10^{-19}}\frac{V}{K}\right)\left(273K + 27K\right) = 25.861\,mV \quad | \quad I_S = \frac{I_C}{\exp\left(\frac{V_{BE}}{V_T}\right)} = \frac{245\mu A}{\exp\left(\frac{0.700V}{0.025861V}\right)} = 0.430\,fA$$

– – –

$$g_m R_L = \text{-9.80mS}\left(18k\Omega\right) = -176 \quad | \quad A_v^{CE} \cong -\frac{18k\Omega}{3k\Omega} = -6.00 \quad | \quad 5.72 < 6.00$$

$$g_m R_L = \text{-0.503mS}\left(18k\Omega\right) = -9.05 \quad | \quad A_v^{CS} \cong -\frac{18k\Omega}{2k\Omega} = -9.00 \quad | \quad 4.50 < 9.00$$

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$$R_B = 160k\Omega \| 300k\Omega = 104k\Omega \quad | \quad R_{iB} \cong r_\pi\left(1+g_mR_L\right) = \frac{2.5V}{0.25mA}\left[1+10mS\left(11.5k\Omega\right)\right] = 1.16\ M\Omega$$

$$v_i \le 0.005V\left(1+g_mR_L\right)\frac{R_I + R_B\|R_{iB}}{R_B\|R_{iB}} = 0.005V\left[1+10mS\left(11.5k\Omega\right)\right]\frac{2k\Omega+95.4k\Omega}{95.4k\Omega} = 0.592\ V$$

$$v_i \le 0.2\left(V_{GS}-V_{TN}\right)\left(1+g_mR_L\right)\frac{R_I+R_G}{R_G} = 0.2\left(1V\right)\left[1+0.5mS\left(10.7k\Omega\right)\right]\frac{2k\Omega+892k\Omega}{892k\Omega} = 1.27\ V$$

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$$A_{vt} = \frac{2k\Omega+892k\Omega}{892k\Omega}0.971 = 0.973 \quad | \quad \frac{\left(0.491ms\right)R_L}{1+\left(0.491ms\right)R_L} = 0.973 \rightarrow R_L = 73.4k\Omega$$

$R_6 \| 100k\Omega = 73.4k\Omega \rightarrow R_6 = 276\ k\Omega$ | Note, however, that the 12 kΩ resistor can't simply be replaced with a 276 kΩ resistor because of Q-point problems.

– – –

$$R_{iB} = 10.2k\Omega + 101\left(13k\Omega\right) = 1.32M\Omega \quad | \quad R_{in}^{CC} = 104k\Omega\|1.32M\Omega = 96.4k\Omega$$

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

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

– – –

BJT: $g_mR_L = 9.80mS\left(11.5k\Omega\right) = 113$ | FET: $g_mR_L = 0.491mS\left(10.7k\Omega\right) = 5.25$

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

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

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

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

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

$$R_{iD} = r_o\left[1+g_m R_{th}\right] = 223k\Omega\left[1+0.491(1.71k\Omega)\right] = 410\ k\Omega$$

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

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

– – –

The voltage gains are proportional to the load resistance

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

– – –

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

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

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$$A_v^{CS} = \frac{1}{1+\eta}\sqrt{\frac{(W/L)_1}{(W/L)_2}} \quad | \quad 10^{\frac{26}{20}} = \frac{1}{1+0.2}\sqrt{\frac{(W/L)_1}{4}} = \frac{2290}{1}$$

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$\eta = 0$ | $I_{D2} = I_{D1}$ | Both transistors are in the active region since $V_{DS} = V_{GS}$.

Neglecting λ: $\frac{10^{-4}}{2}\left(\frac{2}{1}\right)\left(5 - V_O - 1\right)^2 = \frac{10^{-4}}{2}\left(\frac{8}{1}\right)\left(V_O - 1\right)^2 \rightarrow V_O = 2.00\ V$

Keeping λ: $\frac{10^{-4}}{2}\left(\frac{2}{1}\right)\left(5 - V_O - 1\right)^2\left[1 + 0.02\left(5 - V_O\right)\right] = \frac{10^{-4}}{2}\left(\frac{8}{1}\right)\left(V_O - 1\right)^2\left(1 + 0.02V_O\right) \rightarrow$

$V_O = 2.0064\ V,\ I_D = 421.39\ \mu A \rightarrow \text{Q-point}: \left(2.01\ V,\ 421\ \mu A\right)$

– – –

$I_{D2} = I_{D1}$ | Both transistors are in the active region since $V_{DS} = V_{GS}$.

$K_n = 10^{-4}\left(\frac{20}{1}\right) = 2x10^{-3}\frac{A}{V^2}$ | $K_p = 4x10^{-5}\left(\frac{50}{1}\right) = 2x10^{-3}\frac{A}{V^2}$ | The transistors are symmetrical.

$\therefore\ V_O = \frac{V_{DD}}{2} = \frac{3.3V}{2} = 1.65\ V$ | $I_D = \frac{10^{-4}}{2}\left(\frac{20}{1}\right)\left(1.65 - 0.7\right)^2\left[1 + 0.02\left(1.65\right)\right] = 932\ \mu A$

Q – point: $\left(1.65\ V,\ 932\ \mu A\right)$

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

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

– – –

$R_{in}^{CG} \cong \frac{1}{g_m}$ | $I_C \cong \frac{1}{40\left(2k\Omega\right)} = 12.5\ \mu A$

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Common – Emitter :

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

$$C_2 >> \frac{1}{2\pi(250\,Hz)(21.9k\Omega + 82k\Omega)} = 6.13nF \quad | \quad \text{Choose } C_2 = 68\ nF = 0.068\ \mu F$$

$$C_3 >> \frac{1}{2\pi(250\,Hz)\left[10k\Omega \left\| \left(3k\Omega + \frac{1}{9.80mS}\right)\right.\right]} = 0.269\mu F \quad | \quad \text{Choose } C_3 = 2.7\ \mu F$$

Common – Source :

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

$$C_2 >> \frac{1}{2\pi(250\,Hz)(21.5k\Omega + 82k\Omega)} = 6.15nF \quad | \quad \text{Choose } C_2 = 68\ nF = 0.068\ \mu F$$

$$C_3 >> \frac{1}{2\pi(250\,Hz)\left[10k\Omega \left\| \left(2k\Omega + \frac{1}{0.491mS}\right)\right.\right]} = 0.221\mu F \quad | \quad \text{Choose } C_3 = 2.2\ \mu F$$

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Common – Collector :

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

$$C_2 >> \frac{1}{2\pi(250\,Hz)(120\Omega + 82k\Omega)} = 7.75nF \quad | \quad \text{Choose } C_2 = 82\ nF = 0.082\ \mu F$$

Common – Drain :

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

$$C_2 >> \frac{1}{2\pi(250\,Hz)(1.74k\Omega + 82k\Omega)} = 7.60nF \quad | \quad \text{Choose } C_2 = 82\ nF = 0.082\ \mu F$$

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Common – Base:

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

$$C_2 >> \frac{1}{2\pi(250\,Hz)(21.9k\Omega + 82k\Omega)} = 6.13nF \quad | \quad \text{Choose } C_2 = 0.068\ \mu F$$

$$C_3 >> \frac{1}{2\pi(250\,Hz)\left(160k\Omega \| 300k\Omega \| \left[10.2k\Omega + 101(13k\Omega \| 1k\Omega)\right]\right)} = 12.2nF \quad | \quad \text{Choose } C_3 = 0.12\ \mu F$$

Common – Gate:

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

$$C_2 >> \frac{1}{2\pi(250\,Hz)(20.9k\Omega + 82k\Omega)} = 6.19nF \quad | \quad \text{Choose } C_2 = 0.068\ \mu F$$

$$C_3 >> \frac{1}{2\pi(250\,Hz)(1.5\,M\Omega \| 2.2\,M\Omega)} = 714\,pF \quad | \quad \text{Choose } C_3 = 8200\ pF$$

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(a) Common – Source:

$$C_3 = \frac{1}{2\pi(1000\,Hz)\left[10k\Omega \| \left(2k\Omega + \frac{1}{0.491mS}\right)\right]} = 55.3nF \quad | \quad \text{Choose } C_3 = 0.056\ \mu F$$

(b) Common – Collector:

$$C_2 >> \frac{1}{2\pi(2000\,Hz)(120\Omega + 100k\Omega)} = 795\,pF \quad | \quad \text{Choose } C_2 = 820\ pF$$

(c) Common – Gate:

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

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

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

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

– – –

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

– – –

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

– – –

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

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

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

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Reverse the direction of the arrow on the emitter of the transistor as well as the values of V_{EE} and V_{CC}.

– – –

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

– – –

For $v_{CB} \geq 0$, we require $v_C \geq 0$. $V_C = 5 - I_C R_C = 2.29\ V \quad \therefore |v_c| \leq 2.29\ V$

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

– – –

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

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

$V_{EC} = 0.7 + 7.5 - I_C R_C = 5.52\ V$

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

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

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

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

– – –

$$v_{th} = v_i \frac{R_{in}^{CB}}{75\Omega + R_{in}^{CB}} g_m R_C = v_i \frac{75}{75\Omega + 75}(13.2mS)(8200\Omega) = 54.1 v_i \quad | \quad R_{th} = R_{out}^{CB} = 8.2\ k\Omega$$

$$A_v^{CG} = \frac{v_o}{v_i} = \frac{v_{th}}{v_i} \frac{100k\Omega}{R_{th} + 100k\Omega} = 54.1 \frac{100k\Omega}{8.2k\Omega + 100k\Omega} = 50.0$$

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

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

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

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

– – –

$$I_D = \frac{0.01}{2}\left(0.25\right)^2 = 0.3125\ mA \quad | \quad V_{GS} - V_{TN} = 0.25\ V \quad | \quad V_{GS} = 0.25 - 2 = -1.75\ V$$

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

$R_D = 66.7k\Omega \rightarrow 68\ k\Omega$ | C_1 remains unchanged.

$$C_2 >> \frac{1}{10^6\pi\left(68k\Omega + 100k\Omega\right)} = 1.90\,pF \rightarrow \text{Choose } C_2 = 20\ pF$$

$$C_3 >> \frac{1}{10^6\pi\left(5.6k\Omega \| \frac{1}{2.5mS}\right)} = 0.853nF \rightarrow \text{Choose } C_3 = 8200\ pF$$

– – –

$$v_{th} = v_i\frac{R_{\text{in}}^{\text{CG}}}{75\Omega + R_{\text{in}}^{\text{CG}}}g_m R_D = v_i\frac{75\Omega}{75\Omega + 75\Omega}\left(2mS\right)\left(100k\Omega\right) = 100v_i \quad | \quad R_{th} = R_{\text{out}}^{\text{CG}} = 100\ k\Omega$$

$$A_v^{CG} = \frac{v_o}{v_i} = \frac{v_{th}}{v_i}\frac{100k\Omega}{R_{th} + 100k\Omega} = 100\frac{100k\Omega}{100k\Omega + 100k\Omega} = 50.0$$

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$$\text{M}_1: \ I_D = \frac{K_n}{2}\left(V_{GS} - V_{TN}\right)^2 \ \ | \ \ V_{GS} = -R_{S1}I_D \ \ | \ \ I_D = \frac{0.01}{2}\left(-200I_D + 2\right)^2 \rightarrow I_D = 5.00 \ mA$$

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

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

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

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

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

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

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

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

– – –

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

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

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

$$20 \log\left(898\right) = 59.1 \ dB$$

– – –

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

– – –

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

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

– – –

Note that the answers are obtained directly from SPICE.

– – –

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

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

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CHAPTER 15

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

– – –

$$I_C = \alpha_F I_E = \frac{60}{61}\left[\frac{15-V_{BE}}{2\left(75k\Omega\right)}\right] \text{ and } V_{BE} = 0.025V \ln\left(\frac{I_C}{0.5x10^{-15}\ A}\right) \rightarrow I_C = 94.7\ \mu A,\ V_{BE} = 0.649\ V$$

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$$v_{id} = v_1 - v_2 = 1.01 - 0.990 = 0.020\ V \quad | \quad v_{ic} = \frac{v_1 + v_2}{2} = \frac{1.01+0.99}{2} = 1.00\ V$$

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

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

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

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

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

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

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

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

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

Q – point : $(100\ \mu A,\ 8.75\ V)$

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

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

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$I_{C1} = I_{C2} = \frac{100}{101}\left(\frac{150\mu A}{2}\right) = 74.3\ \mu A \quad | \quad I_{C3} = \frac{15V}{20k\Omega} = 750\ \mu A \quad | \quad V_{CE3} = 15 - 0 = 15.0\ V$

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

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

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$A_{dm}^{max} = 560\ (15) = 8400 \quad | \quad I_{C1} \le 50(1\mu A) = 50\ \mu A \quad | \quad A_{dm} = \frac{8400}{1 + \frac{28}{100}\left(\frac{500\mu A}{50\mu A}\right)} = 2210$

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

– – –

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

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

– – –

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

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

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

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

– – –

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

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

– – –

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

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

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

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

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

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

– – –

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

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

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

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

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

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

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

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

– – –

$r_{o3} = \dfrac{50 + 14.3}{550\mu A} = 117\ k\Omega$ | $A_{vt2} = -22mS\left(117k\Omega \| 203k\Omega\right) = -1630$ | $A_{dm} = -3.50(-1630)(0.998) = 5700$

$2\dfrac{100}{40(49.5\mu A)} = 101\ k\Omega$ | $R_{out} \cong \dfrac{1}{g_{m4}} + \dfrac{r_{o3} \| R_2}{\beta_{o4}+1} = \dfrac{1}{40(4.95mA)} + \dfrac{117k\Omega}{101} = 1.16\ k\Omega$

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

– – –

$A_v = \dfrac{T}{1+T} = \dfrac{6920}{6921} = 0.99986$ | $T_{OC} = T$ | $T_{SC} = 0$ | $R_{out} = \dfrac{R_o}{1+T} = \dfrac{1.62k\Omega}{1 + 6920} = 0.234\ \Omega$

$R_{in} \cong R_{id}\left(1 + T_{SC}\right) = 101k\Omega(6921) = R_{id}(1+T) = 699\ \text{M}\Omega$ (Assuming $T_{OC} << 1$)

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

$$A_{vt1} = -\frac{1}{2}\sqrt{2(0.005)(100\mu A)}(16.3k\Omega) = -8.16 \ | \ A_{vt2} = -g_{m3}r_{o3} = -\sqrt{2(0.0025)(0.0005)}\left(\frac{1}{0.01(0.5mA)}\right) = -31($$

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

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

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

– – –

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

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$$A_{dd1} = -\sqrt{\frac{K_n'}{K_P'}}\sqrt{\frac{(W/L)_2}{(W/L)_{L2}}} \quad | \quad 10 = \sqrt{2.5}\sqrt{\frac{(W/L)_2}{4}} \rightarrow (W/L)_2 = \frac{160}{1}$$

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

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

– – –

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

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

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

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

– – –

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

$$I_C = 150\frac{-10.66-0.7-(-15)}{78.2k\Omega+151(18k\Omega)} = 195\ \mu A \quad | \quad V_B = V_{EQ} - I_B R_{EQ} = -10.66 - \frac{195\ \mu A}{150}(78.2\ k\Omega) = -10.8\ V$$

$$P_{R_1} = \frac{(-10.8+15)^2}{110k\Omega} = 0.160\ mW \quad | \quad P_{R_2} = \frac{(-10.8)^2}{270k\Omega} = 0.432\ mW$$

$$P_{R_E} = \frac{(-10.8-0.7+15)^2}{18k\Omega} = 1.33\ mW \quad | \quad r_o = \frac{(75+11.5)V}{195\mu A} = 446\ k\Omega \quad | \quad r_\pi = \frac{150}{40(195\mu A)} = 19.3\ k\Omega$$

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

– – –

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

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

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

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

– – –

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

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

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

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

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

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

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CHAPTER 16

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

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

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

– – –

$V_{DS} \ge V_{GS} - V_{TN} \quad | \quad V_D - (-10V) \ge \sqrt{\dfrac{2I_D}{K_n}} \quad | \quad V_D \ge -10V + \sqrt{\dfrac{2(150\mu A)}{250\mu A/V^2}} = -8.91\ V$

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

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

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

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

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$(a)\ MR = \dfrac{0.5A}{A} = 0.5 \quad | \quad MR = \dfrac{5A}{2A} = 2.50$

$(b)\ MR = \dfrac{0.5}{1+\dfrac{1.5}{75}} = 0.490 \quad | \quad MR = \dfrac{2.50}{1+\dfrac{3.5}{75}} = 2.39$

$(c)\ MR = 0.5\dfrac{1+\dfrac{15}{60}}{1+\dfrac{0.7}{60}+\dfrac{1.5}{75}} = 0.606 \quad | \quad MR = 2.5\dfrac{1+\dfrac{15}{60}}{1+\dfrac{0.7}{60}+\dfrac{3.5}{75}} = 2.95$

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

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

– – –

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

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

– – –

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

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

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

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

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MOS

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

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

BJT

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

– – –

$$R_{out} \cong \frac{\beta_o r_o}{2} = \frac{100}{2}\left(\frac{67V + 14.3V}{50\mu A}\right) = 81.3\ M\Omega \quad | \quad R_{out} = r_o = \frac{67V + 15V}{50\mu A} = 1.64\ M\Omega$$

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$$I_O = 25.014\mu A + \frac{10V - 20V}{1.66G\Omega} = 25.008\ \mu A$$

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

$I_O = 50\mu A \pm 0.1\%$ | $\Delta I_O \leq 50\ nA$ | $R_{out} \geq \dfrac{20V}{50nA} = 400\ M\Omega$ | Choose $R_{out} = 1\ G\Omega$.

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

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

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

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

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

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

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

$$V_{CC} + V_{EE} \geq V_{BE1} + V_{BE4} \cong 1.4\ V$$

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

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$$R = \frac{V_T}{I_O}\ln\left(\frac{I_{C1}}{I_{C2}}\frac{A_{E2}}{A_{E1}}\right) = \frac{0.025875V}{45\mu A}\ln\left(\frac{25}{5}\right) = 925\ \Omega$$

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

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$$V_{PTAT} = V_T \ln\left(\frac{A_{E2}}{A_{E1}}\right) = (27.57mV)\ln(20) = 82.59\ mV \quad | \quad R_1 = \frac{V_{PTAT}}{I_E} = \frac{82.59mV}{25\mu A} = 3.30\ k\Omega$$

$$V_{BE1} = V_T \ln\left(\frac{I_{C1}}{I_{S1}}\right) = (27.57mV)\ln\left(\frac{25\mu A}{0.5 fA}\right) = 0.6792\ V$$

$$\frac{R_2}{R_1} = \frac{V_{GO} + 3V_T - V_{BE1}}{2V_{PTAT}} = \frac{1.12 + 3(0.02757) - 0.6792}{2(0.08259)} = 3.169 \quad | \quad R_2 = 3.169R_1 = 10.5\ k\Omega$$

$$V_{BG} = V_{BE1} + 2\frac{R_2}{R_1}V_{PTAT} = 0.6792 + 2(3.169)(0.08259) = 1.203\ V$$

The other resistors remain the same.

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

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

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

M_1 and M_2 : $(125\ \mu A,\ 4.88\ V)$ | M_3 and M_4 : $(125\ \mu A,\ 1.87\ V)$

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

$$R_o = r_{o2}\|r_{o4} = \frac{75.2V + 4.88V}{125\mu A}\left\|\frac{75.2V + 1.87V}{125\mu A}\right. = 314\ k\Omega \quad | \quad A_v = G_m R_o = 78.5$$

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

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

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

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

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

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$$A_{v1} \cong \left(\beta_{o5}\frac{I_{C2}}{I_{C5}}\right) = \frac{150}{3} = 50$$

– – –

For the whole amplifier: $A_{dm} \cong A_{v1}A_{v2}A_{v3} \quad | \quad A_{v2} \cong \mu_{f5} \cong 40\left(75\right) = 3000 \quad | \quad A_{v3} \cong 1$

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

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$$CMRR = \left[\frac{2}{\beta_{o3}}\left(\frac{1}{\beta_{o2}\mu_{f2}} - \frac{1}{2g_{m2}R_{EE}}\right)\right]^{-1} = \left[\frac{2}{100}\left(\frac{1}{100\left(40\right)\left(75\right)} - \frac{1}{2\left(40\right)\left(10^{-4}\right)\left(10^{7}\right)}\right)\right]^{-1} = 5.45x10^6 \rightarrow 135\ dB$$

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$$A_{dm} \cong A_{v1}A_{v2}A_{v3} \quad | \quad A_{v1} \cong \frac{I_{C2}}{I_{C5}}\beta_{o5} = \frac{I_{REF}}{2}\frac{\beta_{o5}}{5I_{REF}} = \frac{50}{10} = 5 \quad | \quad A_{v2} \cong \frac{\mu_{f5}}{2} \cong \frac{40\left(60+14.7\right)}{2} \cong 1500 \quad | \quad A_{v3} \cong 1$$

$A_{dm} \cong 5\left(1500\right)(1) = 7500$ assuming the input resistance of the emitter followers is much greater than r_{o5} and $V_{A8} = V_{A5}$. Checking: $r_{o5} \cong \dfrac{60V + 14.7V}{500\mu A} = 149\ k\Omega \quad | \quad R_{iB6} \cong \beta_{o6}R_L = 300\ M\Omega$

$$I_{C5} = 10I_{C4} = 10I_{C3} \rightarrow A_{E5} = 10A \quad | \quad R_{id} = 2r_{\pi 1} = 2\frac{150}{40\left(50\mu A\right)} = 150\ k\Omega$$

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

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

– – –

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

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

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$$R_{th} = R_{out4} \| R_{out6} = 2r_{o4} \| 1.3r_{o6} = 2\left(\frac{60+13}{7.25\mu A}\right) \| 1.3\left(\frac{60+1.3}{7.16\mu A}\right) = 20.1M\Omega \| 11.1M\Omega = 7.15\ M\Omega$$

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

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$$R_{eq2} = r_{\pi 15} + (\beta_{o15}+1)R_L = \frac{50(0.025)}{2mA} + 51(2k\Omega) = 103\ k\Omega$$

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

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

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

$$r_{\pi 16} = 50\frac{0.025}{2mA} = 625\ \Omega \quad | \quad R_{out} = \frac{625+1970}{51} + 27 = 78\ \Omega$$

– – –

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

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$$v_o = \left(\frac{R}{I_{EE}R_1R_3}\right)v_1v_2 = K_M v_1 v_2 \quad | \quad K_M = \frac{|v_o|}{|v_1v_2|} = \frac{5}{5^2} = 0.2 \quad | \quad K_M = \frac{|v_o|}{|v_1v_2|} = \frac{1}{1^2} = 1$$

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CHAPTER 17

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

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

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$$f_H \cong \frac{10^6}{2\pi} = 159\ kHz$$

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$$f_H \cong \frac{1}{2\pi}\frac{1}{\sqrt{\left(\frac{1}{10^5}\right)^2 + \left(\frac{1}{5x10^5}\right)^2 - 2\left(\frac{1}{2x10^5}\right)^2 - 2\left(\frac{1}{\infty}\right)^2}} = 21.7\ kHz$$

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The value of C_3 does not change A_{mid}, ω_{P1}, ω_{P2}, ω_{z1}, or ω_{Z2}.

$$\omega_{P3} = -\frac{1}{2\mu F\left(1.3k\Omega \| \frac{1}{1.23mS}\right)} = -1000 \text{ rad/s} \quad | \quad \omega_{Z3} = -\frac{1}{2\mu F(1.3k\Omega)} = -385 \text{ rad/s}$$

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

– – –

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

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

– – –

$$\omega_{P3} = -\frac{1}{10\mu F\left(1.3k\Omega \| \frac{1}{1.23mS} \| 57.5k\Omega\right)} = -202 \text{ rad/s}$$

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

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

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

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

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

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

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.

– – –

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

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

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

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

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

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

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

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

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

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

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

– – –

$$R_{1S}C_1 = (1k\Omega + 243k\Omega)0.1\mu F = 24.4\ ms \quad | \quad R_{2S}C_2 = \left(24k\Omega + 1.3k\Omega \left\| \frac{1}{1mS}\right.\right)47\mu F = 1.15\ s$$

$$f_L \cong \frac{1}{2\pi}\left(\frac{1}{24.4ms} + \frac{1}{1.15s}\right) = 6.66\ Hz$$

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

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

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

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

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

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

– – –

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

– – –

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

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

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

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

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

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

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

– – –

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

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

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

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

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

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

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

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$$1 + g_m R_E = 1 + 0.064\left(100\right) = 7.40 \quad | \quad R_{iB} = 250 + 1560 + 101\left(100\right) = 11.9\ k\Omega$$

$$r_{\pi 0} = 11.9k\Omega \| \left(882 + 250\right) = 1030\ \Omega \quad | \quad A_i = \frac{10k\Omega \| 30k\Omega \| 11.9k\Omega}{1k\Omega + 10k\Omega \| 30k\Omega \| 11.9k\Omega} = 0.821$$

$$A_{mid} = -0.821\left(\frac{264}{7.4}\right) = -29.3 \quad | \quad f_H = \frac{1}{2\pi\left(1.03k\Omega\right)\left[\frac{19.9\,pF}{7.4} + 0.5\,pF\left(1 + \frac{264}{7.4} + \frac{4120}{1030}\right)\right]} = 6.70\ MHz$$

$$GBW = 29.3\left(6.70\,MHz\right) = 196\ MHz$$

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

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

– – –

$$R_{iS} = R_4 \left\| \frac{1}{g_m} \right. = 1.3k\Omega \left\| \frac{1}{3mS} \right. = 265\ \Omega$$

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

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

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$$R_L = 1.3k\Omega \| 24k\Omega = 1.23k\Omega \quad | \quad A_{mid} = 0.998\frac{3mS(1.23k\Omega)}{1+3mS(1.23k\Omega)} = 0.785$$

$$f_H \cong \frac{1}{2\pi}\frac{1}{(1k\Omega \| 430k\Omega)\left(1pF + \frac{10pF}{1+3.69}\right)} = 50.9\ MHz$$

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

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

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

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

$$\text{CC} - \text{CB Cascade}: A_v = \frac{g_{m1}\left(\frac{1}{g_{m2}}\right)}{1+g_{m1}\left(\frac{1}{g_{m2}}\right)}(g_m R_C) = +\frac{198}{2} = +99.0$$

$$f_H \cong \frac{1}{2\pi(50k\Omega)(0.5pF)} = 6.37\ MHz$$

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

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

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

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

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

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

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

– – –

$$X_1 = \frac{1}{2\pi(667kHz)0.01\mu F} = 23.9\ \Omega << 1.01\ M\Omega \quad | \quad X_2 = \frac{1}{2\pi(667kHz)47\mu F} = 5.08\ \text{m}\Omega << 66.7\ \Omega$$

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

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

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

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

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

– – –

$$f_o \text{ is unchanged} \quad | \quad r_o = \frac{50V + 10V - 1.6V}{3.2mA} = 18.3\ k\Omega \quad | \quad Q = \frac{100k\Omega \| 100k\Omega \| r_o}{2\pi(4.59\ MHz)(10\mu H)} = 46.4$$

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$$R_{EQ} = g_m \frac{L_S}{C_{GS}} = \frac{g_m}{C_{GS} + C_{GD}} L_S\left(1 + \frac{C_{GD}}{C_{GS}}\right) = \omega_T L_S\left(1 + \frac{C_{GD}}{C_{GS}}\right)$$

$$R_{EQ} \cong \omega_T L_S \quad \text{for} \quad C_{GS} >> C_{GD}$$

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$$L_S \cong \frac{R_{EQ}}{\omega_T} = \frac{L^2 R_{EQ}}{\mu_n\left(V_{GS} - V_{TN}\right)} = \frac{\left(5x10^{-5}\,cm\right)^2 75\Omega}{\left(400\,cm^2/V - s\right)\left(0.25V\right)} = 1.88\text{x}10^{-9}\,H$$

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$$A_{CG} = \frac{1}{A}\frac{A}{\pi} = \frac{1}{\pi} \quad | \quad 20\log\left(\frac{1}{\pi}\right) = -9.94\ dB$$

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$$A_{CG} = \frac{1}{A}\frac{2A}{\pi} = \frac{2}{\pi} \quad | \quad 20\log\left(\frac{2}{\pi}\right) = -3.92\ dB$$

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From Fig. 17.81(a), the amplitude of the output signal is approximately 70 mV, so the conversion gain is approximately:

$$A_{CG} = \frac{1}{100mV}\left(0.7\right)\left(\frac{200mV}{\pi}\right) = \frac{1.4}{\pi} \quad | \quad 20\log\left(\frac{1.4}{\pi}\right) = -7.02\ dB$$

From Fig. 17.81(b), the spectral components at 46 and 54 kHz have amplitudes of approximately 45 mV, so the conversion gain is:

$$A_{CG} = \frac{45mV}{100mV} = 0.45 \quad | \quad 20\log\left(0.45\right) = -6.93\ dB \quad | \quad \text{Note}: \frac{1.4}{\pi} = 0.446$$

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$$f_C - f_m = 20 - 0.01 = 19.99\ MHz \quad | \quad f_C + f_m = 20 + 0.01 = 10.01\ MHz$$

$$3f_C - f_m = 60 - 0.01 = 59.99\ MHz \quad | \quad 3f_C + f_m = 60 + 0.01 = 60.01\ MHz$$

$$5f_C - f_m = 100 - 0.01 = 99.99\ MHz \quad | \quad 5f_C + f_m = 100 + 0.01 = 100.01\ MHz$$

− − −

$$A_{f_C + f_m} = A_{f_C - f_m} = 3\ V$$

$$A_{3f_C + f_m} = A_{3f_C - f_m} = \frac{A_{f_C - f_m}}{3} = 1\ V$$

$$A_{5f_C + f_m} = A_{5f_C - f_m} = \frac{A_{f_C - f_m}}{5} = 0.6\ V$$

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CHAPTER 18

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$I_{C4} = I_{C3} = I_{C2} = I_{C1} = \frac{I_1}{2} = 1\ mA \quad | \quad V_{CE2} = 0.7\ V \quad | \quad V_{EC3} = 0.7\ V \quad | \quad V_O = 0\ V$

$V_{EC4} = 5V - V_O = 5 - 0 = 5.0\ V \quad | \quad V_{EC1} = 5 - V_{C1} - V_{E1} = 5 - 0.7 - (-0.7) = 5.0\ V$

$(1\ mA,\ 5.0\ V),\ (1\ mA,\ 0.7\ V),\ (1\ mA,\ 0.7\ V),\ (1\ mA,\ 5.0\ V)$

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With the output shorted, current cannot make it around the loop, so $T_{SC} = 0$.

– – –

$T_{OC} = 0$ is zero only if r_{o1} is neglected since the votlage across r_π must be zero for $i_b = 0$.

If we include r_{o1}, and start at the base of Q_2 assuming $r_{o1} >> \frac{1}{g_{m3}}$ and a current mirror gain of 1:

$$v_{c4} \cong \frac{v_{e1}}{r_{o1}}(1)\left[r_{o4} \| R_{iB2} \| R_L \| r_{o4}(1 + g_{m2}r_{o1})\right] = \left(v_{b2}\frac{g_{m2}r_{o1}}{1 + g_{m2}r_{o1}}\right)\left(\frac{1}{r_{o1}}\right)\left[r_{o4} \| R_{iB2} \| R_L\right]$$

$$T \cong \frac{r_{o4} \| R_{iB2} \| R_L}{r_{o1}} = \frac{55k\Omega \| 5.1k\Omega \| 10k\Omega}{55k\Omega} = 0.0579$$

– – –

Evaluating Eq. 18.7 without R_L, $T_{OC} = g_{m2}\left(r_{o1} \| r_{o1} \| R_{iB2}\right) = 0.04\left(55k\Omega \| 55k\Omega \| 5.1k\Omega\right) = 172$

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$$T_{new} = \left[g_{m1}\left(R_3 \| r_{\pi 2}\right)\right]\left[-g_{m2}\left(\left[R_2 + R_1 \| R_{iE1}\right] \| R_5 \| R_L\right)\right]\left(\frac{R_1 \| R_{iE1}}{R_1 \| R_{iE1} + R_2}\right)$$

$$T_{new} = T_{old}\frac{R_3 \| r_{\pi 2}}{R_3 \| R_{iB2}}\left(1 + g_{m2}R_4\right) = -2.01\frac{1k\Omega \| 2.5k\Omega}{970\Omega}\left[1 + 0.04S(300\Omega)\right] = -19.2$$

$A_v = 10\frac{19.2}{1 + 19.2} = 9.50 \quad | \quad$ Now $R_{iC2} = r_{o2} = \infty \quad | \quad R_{in}^D \cong 31.7\ k\Omega \quad | \quad R_{out}^D \cong 1.74\ k\Omega$

Scaling using the previous result : $T_{SC} = -19.2\left(\frac{1.86}{2.01}\right) = 17.8 \quad | \quad R_{in} = 31.7k\Omega\frac{1 + 17.8}{1 + 0} = 596k\Omega$

$R_{out} = 1.74k\Omega\frac{1 + 0}{1 + 19.2} = 86.1\ \Omega \quad | \quad$ Removing R_L : $R'_{out} = \left[\frac{1}{86.1} - \frac{1}{10^4}\right]^{-1} = 86.8\ \Omega$

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$$R_x = R_x^D \frac{1+T_{SC}}{1+T_{OC}} \quad | \quad R_x^D = R_3 \| R_{iD1} \| R_{iG3} = R_3 \| 2r_{o1} \| R_{iG3} = 3k\Omega \| \infty \| \infty = 3k\Omega$$

$$T_{SC} = 0 \quad | \quad T_{OC} = T = 61.1 \quad | \quad R_x = 3k\Omega \left(\frac{1+0}{1+61.1} \right) = 48.3\ \Omega$$

$$I_{D2} = I_{D1} = \frac{I_1}{2} = 0.500\ mA \quad | \quad I_{D4} = I_2 = 2.00\ mA \quad | \quad I_{D3} = \frac{1.63V - (-5V)}{13k\Omega} = 0.510\ mA$$

$$V_{DS1} = 3.5 + V_{GS1} \quad | \quad V_{GS1} = 1 + \sqrt{\frac{2(0.5mA)}{10mA}} = 1.32\ V \quad | \quad V_{DS1} = 3.5 + 1.32 = 4.82\ V$$

$$V_{DS2} = 5 + 1.32 = 6.32\ V \quad | \quad V_{DS3} = 5 - 1.63 = 3.37\ V \quad | \quad V_{DS4} = 5 - V_O = 5.00\ V$$

$$(0.5\ mA,\ 4.82\ V),\ (0.5\ mA,\ 6.32\ V),\ (0.51\ mA,\ 3.37\ V),\ (2\ mA,\ 5.0\ V)$$

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R_i appears in parallel with r_π : $r_\pi' = r_\pi \| R_i = 4.69k\Omega \| 10k\Omega = 3.19\ k\Omega$

$$T = -g_m \left(R_C \| (R_F + r_\pi') \| r_o \right) \left(\frac{r_\pi'}{r_\pi' + R_F} \right) = -0.032S \left(5k\Omega \| (50k\Omega + 3.19k\Omega) \| 62.4k\Omega \right) \left(\frac{3.19k\Omega}{3.19k\Omega + 50k\Omega} \right) = -8.17$$

$$A_{tr} = A_{tr}^{Ideal} \frac{T}{1+T} = -50k\Omega \frac{8.17}{1+8.17} = -44.5\ k\Omega$$

$$R_{in}^D = r_\pi' \| (R_F + R_C \| r_o) = 3.19k\Omega \| (50k\Omega + 5k\Omega \| 62.4k\Omega) = 3.01\ k\Omega \quad | \quad T_{SC} = 0 \quad | \quad |T_{OC}| = |T|$$

$$R_{in} = 3.01k\Omega \frac{1+0}{1+8.17} = 328\ \Omega$$

$$R_{out}^D = R_C \| r_o \| (R_F + r_\pi') = 5k\Omega \| 62.4k\Omega \| (50k\Omega + 3.19k\Omega) = 4.26\ k\Omega \quad | \quad T_{SC} = 0 \quad | \quad |T_{OC}| = |T|$$

$$R_{out} = 4.26k\Omega \frac{1+0}{1+8.17} = 463\ \Omega$$

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$$A_v = -\left(\frac{R_F}{R_i + R_{in}}\right)\left(\frac{R_L}{R_{out} + R_L}\right) = -\left(\frac{45.1k\Omega}{2k\Omega + 340\Omega}\right)\left(\frac{10k\Omega}{336\Omega + 10k\Omega}\right) = -18.6$$

$$A_v = -\left(\frac{R_F}{R_i + R_{in}}\right)\left(\frac{R_L}{R_{out} + R_L}\right) = -\left(\frac{45.1k\Omega}{10k\Omega + 340\Omega}\right)\left(\frac{2k\Omega}{336\Omega + 2k\Omega}\right) = -3.73$$

– – –

$$T = \frac{-A_{tr}}{R_F + A_{tr}} = \frac{48.5k\Omega}{50k\Omega - 48.5k\Omega} = 32.3 \quad | \quad g_{m3} = \frac{1}{R_{out}}\left(\frac{1}{1+T}\right) = \frac{1}{12\Omega}\left(\frac{1}{1+32.3}\right) = 2.50\ mS$$

$$R_{in} = \left(R_F + \frac{1}{g_{m3}}\right)\left(\frac{1}{1+T}\right) = \left(50k\Omega + \frac{1}{2.5mS}\right)\left(\frac{1}{1+32.3}\right) = 1.51\ k\Omega$$

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$$T \text{ is the same}: |T| = 306. \quad | \quad A_v^{Ideal} = 1 \quad | \quad A_v = A_{tr}^{Ideal}\frac{T}{1+T} = 1\left(\frac{306}{1+306}\right) = 0.997$$

$$R_{out}^D = R_F \| \frac{1}{g_{m5}} = 10k\Omega \| \frac{1}{3.16mS} = 307\ \Omega \quad | \quad T_{SC} = 0 \quad | \quad |T_{OC}| = |T|$$

$$R_{out} = 307\Omega\frac{1+0}{1+306} = 1.00\ \Omega$$

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$$T \text{ is the same}: |T| = 306. \quad | \quad A_v^{Ideal} = 1 \quad | \quad A_v = A_{tr}^{Ideal}\frac{T}{1+T} = 1\left(\frac{306}{1+306}\right) = 0.997$$

$$R_{in}^D = r_{o1}\left(1 + g_{m1}\frac{2}{g_{m2}}\right) \| \frac{1}{g_{m3}} = 600k\Omega \| \frac{1}{2.00mS} = 500\ \Omega \quad | \quad |T_{OC}| = 306$$

Note: The impedance looking in the source of a transistor with a high resistance load of r_o is $2/g_m$ rather than $1/g_m$.

$$T_{SC} = -\frac{g_{m2}}{2}\left(2r_{o2} \| r_{o4}\right)\frac{g_{m5}R_F}{1 + g_{m5}R_F} = -\frac{3.16mS}{2}\left(400k\Omega \| 200k\Omega\right)\frac{3.16mS(10k\Omega)}{1 + 3.16mS(10k\Omega)} = -204$$

$$R_{out} = 500\Omega\frac{1+204}{1+306} = 334\ \Omega$$

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T is the same : $\left|T\right| = 152.$ | $A_v^{Ideal} = -\frac{R_2}{R_I} = -1$ | $A_v = A_{tr}^{Ideal}\frac{T}{1+T} = -1\left(\frac{152}{1+152}\right) = -0.993$

$R_{out}^D = \left(R_2 + R_I\right)\left\|R_1\right\|\frac{1}{g_{m5}} = 40k\Omega\left\|10k\Omega\right\|\frac{1}{3.16mS} = 304\ \Omega$ | $T_{SC} = 0$ | $\left|T_{OC}\right| = \left|T\right| = 152$

$R_{out} = 304\Omega\frac{1+0}{1+152} = 1.99\ \Omega$

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There are approximately 15 cycles in 0.8 μsec : $f \cong \frac{15cycles}{0.8us} = 18.8\ MHz$

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$f_T = \frac{1}{2\pi}\frac{g_m}{C_{GS} + C_{GD}}$ | $g_m = \sqrt{2K_nI_D}$ | $f_{T2} = f_{T1} = \frac{1}{2\pi}\frac{\sqrt{2(0.01)(0.0005)}}{5pf + 1pF} = 83.9\ MHz$

$f_{T3} = \frac{1}{2\pi}\frac{\sqrt{2(0.004)(0.0005)}}{5pf + 1pF} = 53.1\ MHz$ | $f_{T4} = \frac{1}{2\pi}\frac{\sqrt{2(0.01)(0.002)}}{5pf + 1pF} = 168\ MHz$

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

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

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

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

– – –

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

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

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

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

– – –

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

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

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

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

– – –

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

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

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When the circuit is drawn symmetrically, capacitor $2C_{GD}$ is replaced with 2 capacitors of value $4C_{GD}$ in series. The circuit can then be cut vertically down the middle to form a differential mode half-circuit. The total capacitance at the drain end of inductor L is $C+C_{GS}+4C_{GD}$.

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

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