Microelectronic Circuit Design Sixth Edition - Part III Solutions to Exercises

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CHAPTER 10

Page 651

$$(a)\ v_{id} = \frac{10V}{100} = 0.100V = 100mV$$

$$(b)\ v_{id} = \frac{10V}{5000} = 0.002V = 2.00\ mV$$

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

Page 653

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

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

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V_I is a dc value

$$I_1 = \frac{2V}{3.9k\Omega} = 0.513\ mA \ \ | \ \ I_2 = I_1 = 0.513\ mA \ \ | \ \ I_O = -I_2 = -0.513\ mA$$

$$A_v = -\frac{22k\Omega}{3.9k\Omega} = -5.64 \ \ | \ \ V_O = -5.64(2V) = -11.3\ V$$

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$$A_{tr} = -R_2 = \frac{5V}{25\mu A} = 200\ k\Omega \ \ | \ \ A_{tr} = -i_1R_2 = -2x10^5A(4x10^{-5}sin2000\pi t) = -8\ sin2000\pi t$$

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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.

Page 662

First exercise: all answers are incorrect! Correct answers appear below.

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

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

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

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

Add resistor R_3 = 2 kΩ in parallel with the opamp input as in the schematic on page 659.

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$$V_{o1} = 3V\left(\frac{3k\Omega}{1k\Omega}\right) = -9V \quad | \quad V_{o2} = 4V\left(\frac{3k\Omega}{2k\Omega}\right) = -6V \quad | \quad v_o = (-9sin1000\pi t \ - \ 6sin2000\pi t)\ V$$

The summing junction is a virtual ground: $R_{in1} = \frac{v_1}{i_1} = R_1 = 1\ k\Omega \quad | \quad R_{in2} = \frac{v_{12}}{i_2} = R_2 = 2\ k\Omega$

$$I_{o1} = \frac{V_{o1}}{R_3} = \left(\frac{-9V}{3k\Omega}\right) = -3\ mA \quad | \quad I_{o2} = \frac{V_{o2}}{R_3} = \left(\frac{-6V}{3k\Omega}\right) = -2\ mA \quad | \quad v_o = (-3sin1000\pi t \ - \ 2sin2000\pi t)\ mA$$

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

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

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

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

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

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

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

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

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

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

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

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

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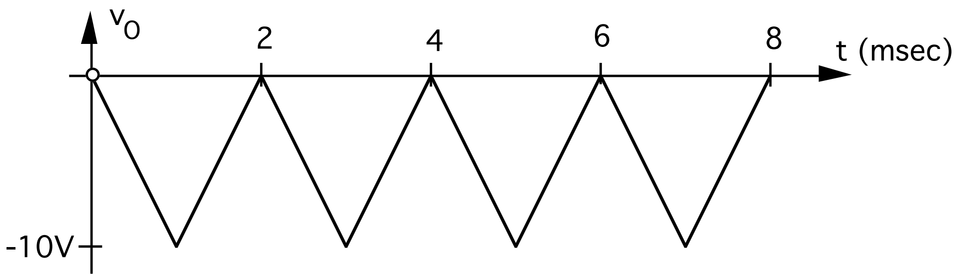
$R_{in} = R_1 = 10\ k\Omega \quad | \quad \Delta V = -\frac{I}{C}\Delta T \quad | \quad \text{C} = \frac{(10V/2)}{10k\Omega}\left(\frac{1}{10V}\right)(1ms) = 0.05\ \mu F$



Page 675

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

CHAPTER 11

Page 688

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

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

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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)

Note that as Specification Sheets are updated over time, the various values may change.

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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)
Note that as Specification Sheets are updated over time, the various values may change.

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

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

- - -

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

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

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

Page 695

Values taken from op - amp specification sheets (www.jaegerblalock.com or www.analog.com)
Note that as Specification Sheets are updated over time, the various values may change.

Page 696

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

$$R_{in} = 1M\Omega\ \left[1+248\right] = 249\ M\Omega$$

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

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

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

$$R_{in} = 1M\Omega\ \left[1+250\right] = 251\ M\Omega$$

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

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

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

Page 705

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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Continued on next page.

Page 705 cont.

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

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

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

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

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

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

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

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

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

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

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

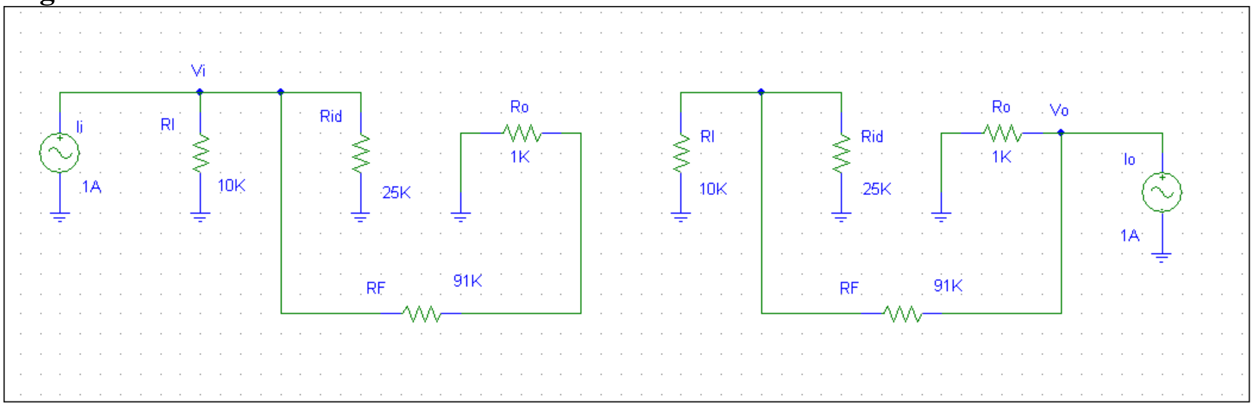
$$T = \frac{v_{th}}{v_{id}} \frac{R_{id}}{R_{th} + R_{id} + R_I} = 980 \frac{25k\Omega}{9.02k\Omega + 25k\Omega + 5k\Omega} = 628$$

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

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

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

Page 709



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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

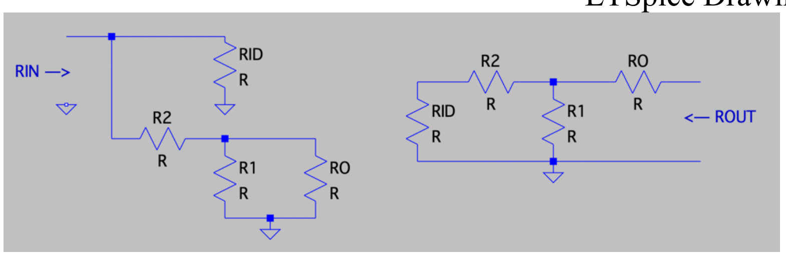
$$A_{tc} = -\frac{1}{R}\left(\frac{T}{1+T}\right) = -\frac{1}{10k\Omega}\left(\frac{8770}{1+8770}\right) = -0.100\ mS$$

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

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

Page 718

LTSpice Drawing



$R_{in} = R_{id}||(R_2 + R_1||R_o)$ | $R_{in} = R_o + R_1||(R_2 + R_{id})$

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

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

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

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

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

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

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

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

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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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$$V_O = V_{OS}\frac{A}{1+A} = 0.001V\left(\frac{1000}{1001}\right) = .999\ mV \quad | \quad V_O = AV_{OS} = 100\left(0.001V\right) = 1.00V$$

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

– – –

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

Note that as Specification Sheets are updated over time, the various values may change.

Page 730

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.

– – –

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

Note that as Specification Sheets are updated over time, the various values may change.

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

Page 733

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

– – –

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

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

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

– – –

$$I_O^{Max} = \frac{10V}{[0.9(100k\Omega)] \| [0.9(5k\Omega)]} = 2.33\ mA$$

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

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

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

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

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

Page 740

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

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

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

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

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

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Values taken from op-amp specification sheets (via www.jaegerblalock.com or www.analog.com)
Note that as Specification Sheets are updated over time, the various values may change.

Page 745

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

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

– – –

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

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

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

– – –

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

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

$$A(s) = \frac{2\pi\left(5x10^6\right)}{s+2\pi(158)} = \frac{10^7\pi}{s+316\pi} \quad | \quad A_v(s) = \frac{2\pi\left(5x10^6\right)}{s+2\pi\left(16.0x10^3\right)} = \frac{10^7\pi}{s+3.20x10^4\pi}$$

– – –

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

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

$$A(s) = \frac{\omega_T}{s+\omega_B} = \frac{2\pi\left(10^7\right)}{s+2\pi(100)} = \frac{2x10^7\pi}{s+200\pi} \quad | \quad A_v(s) = \frac{2x10^7\pi}{s+2.02x10^4\pi} \cong \frac{2x10^7\pi}{s+2x10^4\pi}$$

Page 753

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

Page 754

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

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

Note that as Specification Sheets are updated over time, the various values may change.

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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 $\omega_n t \ge 13$. $\therefore \omega_n \ge \frac{13}{10^{-5}s} = 1.3\text{x}10^6 rad/s$

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

Page 762

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

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

Page 766

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.

CHAPTER 12

Page 784

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

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

– – –

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

– – –

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

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

Page 789

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

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

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

– – –

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

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

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

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

– – –

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

Page 795

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

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

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

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

Page 798

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

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

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

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

Page 801

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

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 $\frac{10\text{kHz}}{5\text{kHz}} = 2$

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

– – –

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

Page 802

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

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

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

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

Page 803

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

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

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

Page 804

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

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

Page 805

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

Page 807

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

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

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

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

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

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

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

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

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

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

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

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

Page 808

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

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

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

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

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

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

– – –

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

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

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

Page 810

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

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

Page 812

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

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

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

Page 815

$0.01100001_2 = \left(2^{-2} + 2^{-3} + 2^{-8}\right)_{10} = 0.37890625_{10}$ | $0.10001000_2 = \left(2^{-1} + 2^{-5}\right)_{10} = 0.53125_{10}$

Page 816

(a)

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

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

Page 818

Answers are correct

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

Page 819

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

$128R = 64\ k\Omega$ | $256R = 128\ k\Omega$ | $R = 500\ \Omega$

Page 820

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

– – –

$R = 1\ \text{k}\Omega$ | $2R = 2\ k\Omega$ | $4R = 4\ k\Omega$ | $8R = 8\ k\Omega$ | $16R = 16\ k\Omega$ | $32R = 32\ k\Omega$

$64R = 64\ k\Omega$ | $128R = 128\ k\Omega$ | $256R = 256\ k\Omega$ | $R_{Total} = 511\ k\Omega$

In general: $R_{Total} = R\left(2^0 + 2^1 + \ldots + 2^{n-1} + 2^n\right) = \left(2^{n+1} - 1\right)R$ | $R_{Total} = \left(2^{8+1} - 1\right)1k\Omega = 511\ k\Omega$

Page 821

The general case requires 2^n resistors, and the number of switches is

$\left(2^1 + 2^2 + \ldots + 2^n\right) = 2\left(2^0 + 2^2 + \ldots + 2^{n-1}\right) = 2\left(2^n - 1\right) = 2^{n+1} - 2$

$2^{10} = 1024$ resistors | $2^{10+1} - 2 = 2046$ switches.

Page 822

(a) In general: $C_{Total} = C\left(2^0 + 2^1 + \ldots + 2^n\right) = \left(2^{n+1} - 1\right)C$ | $C_{Total} = \left(2^{8+1} - 1\right)1pF = 511\ pF$

(b) In general: $C_{Total} = 2C + 2C + (n-1)(2C + C) = (3n+1)C$ | $C_{Total} = 25(1pF) = 25\ pF$

$$(c)\ A = \frac{25pF}{5fF/\mu m^2} = \frac{25x10^{-12}}{5x10^{-15}}\mu m^2 = 5000\ \mu m^2$$

Page 823

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

Page 825

$2^n \geq 10^6$ | $n \geq \frac{6\log 10}{\log 2} = 19.93 \rightarrow n \geq 20\ bits$

– – –

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.

$\therefore INL = 1\ LSB$

Page 826

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

Page 827

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

Page 830

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

Page 831

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

Page 832

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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Page 840

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

– – –

SPICE Results : 15.90 kHz, 3.33 V

Page 841

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 $V_Z > 10\ V$.

Page 843

$v_S = +2\ V$: 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 $V_Z = 15\ V$.

Page 844

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

Page 846

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

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

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

Page 847

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

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

Page 851

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

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

CHAPTER 13

Page 870

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

– – –

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

$$I_S = \frac{I_C}{\exp\left(\frac{V_{BE}}{V_T}\right)} = \frac{94.7\mu A}{\exp\left(\frac{0.700V}{25.9mV}\right)} = 0.173\,fA$$

Page 872

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

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

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

$$\begin{bmatrix} v_{od} \\ v_{oc} \end{bmatrix} = \begin{bmatrix} A_{dd} & A_{cd} \\ A_{dc} & A_{cc} \end{bmatrix}\begin{bmatrix} v_{id} \\ v_{ic} \end{bmatrix} \quad | \quad \begin{bmatrix} 2.2 \\ 1.002 \end{bmatrix} = \begin{bmatrix} A_{dd} & A_{cd} \\ A_{dc} & A_{cc} \end{bmatrix}\begin{bmatrix} 0.02 \\ 1 \end{bmatrix} \quad | \quad \begin{bmatrix} 0 \\ 5.001 \end{bmatrix} = \begin{bmatrix} A_{dd} & A_{cd} \\ A_{dc} & A_{cc} \end{bmatrix}\begin{bmatrix} -0.01 \\ 5 \end{bmatrix}$$

$$v_{id} = v_1 - v_2 = 4.995 - 5.005 = -0.01\,V \quad | \quad v_{ic} = \frac{v_1+v_2}{2} = 4.995 + 5.005 = 5.00\,V$$

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

$$\begin{bmatrix} 2.20 \\ 0 \end{bmatrix} = \begin{bmatrix} 0.02 & 1.00 \\ -0.01 & 5.00 \end{bmatrix}\begin{bmatrix} A_{dd} \\ A_{cd} \end{bmatrix} \quad | \quad \begin{bmatrix} 1.002 \\ 5.001 \end{bmatrix} = \begin{bmatrix} 0.02 & 1.00 \\ -0.01 & 5.00 \end{bmatrix}\begin{bmatrix} A_{dc} \\ A_{cc} \end{bmatrix}$$

$$A_{dd} = 100 \quad | \quad A_{cd} = 0.200 \quad | \quad A_{dc} = 0.0818 \quad | \quad A_{cc} = 1.00$$

Page 877

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

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

$CMRR = 20V_{EE} = 300 \quad | \quad CMRR_{dB} = 20\log\left(300\right) = 49.5\ dB$

Page 880

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

Page 881

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

Page 884

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

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

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

$$\text{Q – point}: \left(100\ \mu A,\ 8.75\ V\right)$$

Page 885 The problem should refer to Fig. 13.6.
The MOS schematic will be identical except resistors r_π are removed.
The analyses are identical to Section 13.1.5 except $g_\pi = 0$ and $R_{id} = \infty$.

Page 888

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

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

Page 892

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

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

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

(74.3 μA, 15 V), (74.3 μA, 15 V), (750 μA, 15 V)

Page 895

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

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

– – –

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

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

– – –

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

Page 896

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

Page 897

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

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

– – –

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

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

– – –

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

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

Page 902

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

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

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

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

– – –

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

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

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

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

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

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

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

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

– – –

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

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

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

– – –

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

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

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

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

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

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

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

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

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

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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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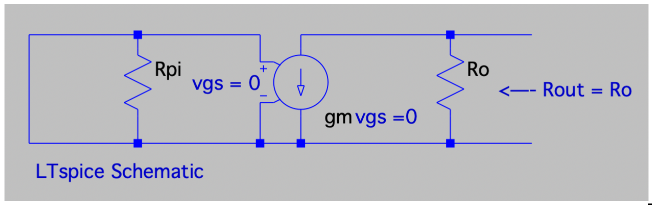

Bipolar Schematic. The MOS schematic is the same except R_{pi} is not included. $R_{out} = R_o$ in both cases.

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

– – –

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

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

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

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

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

– – –

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

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

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

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$$V_{DS} \geq V_{GS} - V_{TN} = 1 + \sqrt{\frac{2(0.2mA)}{2.49mA/V^2}} = 1.40\ V$$

$$V_D = V_S + 1.40 = -15 + 0.2mA(18.2k\Omega) + 1.40 = -9.96\ V$$

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

$$V_C \geq -15 + \frac{I_O}{\alpha_F} R_E + 0.7 \geq -15 + \frac{151}{150}(200\mu A)(18.4k\Omega) + 0.7 = -10.6\ V$$

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

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

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

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

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

CHAPTER 14

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

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

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

– – –

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

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$MR_1 = \dfrac{25/1}{3/1} = 8.33$ | $MR_2 = \dfrac{2/1}{5/1} = 0.400$ | $MR_3 = \dfrac{7.5/1}{3/1} = 2.5$

– – –

$V_{DS1} = 1V + \sqrt{\dfrac{2(50\mu A)}{3(25\mu A/V^2)}} = 2.16\ V$ | $MR_1 = 8.33\dfrac{1+0.02(15)}{1+0.02(2.16)} = 10.4$

$V_{DS2} = 1V + \sqrt{\dfrac{2(50\mu A)}{5(25\mu A/V^2)}} = 1.89\ V$ | $MR_2 = 0.400\dfrac{1+0.02(10)}{1+0.02(1.89)} = 0.462$

$V_{DS3} = 1V + \sqrt{\dfrac{2(50\mu A)}{3(25\mu A/V^2)}} = 2.16\ V$ | $MR_3 = 2.5\dfrac{1+0.02(12)}{1+0.02(2.16)} = 2.97$

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$$I_{REF} = I_S \exp\left(\frac{V_{BE1}}{V_T}\right)\left(1+\frac{V_{BE1}}{V_{A1}}+\frac{2}{\beta_{FO}}\right)$$

$$100\mu\text{A} = (0.1fA)\exp(40V_{BE1})\left(1+\frac{V_{BE1}}{50V}+\frac{2}{100}\right) \rightarrow V_{BE1} = 0.690$$

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

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$$(a)\ MR_1 = \frac{0.5A}{A} = 0.5 \ \mid\ MR_2 = \frac{5A}{2A} = 2.50 \ \mid\ MR_3 = \frac{4.3A}{A} = 4.30$$

$$(b)\ MR_1 = \frac{0.5}{1+\frac{1.5}{75}} = 0.490 \ \mid\ MR_2 = \frac{2.50}{1+\frac{3.5}{75}} = 2.39 \ \mid\ MR_3 = \frac{4.3}{1+\frac{5.3}{75}} = 4.02$$

$$(c)\ MR_1 = 0.5\frac{1+\frac{15}{60}}{1+\frac{0.7}{60}+\frac{1.5}{75}} = 0.606 \ \mid\ MR_2 = 2.5\frac{1+\frac{15}{60}}{1+\frac{0.7}{60}+\frac{3.5}{75}} = 2.95 \ \mid\ MR_3 = 4.30\frac{1+\frac{5}{60}}{1+\frac{0.7}{60}+\frac{5.3}{75}} = 4.30$$

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

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

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

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

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

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

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

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

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

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

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

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

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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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$$I_{D1}=I_{REF}=I_{DO}exp\left(\frac{V_{GS}-V_{TN}}{nV_T}\right)\quad|\quad I_{D2}=55I_{DO}exp\left(\frac{V_{GS}-V_{TN}-I_{D2}R}{nV_T}\right)\quad|\quad I_{D2}=I_{D1}$$

$$\frac{I_{D2}}{I_{D1}}=\frac{55I_{DO}exp\left(\frac{V_{GS}-V_{TN}-I_{D2}R}{nV_T}\right)}{I_{DO}exp\left(\frac{V_{GS}-V_{TN}}{nV_T}\right)}\quad|\quad\frac{55I_{DO}exp\left(\frac{V_{GS}-V_{TN}-I_{D2}R}{nV_T}\right)}{I_{DO}exp\left(\frac{V_{GS}-V_{TN}}{nV_T}\right)}=1$$

$$55=\frac{exp\left(\frac{V_{GS}-V_{TN}}{nV_T}\right)}{exp\left(\frac{V_{GS}-V_{TN}-I_{D2}R}{nV_T}\right)}=exp\left(\frac{I_{D2}R}{nV_T}\right)$$

$$I_{D2}=\frac{nV_T}{R}ln(55)=\frac{1.4V_T}{10^7}ln(55)=5.610x10^{-7}V_T$$

$$V_T=\frac{kT}{q}=\frac{1.381x10^{-23}(300)}{1.602x10^{-19}}=25.86\ mV\ \rightarrow\ I_{D2}=14.5\ nA$$

$$V_T=\frac{kT}{q}=\frac{1.381x10^{-23}(350)}{1.602x10^{-19}}=30.17\ mV\ \rightarrow\ I_{D2}=16.9\ nA$$

$$V_T=\frac{kT}{q}=\frac{1.381x10^{-23}(400)}{1.602x10^{-19}}=34.48\ mV\ \rightarrow\ I_{D2}=19.3\ nA$$

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

– – –

SPICE: $r_o = 1.27\ M\Omega$ | $R_{out} = 115.8\ M\Omega$

$$\beta = 150\left(1 + \frac{V_{CB}}{50}\right) = 150\left(1 + \frac{14.3}{50}\right) = 193 \rightarrow R_{out} \cong 1.27M\Omega\left(\frac{193}{2}\right) = 123\ M\Omega$$

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

– – –

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

– – –

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

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

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

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

– – –

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

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

– – –

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

$$S_{V_{EE}}^{I_O} = \frac{V_{EE}}{I_O}\frac{\partial I_O}{\partial V_{EE}} = \frac{5V}{101\mu A}\frac{2\mu A}{2.5V} = 0.040$$

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

– – –

Assume that the collector-base junctions of Q_2 and Q_3 can never be forward biased

$V_{CC} + V_{EE} \geq V_{EB3} + V_{BC3} + V_{BE1} = 0.6V + 0 + 0.6V = 1.2\ V$

Similarly: $V_{CC} + V_{EE} \geq V_{EB4} + V_{CB2} + V_{BE1} = 0.6V + 0 + 0.6V = 1.2\ V$

However, we know that we can actually forward-bias those junctions by 0.3 V or so and not effect the transistor behavior by much. In that case, the minimum bias would drop to 0.9 V.

– – –

$T = 300\ K$ & $TCR = \text{-2000 ppm/°C}$

$$TC = \frac{1}{I}\frac{\partial I}{\partial T} = \frac{1}{T} - \frac{1}{R}\frac{\partial R}{\partial T}$$

$$(a)\ TC = \frac{1}{T} = \frac{1}{300K} = 3300\ \text{ppm/°K} = 3300\ \text{ppm/°C}$$

$$(b)\ TC = 3300\ \text{ppm/°C} - \left(\text{-2000 ppm/°C}\right) = 5300\ \text{ppm/°C}$$

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

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

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

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

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

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

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

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 : $(125\ \mu A,\ 1.87\ V)$

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

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

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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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$V_{OS} = \dfrac{\Delta i}{g_m}$ where Δi is the difference in current on the two sides of the current mirror.

For the buffered current mirror, the error current is $\Delta i = 2\dfrac{I_C}{\beta_{FO4}\left(\beta_{FO11}+1\right)}$

$$V_{OS} = \frac{\Delta i}{g_m} = \frac{2I_C}{\beta_{FO4}\left(\beta_{FO11}+1\right)}\left(\frac{V_T}{I_C}\right) = \frac{2V_T}{\beta_{FO4}\left(\beta_{FO11}+1\right)} = \frac{2\left(0.025V\right)}{80\left(81\right)} = 7.72\ \mu V$$

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

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

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

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

Page 997 Note Twice: 14.7 V should be 14.3 V

$$A_{v2} \cong \frac{\mu_{f2}}{2} = \frac{40(60+14.3)}{2} \cong 1490 \mid A_{dm} = 5(1490)(1) = 7450 \mid r_{o5} = \frac{(60+14.3)}{2} \cong 149\ k\Omega$$

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

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

$I_{C5} = 10I_{C4} = 10I_{C3} \rightarrow A_{E5} = 10A$ | $R_{id} = 2r_{\pi1} = 2\dfrac{150}{40\left(50\mu A\right)} = 150\ k\Omega$

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

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

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

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

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

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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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$$R_{eq2} = r_{\pi15} + \left(\beta_{o15}+1\right)R_L = \frac{50\left(0.025\right)}{2mA} + 51\left(2k\Omega\right) = 103\ k\Omega$$

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

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

$$R_{eq3} = \left(r_{d13}+R_3\right)\Bigg\|\left(r_{d14} + \frac{r_{\pi12}+y_{22}^{-1}}{\beta_{o12}+1}\right) = \left(\frac{0.025V}{0.216mA} + 344k\Omega\right)\Bigg\|\left(\frac{0.025V}{0.216mA} + \frac{5.79k\Omega + 89.1k\Omega}{51}\right) = 1.97\ k\Omega$$

$$r_{\pi16} = 50\frac{0.025}{2mA} = 625\ \Omega \quad | \quad R_{out} = \frac{625+1970}{51} + 27 = 78\ \Omega$$

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

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$$v_o = \left(\frac{R}{I_{EE}R_1R_3}\right)v_1v_2 = K_Mv_1v_2 \quad | \quad K_M = \frac{|v_o|}{|v_1v_2|} = \frac{5}{5^2} = 0.2 \quad | \quad K_M = \frac{|v_o|}{|v_1v_2|} = \frac{1}{1^2} = 1$$

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$$I_{C4} = I_{C3} = I_{C2} = I_{C1} = \frac{I_1}{2} = 1\ mA \quad | \quad V_{CE2} = 0.7\ V \quad | \quad V_{EC3} = 0.7\ V \quad | \quad V_O = 0\ V$$

$$V_{EC4} = 5V - V_O = 5 - 0 = 5.0\ V \quad | \quad V_{EC1} = 5 - V_{C1} - V_{E1} = 5 - 0.7 - (-0.7) = 5.0\ V$$

$$(1\ mA,\ 5.0\ V),\ (1\ mA,\ 0.7\ V),\ (1\ mA,\ 0.7\ V),\ (1\ mA,\ 5.0\ V)$$

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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 voltage 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:

$$v_{c4} \cong \frac{v_{e1}}{r_{o1}}(1)\left[r_{o4} \| R_{iB2} \| R_L \| r_{o4}\left(1 + g_{m2} r_{o1}\right)\right] = \left(v_{b2}\frac{g_{m2} r_{o1}}{1 + g_{m2} r_{o1}}\right)\left(\frac{1}{r_{o1}}\right)\left[r_{o4} \| R_{iB2} \| R_L\right]$$

$$T_{OC} \cong \frac{r_{o4} \| R_{iB2} \| R_L}{r_{o1}} = \frac{55k\Omega \| 5.1k\Omega \| 10k\Omega}{55k\Omega} = 0.0579 \text{ - non-zero but small compared to 1.}$$

– – –

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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$$T_{new} = \left[g_{m1}\left(R_3 \| r_{\pi 2}\right)\right]\left[-g_{m2}\left(\left[R_2 + R_1 \| R_{iE1}\right] \| R_5 \| R_L\right)\right]\left(\frac{R_1 \| R_{iE1}}{R_1 \| R_{iE1} + R_2}\right)$$

$$T_{new} = T_{old}\frac{R_3 \| r_{\pi 2}}{R_3 \| R_{iB2}}\left(1 + g_{m2} R_4\right) = -2.01\frac{1k\Omega \| 2.5k\Omega}{970\Omega}\left[1 + 0.04S\left(300\Omega\right)\right] = -19.2$$

$$A_v = 10\frac{19.2}{1 + 19.2} = 9.50 \quad | \quad \text{Now } R_{iC2} = r_{o2} = \infty \quad | \quad R_{in}^D \cong 31.7\ k\Omega \quad | \quad R_{out}^D \cong 1.74\ k\Omega$$

$$\text{Scaling using the previous result}: T_{SC} = -19.2\left(\frac{1.86}{2.01}\right) = 17.8 \quad | \quad R_{in} = 31.7k\Omega\frac{1 + 17.8}{1 + 0} = 596k\Omega$$

$$R_{out} = 1.74k\Omega\frac{1 + 0}{1 + 19.2} = 86.1\ \Omega \quad | \quad \text{Removing } R_L:\ R'_{out} = \left[\frac{1}{86.1} - \frac{1}{10^4}\right]^{-1} = 86.8\ \Omega$$

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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: $r'_\pi = r_\pi \| R_i = 4.69k\Omega \| 10k\Omega = 3.19\ k\Omega$

$$T = g_m \left(R_C \| (R_F + r'_\pi) \| r_o\right)\left(\frac{r'_\pi}{r'_\pi + R_F}\right) = 0.032S\left(5k\Omega \| (50k\Omega + 3.19k\Omega) \| 62.4k\Omega\right)\left(\frac{3.19k\Omega}{3.19k\Omega + 50k\Omega}\right)$$

$$T = 8.17 \quad | \quad A_{tr} = A_{tr}^{Ideal} \frac{T}{1+T} = -50k\Omega \frac{8.17}{1+8.17} = -44.5\ k\Omega$$

$$R_{in}^D = r'_\pi \| (R_F + R_C \| r_o) = 3.19k\Omega \| (50k\Omega + 5k\Omega \| 62.4k\Omega) = 3.01\ k\Omega \quad | \quad T_{SC} = 0 \quad | \quad |T_{OC}| = |T|$$

$$R_{in} = 3.01k\Omega \frac{1+0}{1+8.17} = 328\ \Omega$$

$$R_{out}^D = R_C \| r_o \| (R_F + r'_\pi) = 5k\Omega \| 62.4k\Omega \| (50k\Omega + 3.19k\Omega) = 4.26\ k\Omega \quad | \quad T_{SC} = 0 \quad | \quad |T_{OC}| = |T|$$

$$R_{out} = 4.26k\Omega \frac{1+0}{1+8.17} = 463\ \Omega$$

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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 is the same: $|T| = 306 \quad | \quad A_v^{Ideal} = 1 \quad | \quad A_v = A_{tr}^{Ideal}\dfrac{T}{1+T} = 1\left(\dfrac{306}{1+306}\right) = 0.997$

$$R_{out}^D = R_F \| \frac{1}{g_{m5}} = 10k\Omega \| \frac{1}{3.16mS} = 307\ \Omega \quad | \quad T_{SC} = 0 \quad | \quad |T_{OC}| = |T|$$

$$R_{out} = 307\Omega\frac{1+0}{1+306} = 1.00\ \Omega$$

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T is the same: $|T| = 306 \quad | \quad A_v^{Ideal} = 1 \quad | \quad A_v = A_{tr}^{Ideal}\dfrac{T}{1+T} = 1\left(\dfrac{306}{1+306}\right) = 0.997$

$$R_{in}^D = r_{o1}\left(1 + g_{m1}\frac{2}{g_{m2}}\right) \| \frac{1}{g_{m3}} = 600k\Omega \| \frac{1}{2.00mS} = 500\ \Omega \quad | \quad |T_{OC}| = 306$$

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: $|T| = 152$ | $A_v^{Ideal} = -\frac{R_2}{R_I} = -1$ | $A_v = A_{tr}^{Ideal}\frac{T}{1+T} = -1\left(\frac{152}{1+152}\right) = -0.993$

$R_{out}^D = (R_2 + R_I)\|R_1\|\frac{1}{g_{m5}} = 40k\Omega\|10k\Omega\|\frac{1}{3.16mS} = 304\ \Omega$ | $T_{SC} = 0$ | $|T_{OC}| = |T| = 152$

$R_{out} = 304\Omega\frac{1+0}{1+152} = 1.99\ \Omega$

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There are approximately 15 cycles in 0.8 μsec : $f \cong \frac{15cycles}{0.8us} = 18.8\ MHz$

$f_T = \frac{1}{2\pi}\frac{g_m}{C_{GS}+C_{GD}}$ | $g_m = \sqrt{2K_nI_D}$ | $f_{T2} = f_{T1} = \frac{1}{2\pi}\frac{\sqrt{2(0.01)(0.0005)}}{5pf + 1pF} = 83.9\ MHz$

$f_{T3} = \frac{1}{2\pi}\frac{\sqrt{2(0.004)(0.0005)}}{5pf + 1pF} = 53.1\ MHz$ | $f_{T4} = \frac{1}{2\pi}\frac{\sqrt{2(0.01)(0.002)}}{5pf + 1pF} = 168\ MHz$

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

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

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

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

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

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

(a) $I_{D5} = I_{D4} = 500\ \mu A$ | $I_{D6} = 1\ mA$ | Current error $\Delta I = 500\mu A$ | $g_m \propto \sqrt{W/L}$

$$V_{OS} = \frac{\Delta I}{G_{m12}} = \frac{\Delta I}{A_{v1}g_{m5}} = \frac{500\mu A}{-192\left(\frac{-4.33mS}{\sqrt{2}}\right)} = +0.85\ mV$$

(b) $I_{D5} = 3I_{D4} = 1.500\ \mu A$ | $I_{D6} = 1\ mA$ | Current error $\Delta I = -500\mu A$ | $g_m \propto \sqrt{W/L}$

$$V_{OS} = \frac{\Delta I}{G_{m12}} = \frac{\Delta I}{A_{v1}g_{m5}} = \frac{-500\mu A}{-192\left(-4.33mS\sqrt{1.5}\right)} = -0.49\ mV$$

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For the Hartley circuit in Fig. 18.34(a), $Z_{gs} = j\omega L_2$ and $Z_s = j\omega L_1$

$$Z_{in} = j\omega L_2\left[1 + g_m\left(j\omega L_1\right)\right] + j\omega L_1 = j\omega\left(L_1 + L_2\right) - \omega^2 g_m L_1 L_2$$

$$\text{Re}\left(Z_{in}\right) = -\omega^2 g_m L_1 L_2$$

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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 $C_{EQ} = C + C_{GS} + 4C_{GD}$.

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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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Three cascaded inverting amplifiers assuming a normal rolloff: $3\phi = -360^o$ | $\phi = -120^o$
