

# Microelectronic Circuit Design

## Fifth Edition - Part III

### Solutions to Exercises

Updated - 07/20/15

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## CHAPTER 10

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### Page 522

$$(a) A_p = |A_v||A_i| = 4 \times 10^4 (2.75 \times 10^8) = 1.10 \times 10^{13}$$

$$(b) V_o = \sqrt{2P_o R_L} = \sqrt{2(20W)(16\Omega)} = 25.3 \text{ V} \quad | \quad A_v = \frac{V_o}{V_i} = \frac{25.3V}{0.005V} = 5.06 \times 10^3$$

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

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

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$$A_{vdB} = 20 \log(5060) = 74.1 \text{ dB} \quad | \quad A_{idB} = 20 \log(9.48 \times 10^6) = 140 \text{ dB} \quad | \quad A_{pdB} = 10 \log(4.80 \times 10^{10}) = 107 \text{ dB}$$

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

### Page 529

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

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

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

**Page 530**

$$R_{in} = \infty \rightarrow I_1 = 0 \quad | \quad I_o \neq 0 \rightarrow A_i = \infty$$

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$$A_p = A_v A_i = A_v \left( A_v \frac{R_I + R_{in}}{R_L} \right) = A_v^2 \left( \frac{R_I + R_{in}}{R_L} \right)$$

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$$V_o = \sqrt{2PR_L} = \sqrt{2(100W)(8\Omega)} = 40 \text{ V} \quad | \quad V_o = AV_i \left( \frac{R_{in}}{R_I + R_{in}} \right) \left( \frac{R_L}{R_{out} + R_L} \right)$$

$$A = \frac{V_o}{V_i} \left( \frac{R_I + R_{in}}{R_{in}} \right) \left( \frac{R_{out} + R_L}{R_L} \right) = \frac{40V}{0.001V} \left( \frac{5k\Omega + 50k\Omega}{50k\Omega} \right) \left( \frac{0.5\Omega + 8\Omega}{8\Omega} \right) = 4.68 \times 10^4$$

$$A_{db} = 20 \log(4.68 \times 10^4) = 93.4 \text{ dB} \quad | \quad P = \frac{I_o^2}{2} R_{out} = \left( \frac{40V}{8\Omega} \right)^2 \frac{0.5\Omega}{2} = 6.25 \text{ W}$$

$$A_i = \frac{I_o}{I_i} = \frac{I_o}{V_i} (R_I + R_{in}) = \frac{5V}{0.001V} (5k\Omega + 50k\Omega) = 2.75 \times 10^8$$

$$A_{db} = 20 \log(2.75 \times 10^8) = 169 \text{ dB}$$

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$$A = \frac{40V}{0.001V} \left( \frac{5k\Omega + 5k\Omega}{5k\Omega} \right) \left( \frac{8\Omega + 8\Omega}{8\Omega} \right) = 1.6 \times 10^5 \quad | \quad A_{db} = 20 \log(1.6 \times 10^5) = 104 \text{ dB}$$

$$P = \frac{I_o^2}{2} R_{out} = \left( \frac{40V}{8\Omega} \right)^2 \frac{8\Omega}{2} = 100 \text{ W!} \quad | \quad A_i = \frac{5V}{0.001V} (5k\Omega + 5k\Omega) = 5 \times 10^7 \quad (154 \text{ dB})$$

**Page 535**

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

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

$$v_{ID} = V_{ID} + v_{id} \quad | \quad -0.5 \text{ V} \leq 0.5 \text{ V} + v_{id} \rightarrow v_{id} \geq -1 \text{ V} \quad \text{and} \quad 0.5 \text{ V} + v_{id} \leq 1.5 \rightarrow v_{id} \leq +1 \text{ V}$$

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

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

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$$v_o = 10(v_{ID} - 0.5V) = 10(-0.5 + 0.25 + 0.75 \sin 1000\pi t) = (-2.5 + 7.5 \sin 1000\pi t) \text{ V} \quad | \quad V_o = -2.5 \text{ V}$$

**Page 540**

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

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


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**Page 542**

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

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


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**Page 544**

$$I_1 = \frac{2V}{4.7k\Omega} = 426 \text{ } \mu A \quad | \quad I_2 = I_1 = 426 \text{ } \mu A \quad | \quad I_o = -I_2 = -426 \text{ } \mu A$$

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


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**Page 546**

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

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


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**Page 548**

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

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

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

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$$A_v = 10^{54} = 501 \quad 1 + \frac{R_2}{R_1} = 501 \quad \frac{R_2}{R_1} = 500 \quad i_o = \frac{v_o}{R_2 + R_1} \quad \frac{10}{R_2 + R_1} \leq 0.1 \text{ mA}$$

$R_1 + R_2 \geq 100k\Omega$     $501R_1 \geq 100k\Omega \rightarrow R_1 \geq 200 \Omega$    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  $0.1 \text{ mA}$  in the first case.

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**Page 551**

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

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

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

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

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

**Page 552**

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

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

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

**Page 555**

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

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

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

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

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

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

**Page 558**

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

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


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**Page 559**

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


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**Page 561**

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


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**Page 562**

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


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**Page 564**

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

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

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

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

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

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

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

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

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

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

**Page 565**

$$A_v(s) = -\frac{2 \times 10^7 s}{(s+100)(s+50000)} = \frac{-400}{\left(1 + \frac{100}{s}\right)\left(1 + \frac{s}{50000}\right)}$$

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

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

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

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

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

**Page 568**

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

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

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

**Page 570**

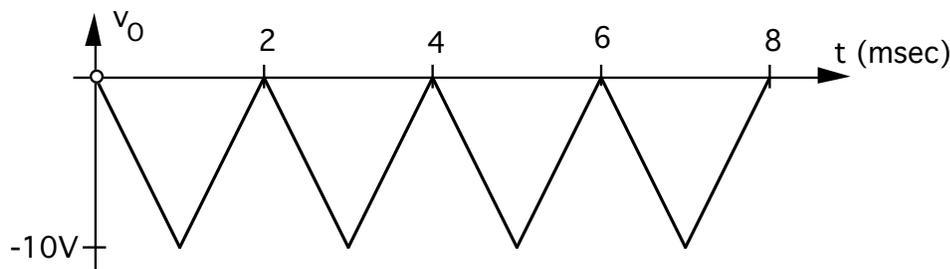
$$A_v = -\frac{R_2}{R_1} = -10^{\frac{20}{20}} = -10.0 \quad | \quad R_1 = R_{in} = 18 \text{ k}\Omega$$

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

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

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



**Page 574**

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

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# CHAPTER 11

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## Page 592

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

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

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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](http://www.jaegerblalock.com) or [www.analog.com](http://www.analog.com))

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Values taken from OP - 27 specification sheet  
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## Page 593

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

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

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

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

**Page 595**

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

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**Page 596**

$$1 + T = \frac{R_o}{R_{out}} \rightarrow T = \frac{50\Omega}{0.1\Omega} - 1 = 499 \quad | \quad A = T \left( \frac{1}{\beta} \right) = 499(40) = 2.00 \times 10^4$$

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

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

**Page 597**

$$1 + T = \frac{R_o}{R_{out}} \rightarrow T = \frac{200\Omega}{0.1\Omega} - 1 = 1999 \quad | \quad A = T \left( \frac{1}{\beta} \right) = 1999(100) = 2.00 \times 10^5 \text{ or } 106 \text{ dB}$$

**Page 599**

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

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**Page 600**

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

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

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

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

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

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

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

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

**Page 601**

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


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Page 609

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

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

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

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

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

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

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

---

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

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

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

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

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

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

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

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

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

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Continued on next page.

Page 609 cont.

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

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

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

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

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

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

---

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

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

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

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

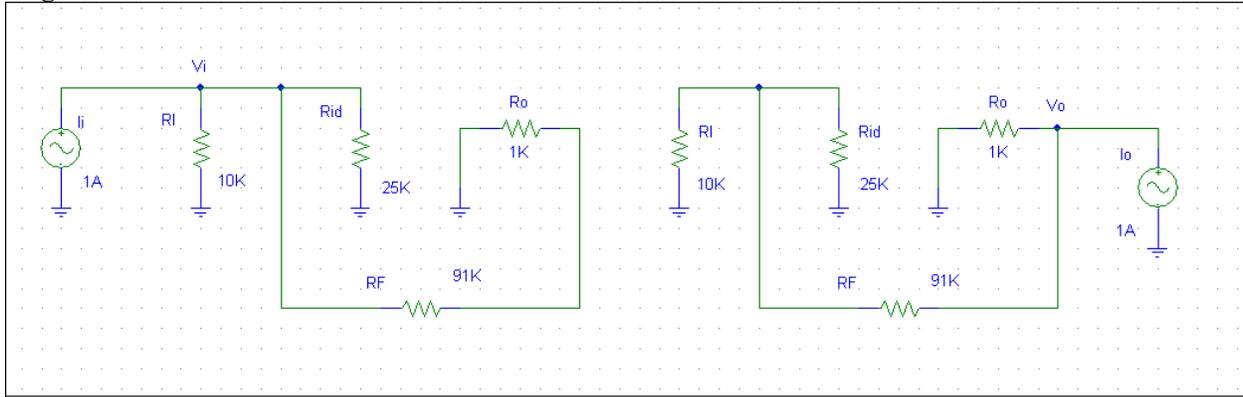
$$R_{th} = R_1 \parallel (R_2 + R_o) = 10k\Omega \parallel (91k\Omega + 1k\Omega) = 9.02 k\Omega$$

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

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

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

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



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

Page 615

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

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

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

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

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

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

---

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

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

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

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

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

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

**Page 620**

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

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

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

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

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

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

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


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**Page 624**

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

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

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

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

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

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

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

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


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**Page 625**

$$R'_{id} = R_1 \parallel R_{id} = 10k\Omega \parallel 25k\Omega = 7.14 k\Omega$$

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

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

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

$$T = A_o \frac{[R_1 \parallel (R_2 + R'_{id})]}{R_1 \parallel (R_2 + R'_{id}) + R_o} \left( \frac{R'_{id}}{R_2 + R'_{id}} \right)$$

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

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

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

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

**Page 630:**

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

**Page 631**

Values taken from op - amp specification sheets ([www.jaegerblalock.com](http://www.jaegerblalock.com) or [www.analog.com](http://www.analog.com))

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$$|V_o| \leq 50(0.002V) \rightarrow -0.100 V \leq V_o \leq +0.100 V$$

**Page 634**

Values taken from op - amp specification sheets (via [www.jaegerblalock.com](http://www.jaegerblalock.com) or [www.analog.com](http://www.analog.com))

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

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

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

**Page 635**

Values taken from op - amp specification sheets (via [www.jaegerblalock.com](http://www.jaegerblalock.com) or [www.analog.com](http://www.analog.com))

**Page 637**

Values taken from op-amp specification sheets (via [www.jaegerblalock.com](http://www.jaegerblalock.com) or [www.analog.com](http://www.analog.com))

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

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

A few possibilities: 27 k $\Omega$  and 3 k $\Omega$ , 270 k $\Omega$  and 30 k $\Omega$ , 180 k $\Omega$  and 20 k $\Omega$ , etc.

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

**Page 638**

Values taken from op - amp specification sheets (via [www.jaegerblalock.com](http://www.jaegerblalock.com) or [www.analog.com](http://www.analog.com))

**Page 641**

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

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

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

**Page 643**

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

**Page 644**

$$GE = FGE(A_v) \leq 5 \times 10^{-5}(1) = 5 \times 10^{-5} \quad \text{Worst case occurs for negative CMRR: } GE \cong \frac{1}{A} + \frac{1}{CMRR}$$

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

$$\text{For other cases: } CMRR = \left(5 \times 10^{-5} - \frac{1}{A}\right)^{-1} \quad \text{or} \quad A = \left(5 \times 10^{-5} - \frac{1}{CMRR}\right)^{-1}$$

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

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

**Page 645**

Values taken from op - amp specification sheets (via [www.jaegerblalock.com](http://www.jaegerblalock.com) or [www.analog.com](http://www.analog.com))

**Page 649**

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

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

---

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

**Page 652**

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

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

---

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

**Page 654**

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

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

---

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

**Page 655**

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

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

**Page 657**

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

**Page 658**

Values taken from op - amp specification sheets (via [www.jaegerblalock.com](http://www.jaegerblalock.com) or [www.analog.com](http://www.analog.com))

$$A_o = 1.8 \times 10^6 \quad | \quad f_T = 8 \text{ MHz} \quad | \quad \omega_B = \frac{\omega_T}{A_o} = \frac{2\pi(8 \text{ MHz})}{1.8 \times 10^6} = 8.89\pi \quad | \quad RC = \frac{1}{\omega_B} = \frac{1}{8.89\pi} \text{ s}$$

**Page 665**

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

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

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

---

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

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

**Page 666**

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

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

**Page 670**

From the upper graph, the final value of the first step is 5 mV, and the peak of the response is

approximately  $4mV + 2mV\left(\frac{9.5mm}{11mm}\right) = 5.7mV$ . Overshoot =  $100\% \frac{5.7mV - 5mV}{5mV} = 14\%$

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

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

---

From the lower graph, the final value of the first step is 5 mV, and the peak of the response is

approximately  $5mV + 5mV\left(\frac{10mm}{12mm}\right) = 9.2mV$ . Overshoot =  $100\% \frac{9.2mV - 5mV}{5mV} = 84\%$

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

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

---

The  $\mu A741$  curves will be distorted by slew rate limiting.

# CHAPTER 12

## Page 688

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

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

---

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

---

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

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

## Page 693

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

$$\left[ 1 + \frac{\omega_H^2}{(10000\pi)^2} \right] \left[ 1 + \frac{\omega_H^2}{(20000\pi)^2} \right] = 2 \rightarrow (\omega_H^2)^2 + 4.935 \times 10^9 \omega_H^2 - 3.896 \times 10^{18} = 0$$

$$\omega_H^2 = 6.925 \times 10^8 \rightarrow \omega_H = 26.3 \times 10^3 \rightarrow f_H = \frac{26.3 \times 10^3}{2\pi} = 4190 \text{ Hz}$$

---

$$A_v(0) = -100(66.7)(50) = -3.33 \times 10^5 \quad | \quad |A_v(\omega_H)| = \frac{-3.34 \times 10^5}{\sqrt{2}} = -2.36 \times 10^5$$

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

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

$$\text{Using MATLAB, } \omega_H = 21.7 \times 10^3 \rightarrow f_H = \frac{21.7 \times 10^3}{2\pi} = 3450 \text{ Hz}$$

---

$$A_v(0) = (-30)^3 = -2.70 \times 10^4 \quad | \quad f_H = (33.3 \text{ kHz}) \sqrt[3]{2^{\frac{1}{3}} - 1} = 17.0 \text{ kHz}$$

**Page 699**

$$A_{v1} = 1 + \frac{130k\Omega}{22k\Omega} = 6.909 \quad | \quad v_{o1} = 0.001(6.909) = 6.91 \text{ mV} \quad | \quad v_{o2} = 0.001V(6.909)^2 = 47.7 \text{ mV}$$

$$v_{o3} = 0.001(6.909)^3 = 330 \text{ mV} \quad | \quad v_{o4} = 0.001V(6.909)^4 = 2.28 \text{ V}$$

$$v_{o5} = 0.001V(6.909)^5 = 15.7 \text{ V} > 15 \text{ V}. \quad \therefore v_{o5} = V_O^{\max} = 15 \text{ V}$$

$$v_{o6} = 15V(6.909) = 104 \text{ V} > 15 \text{ V}. \quad \therefore v_{o6} = V_O^{\max} = 15 \text{ V}$$

**Page 702**

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

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

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

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

**Page 705**

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

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

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

---

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

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

---

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

**Page 706**

To decrease the cutoff frequency from 5 kHz to 2 kHz, we must increase the

resistances by a factor of  $\frac{5\text{kHz}}{2\text{kHz}} = 2.50 \rightarrow R_1 = R_2 = 2.50(2.26\text{k}\Omega) = 5.65\text{ k}\Omega$

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

---

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

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

**Page 707**

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

---

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

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

**Page 708**

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

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

**Page 709**

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

$$S_{C_1}^Q = \frac{C_1}{Q} \frac{dQ}{dC_1} = \frac{C_1}{Q} \left[ \frac{1}{2\sqrt{C_1 C_2}} \frac{\sqrt{R_1 R_2}}{R_1 + R_2} \right] = \frac{C_1}{Q} \frac{Q}{2C_1} = 0.5$$

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

---

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

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

---

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

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

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

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

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

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

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

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

**Page 712**

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

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

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

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

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

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

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

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

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

**Page 714**

$$\Delta v_o = -\frac{C_1}{C_2} V_1 = -\frac{2pF}{0.5pF} 0.1V = -0.4 V$$

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

**Page 716**

$$f_o = \frac{1}{2\pi} f_c \sqrt{\frac{C_3 C_4}{C_1 C_2}} = \frac{200kHz}{2\pi} \sqrt{\frac{4pF(0.25pF)}{3pF(3pF)}} = 10.6 \text{ kHz}$$

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

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

**Page 719**

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


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**Page 720**

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

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


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**Page 722**

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


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**Page 723**

$$2R = 1 \text{ k}\Omega \quad | \quad 4R = 2 \text{ k}\Omega \quad | \quad 8R = 4 \text{ k}\Omega \quad | \quad 16R = 8 \text{ k}\Omega \quad | \quad 32R = 16 \text{ k}\Omega \quad | \quad 64R = 32 \text{ k}\Omega$$

$$128R = 64 \text{ k}\Omega \quad | \quad 256R = 128 \text{ k}\Omega \quad | \quad R = 500 \text{ }\Omega$$


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**Page 724**

$$R_{Total} = R + 2R + 2R + (n-1)(2R + R) = (3n+2)R \quad | \quad R_{Total} = (3 \times 8 + 2)(1 \text{ k}\Omega) = 26 \text{ k}\Omega$$

---

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

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

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


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**Page 725**

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

$$(2^1 + 2^2 + \dots + 2^n) = 2(2^0 + 2^1 + \dots + 2^{n-1}) = 2(2^n - 1) = 2^{n+1} - 2$$

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


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**Page 726**

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

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

$$(c) A = \frac{25 \text{ pF}}{5 \text{ fF}/\mu\text{m}^2} = \frac{25 \times 10^{-12}}{5 \times 10^{-15}} \mu\text{m}^2 = 5000 \mu\text{m}^2$$


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**Page 727**

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

**Page 729**

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

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

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

$$DNL = 2.5 - 1 = 1.5 \text{ LSB}$$

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

$$\therefore INL = 1 \text{ LSB}$$

**Page 730**

$$T_T^{\max} = \frac{2^n}{f_C} = \frac{2^{12}}{2 \times 10^6} = 2.048 \text{ ms} \quad | \quad N_{\max} = \frac{1}{T_T^{\max}} = \frac{1}{2.048 \text{ ms}} = 488 \frac{\text{conversions}}{\text{second}}$$

**Page 731**

$$T_T = \frac{n}{f_C} = \frac{12}{2 \times 10^6} = 6.00 \mu\text{s} \quad | \quad N_{\max} = \frac{1}{T_T} = \frac{1}{6 \mu\text{s}} = 167,000 \frac{\text{conversions}}{\text{second}}$$

**Page 734**

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

**Page 735**

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

**Page 736**

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

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

**Page 744**

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

---

SPICE Results : 15.90 kHz, 3.33 V

**Page 745**

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 747**

$v_S = +2 V$ : 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 748**

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

**Page 750**

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

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

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

**Page 751**

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

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

**Page 752**

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

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

# CHAPTER 13

## Page 773

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

(c)  $R_{in} = \frac{v_{be}}{i_b} = \frac{8mV}{5\mu A} = 1.6 k\Omega$       (d) 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)  $A_{vdB} = 20 \log|-206| = 46.3 dB$

## Page 774

(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,

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

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

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

## Page 775

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

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

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

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

**Page 776**

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

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

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

---

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

**Page 779**

$$R_B = 20 \text{ k}\Omega \parallel 62 \text{ k}\Omega = 15.1 \text{ k}\Omega \quad | \quad R_L = 8.2 \text{ k}\Omega \parallel 100 \text{ k}\Omega = 7.58 \text{ k}\Omega$$

**Page 783**

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

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

---

$$r_d = \frac{0.025 \text{ V}}{1.5 \text{ mA}} = 16.7 \text{ }\Omega \quad | \quad \frac{kT}{q} = \left( 8.62 \times 10^{-5} \frac{\text{V}}{\text{K}} \right) (373 \text{ K}) = 0.0322 \text{ V} \quad | \quad r_d = \frac{0.0322 \text{ V}}{1.5 \text{ mA}} = 21.4 \text{ }\Omega$$

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

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

---

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

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

---

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

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

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

**Page 798**

$A_{v_i} = -g_m R_L = -9.80 \text{ mS}(18 \text{ k}\Omega) = -176$  | 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.

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

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

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

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

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

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

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

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

---

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

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

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

**Page 799**

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

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

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

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$$I_C = I_S \exp\left(\frac{V_{BE}}{V_T}\right) \left(1 + \frac{V_{CB}}{V_A}\right) \quad | \quad V_T = \frac{kT}{q} = \frac{1.38 \times 10^{-23}(300)}{1.6 \times 10^{-19}} = 0.025875V$$

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

**Page 802**

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

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

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

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

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

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

**Page 803**

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

**Page 804**

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

**Page 806**

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

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

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

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

**Page 813**

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

Neglect  $\lambda$  in hand calculations of the Q-point.

$$4.87 = V_{GS} + 12000 I_D \quad | \quad 4.87 = V_{GS} + 12000 \left( \frac{5 \times 10^{-4}}{2} \right) (V_{GS} - 1)^2$$

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

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

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

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$$V_{GS} - V_{TN} \cong \sqrt{\frac{2(241 \mu A)}{2 \times 10^{-3}}} = 0.491 \text{ V} \quad | \quad A_v^{CS} \cong -\frac{12V}{0.491V} = -24.4 \quad | \quad M = \frac{K_{n2}}{K_{n1}} = \frac{2 \times 10^{-3}}{5 \times 10^{-4}} = 4$$

**Page 815**

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

**Page 816**

$$R_{in}^{CS} = 680 \text{ k}\Omega \parallel 1.0 \text{ M}\Omega = 405 \text{ k}\Omega \quad | \quad V_{EQ_{new}} = \frac{680 \text{ k}\Omega}{680 \text{ k}\Omega + 1 \text{ M}\Omega} V_{DD} = 0.405 V_{DD}$$

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

**Page 821**

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

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

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

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SPICE Results :

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

**Page 824**

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

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

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

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

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

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

**Page 826**

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

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

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

Limited by the value of  $V_{DS}$ .

# CHAPTER 14

## Page 844

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

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

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

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

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

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

Neglect  $\lambda$  in hand calculations of the Q-point.

$$4.87 = V_{GS} + 12000I_D \quad | \quad 4.87 = V_{GS} + 12000\left(\frac{5 \times 10^{-4}}{2}\right)(V_{GS} - 1)^2$$

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

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

$$g_m = \sqrt{2K_n I_D} = \sqrt{2(5 \times 10^{-4})(2.41 \times 10^{-4})} = 0.491mS \quad | \quad r_o = \frac{\lambda^{-1} + V_{CE}}{I_C} = \frac{53.8V}{0.241mA} = 223k\Omega$$

$$\mu_f = g_m r_o = 110$$

## Page 845

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

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

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

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

**Page 847**

$$R_7 = 2 \text{ k}\Omega \quad | \quad R_6 = 13 \text{ k}\Omega \quad | \quad R_L = 22 \text{ k}\Omega \parallel 100 \text{ k}\Omega = 18.0 \text{ k}\Omega$$

$$R_7 = 2 \text{ k}\Omega \quad | \quad R_6 = 12 \text{ k}\Omega \quad | \quad R_L = 22 \text{ k}\Omega \parallel 100 \text{ k}\Omega = 18.0 \text{ k}\Omega$$

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**Page 859**

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

$$\text{For large } g_m R_E, \quad A_{vt}^{CE} = -\frac{g_m R_L}{1 + g_m R_E} \cong -\frac{R_L}{R_E} = -\frac{R_C \parallel R_3}{R_E}$$

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

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

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

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

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

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

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

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

(b) Assume the collector current does not change.

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

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

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

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

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

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

Continued on the next page

Page 859 cont.

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

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

---

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

Page 861

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

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

---

$$I_C = I_S \exp\left(\frac{V_{BE}}{V_T}\right) \left( 1 + \frac{V_{CB}}{V_A} \right) \quad | \quad V_T = \frac{kT}{q} = \frac{1.38 \times 10^{-23}(300)}{1.60 \times 10^{-19}} = .025875 V$$

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

---

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

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

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

**Page 868**

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

Neglect  $\lambda$  in hand calculations of the Q - point.

$$4.87 = V_{GS} + 12000 I_D \quad | \quad 4.87 = V_{GS} + 12000 \left( \frac{5 \times 10^{-4}}{2} \right) (V_{GS} - 1)^2$$

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

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

---

$$A_{v_{dB}}^{CS} = 20 \log |-4.50| = -13.1 dB$$

---

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

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

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

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

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

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

**Page 869**

$$V_T = \left( \frac{1.381 \times 10^{-23} V}{1.602 \times 10^{-19} K} \right) (273 K + 27 K) = 25.861 mV \quad | \quad I_S = \frac{I_C}{\exp\left(\frac{V_{BE}}{V_T}\right)} = \frac{245 \mu A}{\exp\left(\frac{0.700 V}{0.025861 V}\right)} = 0.430 fA$$

---

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

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

**Page 873**

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

$$v_i \leq 0.005V(1 + g_m R_L) \frac{R_I + R_B \parallel R_{iB}}{R_B \parallel R_{iB}} = 0.005V [1 + 10mS(11.5k\Omega)] \frac{2k\Omega + 95.4k\Omega}{95.4k\Omega} = 0.592 V$$

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

**Page 878**

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

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

---

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

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

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

---

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

**Page 881**

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

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

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

$$\text{Neglecting } R_6, \quad v_i \leq 0.2(V_{GS} - V_{TN})(1 + g_m R_I) = 0.2(0.982) [1 + 0.491mS(2k\Omega)] = 389 mV$$

**Page 882**

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

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

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

**Page 886**

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

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

---

The voltage gains are proportional to the load resistance

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

---

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

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

---

$$R_{iE} \cong \frac{1}{g_m} = \frac{1}{40I_C} \quad | \quad R_{iS} = \frac{1}{g_m} = \frac{V_{GS} - V_{TN}}{2I_D} \quad | \quad \frac{R_{iE}}{R_{iS}} = \frac{1}{40I_C} \left( \frac{2I_D}{V_{GS} - V_{TN}} \right) = \frac{2}{40(1)} = \frac{1}{20}$$

**Page 893**

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

**Page 895**

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

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

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

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

---

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

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

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

Q-point:  $(1.65 \text{ V}, 932 \text{ } \mu\text{A})$

**Page 898**

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

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

---

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

**Page 902**

Common – Emitter :

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

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

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

Common – Source :

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

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

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

**Page 905**

Common – Collector :

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

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

Common – Drain :

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

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

**Page 908**

Common – Base:

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

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

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

Common – Gate:

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

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

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

**Page 909**

(a) Common – Source :

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

(b) Common – Collector :

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

(c) Common – Gate :

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

**Page 913**

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

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

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

---

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

---

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

---

$$\frac{W}{L} = \frac{K_n}{K'_n} = \frac{2 \times 10^{-2}}{5 \times 10^{-5}} = \frac{400}{1}$$

**Page 914**

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

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

**Page 917**

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  $v_c \geq 0$ .  $V_c = 5 - I_C R_C = 2.29 V \quad \therefore |v_c| \leq 2.29 V$

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

---

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

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

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

---

$$f_1 = \frac{1}{2\pi(R_1 + R_{in})C_1} = \frac{1}{2\pi(75\Omega + 75.1\Omega)(0.022\mu F)} = 48.2 kHz$$

$$f_2 = \frac{1}{2\pi(R_3 + R_{out})C_2} = \frac{1}{2\pi(100k\Omega + 8.2k\Omega)(33pF)} = 44.6 kHz$$

We have two almost identical poles and can estimate  $f_L$  by applying the bandwidth shrinkage factor

$$\text{from Table 14.13 to the mean of the two frequencies: } f_L \cong 1.55 \left( \frac{48.2 + 44.6}{2} \right) kHz = 72 kHz$$

$$\text{Using the design value: } f_L \cong 1.55 \left( \frac{50 + 50}{2} \right) kHz = 77.5 kHz$$

**Page 918**

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

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

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

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

---

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

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

---

$$f_1 = \frac{1}{2\pi(R_I + R_{in})C_1} = \frac{1}{2\pi(75\Omega + 75\Omega)(0.022\mu F)} = 48.2 \text{ kHz}$$

$$f_2 = \frac{1}{2\pi(R_7 + R_{out})C_2} = \frac{1}{2\pi(100k\Omega + 100k\Omega)(20pF)} = 39.8 \text{ kHz}$$

$$f_3 = \frac{1}{2\pi(R_s \parallel 1/g_m)C_3} = \frac{1}{2\pi(9.1k\Omega \parallel 500\Omega)(0.0068\mu F)} = 49.4 \text{ kHz}$$

We have three almost identical poles and can estimate  $f_L$  by applying the bandwidth shrinkage factor from Table 14.13 to the mean of the three frequencies:  $f_L \cong 1.95 \left( \frac{48.2 + 39.8 + 49.4}{3} \right) \text{ kHz} = 89 \text{ kHz}$

---

$$r_o \cong r_o = \frac{1}{\lambda I_D} = \frac{1}{0.015(2 \times 10^{-4})} = 333 \text{ k}\Omega$$

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

$$r_o = \frac{1}{\lambda} + \frac{V_{DS}}{I_D} = \frac{1}{0.015} + \frac{3.18}{2 \times 10^{-4}} = 349 \text{ k}\Omega \quad | \quad R_L = 100k\Omega \parallel 100k\Omega \parallel 349k\Omega = 43.7 \text{ k}\Omega$$

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

---

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

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

$$R_D = 66.7 \text{ k}\Omega \rightarrow 68 \text{ k}\Omega \quad | \quad C_1 \text{ remains unchanged.}$$

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

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

---

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

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

**Page 925**

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

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

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

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

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

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

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

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

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

---

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

**Page 927**

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

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

$$20 \log(898) = 59.1 \text{ dB}$$

---

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

---

$$A_v = -10\text{mS}(2.39\text{k}\Omega)(-62.8\text{mS})(19.8\text{k}\Omega)(0.95)(0.99) = 28000$$

**Page 932**

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

---

Note that the answers are obtained directly from SPICE.

---

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

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

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# CHAPTER 15

**Page 956**

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

---

$$I_C = \alpha_F I_E = \frac{60}{61} \left[ \frac{15 - V_{BE}}{2(75k\Omega)} \right] \quad \text{and} \quad V_{BE} = 0.025V \ln \left( \frac{I_C}{0.5 \times 10^{-15} A} \right) \rightarrow I_C = 94.7 \mu A, \quad V_{BE} = 0.649 V$$

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

**Page 958**

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

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

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

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

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

**Page 963**

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

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

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

**Page 966**

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

**Page 967**

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

**Page 970**

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

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

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

Q - point : (100  $\mu A$ , 8.75 V)

**Page 974**

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

$$i_{dm} = g_m v_{dm} = 40(37.5\mu A)v_{dm} = 1.5 \times 10^{-3} v_{dm} \quad | \quad i_{cm} \cong \frac{v_{cm}}{2R_{EE}} = \frac{v_{cm}}{2M\Omega} = 5.00 \times 10^{-7} v_{cm}$$

**Page 978**

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

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

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

**Page 981**

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

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

---

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

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

---

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

**Page 982**

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

**Page 983**

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

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

---

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

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

---

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

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

**Page 988**

$$A_{v1} = -3.50 \quad | \quad A_{v2} = -22mS(150k\Omega \parallel 162k\Omega \parallel 203k\Omega) = -1238$$

$$A_{v3} = \frac{0.198S(2k\Omega \parallel 18k\Omega)}{1 + 0.198S(2k\Omega \parallel 18k\Omega)} = 0.9971 \quad | \quad A_{dm} = -3.50(-1238)(0.9971) = 4320$$

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

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

---

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

$$r_{\pi 3} = \frac{150}{40(533\mu A)} = 7.04 k\Omega \quad | \quad A_{v2} = -20(49.7\mu A)(15.2k\Omega \parallel 7.04k\Omega) = -4.68$$

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

$$A_{v2} = -40(533\mu A) \left[ 168k\Omega \parallel 755 + 151(2k\Omega) \right] = -2304$$

$$g_{m4} = 40(4.97mA) = 0.199 S \quad | \quad A_{v3} = \frac{0.199S(2k\Omega)}{1 + 0.199S(2k\Omega)} = 0.998$$

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

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

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

---

$$r_{o3} = \frac{50 + 14.3}{550\mu A} = 117 k\Omega \quad | \quad A_{v2} = -22mS(117k\Omega \parallel 203k\Omega) = -1630 \quad | \quad A_{dm} = -3.50(-1630)(0.998) = 5700$$

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

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

---

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

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

**Page 990**

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

$$A_{v1} = -\frac{1}{2} \sqrt{2(0.005)(100\mu A)(16.3k\Omega)} = -8.16$$

$$A_{v2} = -g_{m3}r_{o3} = -\sqrt{2(0.0025)(0.0005)} \left( \frac{1}{0.01(0.5mA)} \right) = -316$$

$$g_{m4} = \sqrt{2(0.005mA)(0.005mA)} = 7.07 mS \quad | \quad A_{v3} = \frac{7.07mS(2k\Omega)}{1 + 7.07mS(2k\Omega)} = 0.934$$

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

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

---

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

**Page 991**

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

**Page 997**

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

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

---

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

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

**Page 1000**

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

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

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

Page 1008

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

---

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

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

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

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

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

---

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

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

$$R_{out} = \left( \frac{75 + 15 - 8.3}{2 \times 10^{-4}} \right) \left[ 1 + \frac{150(40.0k\Omega)}{180k\Omega + 18.75k\Omega + 40.0k\Omega} \right] = 10.7 M\Omega$$

Page 1011

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

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

---

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

---

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

---

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

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

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

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

$$R_{out} \cong \mu_f R_s \cong \frac{1}{0.01} \sqrt{\frac{2(2.49 \times 10^{-3})}{189 \times 10^{-6}}} [1 + 0.01(11.6)](18k\Omega) = 10.3 \text{ M}\Omega$$

# CHAPTER 16

## Page 1033

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

## Page 1036

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

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

---

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

## Page 1037

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

---

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

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

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

## Page 1039

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

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

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

**Page 1040**

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

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

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

**Page 1041**

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

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

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

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

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

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

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

**Page 1042**

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

**Page 1043**

MOS

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

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

BJT

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

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

**Page 1044**

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

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

**Page 1045**

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

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

**Page 1046**

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

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


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**Page 1047**

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

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


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**Page 1048**

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

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

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


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**Page 1051**

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

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

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


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**Page 1053**

$$V_{DS2} = V_{GS2} = 0.8V + \sqrt{\frac{2(5 \times 10^{-5})}{2.5 \times 10^{-4}}} = 1.43V \quad | \quad V_{DS4} = 15 - 1.43 = 13.6V$$

$$R_{out} \cong \mu_{f4} r_{o2} = \sqrt{2(2.5 \times 10^{-4})(5 \times 10^{-5})[1 + 0.015(13.6)]} \left( \frac{1}{\frac{0.015}{50 \mu A} V + 13.6V} \right) \left( \frac{1}{\frac{0.015}{50 \mu A} V + 1.43V} \right) = 379 M\Omega$$

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

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

**Page 1057**

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

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

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

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

$$(W/L)_2 = (W/L)_4 = \frac{2.5 \times 10^{-3}}{5 \times 10^{-5}} = \frac{50}{1} \quad | \quad (W/L)_3 = (W/L)_1 = \frac{1}{2} \left( \frac{50}{1} \right) = \frac{25}{1}$$

**Page 1058**

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

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

$$I_{D2} = I_{D1} = \frac{4 \times 10^{-4}}{2} (1.667 - 1)^2 = 89.0 \mu A \quad | \quad I_{D2} = I_{D1} = \frac{4 \times 10^{-4}}{2} (2.5 - 1)^2 = 450 \mu A$$

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

**Page 1059**

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

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

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

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

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

$$(b) \quad TC = 3300 \text{ ppm}/^\circ C - (-2000 \text{ ppm}/^\circ C) = 5300 \text{ ppm}/^\circ C$$

**Page 1061**

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

**Page 1062**

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

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

**Page 1066**

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

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

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

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

The other resistors remain the same.

**Page 1069**

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

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

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

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

$$G_m = g_{m1} = \sqrt{2(2.5 \times 10^{-4})(1.25 \times 10^{-4})} = 250\mu S$$

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

**Page 1070**

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

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

**Page 1074**

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

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

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

**Page 1075**

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

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

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

**Page 1076**

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

**Page 1081**

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

$A_{dm} \cong 5(1500)(1) = 7500$  assuming the input resistance of the emitter followers is much greater than

$$r_{o5} \text{ and } V_{A8} = V_{A5}. \text{ Checking: } r_{o5} \cong \frac{60V + 14.7V}{500\mu A} = 149 \text{ k}\Omega \quad | \quad R_{iB6} \cong \beta_{o6}R_L = 300 \text{ M}\Omega$$

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

**Page 1083**

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

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

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

**Page 1087**

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

**Page 1090**

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

**Page 1092**

$$A_{v1} = -1.46 \times 10^{-4} (6.54 \text{ M}\Omega \parallel R_{in11}) = -1.46 \times 10^{-4} (6.54 \text{ M}\Omega \parallel 20.7 \text{ k}\Omega) = -3.01$$

**Page 1094**

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

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

$$R_{m12} = \frac{50(0.025V)}{0.216mA} + 51(79.4k\Omega) = 4.06 M\Omega$$

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

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

---

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

**Page 1097**

$$v_o = \left( \frac{R}{I_{EE} R_1 R_3} \right) v_1 v_2 = K_M v_1 v_2 \quad | \quad K_M = \frac{|v_o|}{|v_1 v_2|} = \frac{5}{5^2} = 0.2 \quad | \quad K_M = \frac{|v_o|}{|v_1 v_2|} = \frac{1}{1^2} = 1$$

# CHAPTER 17

**Page 1116**

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

**Page 1117**

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

**Page 1118**

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

**Page 1119**

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

**Page 1124**

The value of  $C_3$  does not change  $A_{mid}$ ,  $\omega_{p1}$ ,  $\omega_{p2}$ ,  $\omega_{z1}$ , or  $\omega_{z2}$ .

$$\omega_{p3} = -\frac{1}{2\mu F \left(1.3k\Omega \parallel \frac{1}{1.23mS}\right)} = -1000 \text{ rad/s} \quad | \quad \omega_{z3} = -\frac{1}{2\mu F (1.3k\Omega)} = -385 \text{ rad/s}$$

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

---

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

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

---

$$\omega_{p2} = -\frac{1}{0.1\mu F (4.3k\Omega \parallel 57.5k\Omega + 100k\Omega)} = -96.2 \text{ rad/s}$$

$$f_L = \frac{1}{2\pi} \sqrt{41.0^2 + 96.2^2 + 202^2 - 2(0^2 + 0^2 + 76.9^2)} = 31.8 \text{ Hz}$$

**Page 1127**

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

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

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

**Page 1129**

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

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

$r_o$  is responsible for most of the discrepancy.  $r_{\pi}$  and  $\beta_o$  will also differ from our hand calculations. Note that 45% of the gain is lost because of the amplifier's low input resistance.

---

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

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

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

**Page 1131**

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

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

$$A_{mid} = \frac{43\text{k}\Omega \parallel 250\Omega}{100\Omega + 43\text{k}\Omega \parallel 250\Omega} (4.00\text{mS})(22\text{k}\Omega \parallel 75\text{k}\Omega) = 48.5$$

---

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

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

**Page 1132**

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

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

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

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

**Page 1133**

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

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

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

**Page 1137**

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

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

$$(2 \text{ mA}, 5 V): C_\mu = \frac{2pF}{\sqrt{1 + \frac{4.3V}{0.6V}}} = 0.700 \text{ pF} \quad | \quad C_\pi = \frac{40(2 \times 10^{-3})}{2\pi(500MHz)} - 0.700 \times 10^{-12} = 24.8 \text{ pF}$$

$$(50 \text{ mA}, 8 V): C_\mu = \frac{2pF}{\sqrt{1 + \frac{7.3V}{0.6V}}} = 0.551 \text{ pF} \quad | \quad C_\pi = \frac{40(5 \times 10^{-2})}{2\pi(500MHz)} - 0.551 \times 10^{-12} = 636 \text{ pF}$$

**Page 1140**

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

---

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

---

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

---

**Page 1142**

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

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

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


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**Page 1152**

The term  $C_L \frac{R_L}{r_{\pi 0}}$  is added to the value of  $C_T$ .

$$C_L \frac{R_L}{r_{\pi 0}} = 3 pF \left( \frac{4120}{656} \right) = 18.8 pF \quad | \quad f_{p1} = \frac{1}{2\pi(656\Omega)(156+18.8)pF} = 1.39 MHz$$

$$f_{p2} = \frac{g_m}{2\pi(C_{\pi} + C_L)} = \frac{0.064S}{2\pi(19.9+3)pF} = 445 MHz$$

---

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

$$C_T = 19.4 + 1 \left[ 1 + 0.064(4120) + \frac{4120}{656} \right] = 290 pF \quad | \quad f_{p1} = \frac{1}{2\pi(656\Omega)290pF} = 837 kHz$$

$$f_{p2} = \frac{g_m}{2\pi C_{\pi}} = \frac{0.064S}{2\pi(19.4pF)} = 525 MHz \quad | \quad f_z = \frac{g_m}{2\pi C_{\mu}} = \frac{0.064S}{2\pi(1pF)} = 10.2 GHz$$

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

---

$$\Delta = s^2 [C_{\pi}(C_{\mu} + C_L) + C_{\mu}C_L] + s [C_{\pi}g_L + C_{\mu}(g_m + g_{\pi 0} + g_L) + C_Lg_{\pi 0}] + g_Lg_{\pi 0}$$

$$C_{\pi} = 19.9 pF \quad C_{\mu} = 0.5 pF \quad C_L = 3 pF \quad r_{\pi 0} = 656 \Omega \quad R_L = 4.12 k\Omega \quad g_m = 64.0 mS$$

$$C_L = 0: \quad 9.95x10^{-24}s^2 + 3.77x10^{-14}s + 3.700x10^{-7} = 0$$

$$\text{MATLAB: roots}([9.950E-24 \ 3.771E-14 \ 3.700E-7]) \rightarrow -3.7801x10^9 \text{rad/s}, -9.8373x10^6 \text{rad/s}$$

$$C_L = 3 pF: \quad 9.95x10^{-24}s^2 + 3.77x10^{-14}s + 3.700x10^{-7} = 0$$

$$\text{MATLAB: roots}([7.115E-23 \ 4.240E-14 \ 3.700E-7]) \rightarrow -5.8707x10^8 \text{rad/s}, -8.8581x10^6 \text{rad/s}$$

---

$$(a) \quad C_T = 10 + 2 \left[ 1 + 1.23mS(4.12k\Omega) + \frac{4120}{996} \right] = 30.4 pF \quad | \quad f_{p1} = \frac{1}{2\pi(996\Omega)30.4pF} = 5.26 MHz$$

$$f_{p2} = \frac{g_m}{2\pi C_{GS}} = \frac{1.23mS}{2\pi(10pF)} = 19.6 MHz \quad | \quad f_z = \frac{g_m}{2\pi C_{GD}} = \frac{1.23mS}{2\pi(2pF)} = 97.9 MHz$$

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

$$(b) \quad C_T = 10 + 2 \left[ 1 + 1.23mS(4.12k\Omega) + \frac{4120}{1296} \right] = 28.5 pF \quad | \quad f_{p1} = \frac{1}{2\pi(1296\Omega)28.5pF} = 4.31 MHz$$

**Page 1160**

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

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

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

$$GBW = 29.3(6.70 \text{ MHz}) = 196 \text{ MHz}$$

**Page 1161**

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

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

**Page 1162**

$$R_{iS} = R_4 \parallel \frac{1}{g_m} = 1.3 \text{ k}\Omega \parallel \frac{1}{3 \text{ mS}} = 265 \text{ }\Omega$$

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

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

**Page 1164**

$$g_m = 40(1.5mA) = 60.0 \text{ mS} \quad r_\pi = \frac{100}{.06} = 1.67 \text{ k}\Omega \quad C_\pi = \frac{60.0mS}{2\pi(500MHz)} - 0.5pF = 18.6 \text{ pF}$$

$$\text{Using Eq. (17.138): } \omega_{P1} = \frac{1}{\left\{ (990\Omega + 150\Omega) \parallel [1.67k\Omega + 101(2.82k\Omega)] \right\} \left[ 0.5pF + \frac{18.6pF}{1 + 60.0mS(2.82k\Omega)} \right]}$$

$$f_{P1} = \frac{\omega_{P1}}{2\pi} = 230 \text{ MHz} \quad | \quad A_{be} = \frac{60.0mS(2.82k\Omega)}{1 + 60.0mS(2.82k\Omega)} = 0.9941$$

$$A_i = \frac{100k\Omega \parallel [150\Omega + 1.67k\Omega + 101(2.82k\Omega)]}{1k\Omega + 100k\Omega \parallel [150\Omega + 1.67k\Omega + 101(2.82k\Omega)]} = 0.9867 \quad | \quad A_v = 0.9867(0.9941) = 0.981$$

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

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

$$(b) f_H \cong \frac{1}{2\pi} \frac{1}{(250\Omega + 1k\Omega \parallel 430k\Omega) \left( 1pF + \frac{10pF}{1 + 3.69} \right)} = 40.7 \text{ MHz}$$

**Page 1166**

$$I_C = \frac{10 - 0.7 \text{ V}}{9.3 \text{ k}\Omega} = 1.00 \text{ mA} \quad | \quad g_m = 40I_C = 40.0 \text{ mS} \quad | \quad r_\pi = \frac{150}{40mS} = 3.75k\Omega$$

$$R_{in} = \frac{R_B \parallel [r_\pi + r_x + (\beta_o + 1)R_E]}{2} = \frac{9.3k\Omega \parallel [0 + 3.75k\Omega + (151)0.2k\Omega]}{2} = 3.65 \text{ k}\Omega$$

$$R_{out} = \frac{1}{2} \left( 2R_L \parallel \frac{r_\pi + r_x + R_B}{\beta_o + 1} \right) = \frac{1}{2} \left( 200 \parallel \frac{3750 + 9300}{151} \right) \Omega = 30.2 \text{ }\Omega$$

$$f_{P1} = \frac{1}{2\pi} \frac{1}{R_B \parallel [r_\pi + r_x + (\beta_o + 1)R_E] \left( C_\mu + \frac{C_\pi}{1 + 2g_m R_L} \right)}$$

$$f_{P1} = \frac{1}{2\pi} \frac{1}{\left\{ 9.3k\Omega \parallel [3.75k\Omega + (151)0.2k\Omega] \right\} \left[ 1.7pF + \frac{15.5pF}{1 + 2(40mS)200\Omega} \right]} = 6.37 \text{ MHz}$$

**Page 1170**

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


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**Page 1171**

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

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

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

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

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


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**Page 1172**

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

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

$$f_{p1} \cong \frac{1}{2\pi r_{\pi 0} (C_\pi + 2C_\mu)} = \frac{1}{2\pi(656\Omega)(19.9 + 1) \text{ pF}} = 11.6 \text{ MHz}$$

$$f_{p2} \cong \frac{1}{2\pi R_L (C_\mu + C_L)} = \frac{1}{2\pi(4120\Omega)(0.5 + 5) \text{ pF}} = 7.02 \text{ MHz}$$


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**Page 1173**

$$f_{p1} \cong \frac{1}{4\pi C_{GGD} r_{o2}} = \frac{0.02(100\mu A)}{4\pi(1 \text{ pF})} = 159 \text{ kHz} \quad | \quad f_{p1} \cong \frac{1}{4\pi C_{GGD} r_{o2}} = \frac{0.02(25\mu A)}{4\pi(1 \text{ pF})} = 39.8 \text{ kHz}$$


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**Page 1181**

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

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

---

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

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

**Page 1186**

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

---

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

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

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

---

$$f_o \text{ is unchanged} \quad | \quad r_o = \frac{50\text{V} + 10\text{V} - 1.6\text{V}}{3.2\text{mA}} = 18.3\text{ k}\Omega \quad | \quad Q = \frac{100\text{k}\Omega \parallel 100\text{k}\Omega \parallel r_o}{2\pi(4.59\text{ MHz})(10\mu\text{H})} = 46.4$$

**Page 1192**

$$L_S \cong \frac{R_{EQ}}{\omega_T} = \frac{L^2 R_{EQ}}{\mu_n(V_{GS} - V_{TN})} = \frac{(5 \times 10^{-5}\text{ cm})^2 75\Omega}{(400\text{ cm}^2/\text{V}\cdot\text{s})(0.25\text{V})} = 1.88 \times 10^{-9}\text{ H}$$

**Page 1194**

$$f_{osc} = 100\text{ MHz} + 10.7\text{ MHz} = 110.7\text{ MHz} \quad f_U = 100\text{ MHz} + 110.7\text{ MHz} = 210.7\text{ MHz}$$

---

$$(a) f_{osc} = 104.7\text{ MHz} \pm 10.7\text{ MHz} \rightarrow 94.0\text{ MHz} \text{ or } 115.4\text{ MHz}$$

$$(b) f_{osc} = 88.1\text{ MHz} \pm 10.7\text{ MHz} \rightarrow 77.4\text{ MHz} \text{ or } 98.8\text{ MHz}$$

**Page 1195**

$$A_{CG} = \frac{1}{A} \frac{A}{\pi} = \frac{1}{\pi} \quad | \quad 20\log\left(\frac{1}{\pi}\right) = -9.94 \text{ dB}$$


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**Page 1198**

$$A_{CG} = \frac{1}{A} \frac{2A}{\pi} = \frac{2}{\pi} \quad | \quad 20\log\left(\frac{2}{\pi}\right) = -3.92 \text{ dB}$$


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**Page 1199**

From Fig. 17.81(a), the amplitude of the output signal is approximately 70 mV, so the conversion gain is approximately:

$$A_{CG} = \frac{1}{100mV} (0.7) \left( \frac{200mV}{\pi} \right) = \frac{1.4}{\pi} \quad | \quad 20\log\left(\frac{1.4}{\pi}\right) = -7.02 \text{ dB}$$

From Fig. 17.81(b), the spectral components at 46 and 54 kHz have amplitudes of approximately 45 mV, so the conversion gain is:

$$A_{CG} = \frac{45mV}{100mV} = 0.45 \quad | \quad 20\log(0.45) = -6.93 \text{ dB} \quad | \quad \text{Note: } \frac{1.4}{\pi} = 0.446$$


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**Page 1212**

$$f_c - f_m = 20 - 0.01 = 19.99 \text{ MHz} \quad | \quad f_c + f_m = 20 + 0.01 = 20.01 \text{ MHz}$$

$$3f_c - f_m = 60 - 0.01 = 59.99 \text{ MHz} \quad | \quad 3f_c + f_m = 60 + 0.01 = 60.01 \text{ MHz}$$

$$5f_c - f_m = 100 - 0.01 = 99.99 \text{ MHz} \quad | \quad 5f_c + f_m = 100 + 0.01 = 100.01 \text{ MHz}$$

---

$$A_{f_c+f_m} = A_{f_c-f_m} = 3 \text{ V}$$

$$A_{3f_c+f_m} = A_{3f_c-f_m} = \frac{A_{f_c-f_m}}{3} = 1 \text{ V}$$

$$A_{5f_c+f_m} = A_{5f_c-f_m} = \frac{A_{f_c-f_m}}{5} = 0.6 \text{ V}$$


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# CHAPTER 18

## Page 1221

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

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

$$(1 \text{ mA}, 5.0 \text{ V}), (1 \text{ mA}, 0.7 \text{ V}), (1 \text{ mA}, 0.7 \text{ V}), (1 \text{ mA}, 5.0 \text{ V})$$

## Page 1223

With the output shorted, current cannot make it around the loop, so  $T_{SC} = 0$ .

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$T_{OC} = 0$  is zero only if  $r_{o1}$  is neglected since the voltage across  $r_{\pi}$  must be zero for  $i_b = 0$ .

If we include  $r_{o1}$ , and start at the base of  $Q_2$  assuming  $r_{o1} \gg \frac{1}{g_{m3}}$  and a current mirror gain of 1:

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

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

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Evaluating Eq. 18.7 without  $R_L$ ,  $T_{OC} = g_{m2} (r_{o1} \| r_{o1} \| R_{iB2}) = 0.04 (55\text{k}\Omega \| 55\text{k}\Omega \| 5.1\text{k}\Omega) = 172$

## Page 1229

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

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

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

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

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

**Page 1231**

$$R_x = R_x^D \frac{1+T_{SC}}{1+T_{OC}} \quad | \quad R_x^D = R_3 \parallel R_{iD1} \parallel R_{iG3} = R_3 \parallel 2r_{o1} \parallel R_{iG3} = 3k\Omega \parallel \infty \parallel \infty = 3k\Omega$$

$$T_{SC} = 0 \quad | \quad T_{OC} = T = 61.1 \quad | \quad R_x = 3k\Omega \left( \frac{1+0}{1+61.1} \right) = 48.3 \Omega$$

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$$I_{D2} = I_{D1} = \frac{I_1}{2} = 0.500 \text{ mA} \quad | \quad I_{D4} = I_2 = 2.00 \text{ mA} \quad | \quad I_{D3} = \frac{1.63V - (-5V)}{13k\Omega} = 0.510 \text{ mA}$$

$$V_{DS1} = 3.5 + V_{GS1} \quad | \quad V_{GS1} = 1 + \sqrt{\frac{2(0.5\text{mA})}{10\text{mA}}} = 1.32 \text{ V} \quad | \quad V_{DS1} = 3.5 + 1.32 = 4.82 \text{ V}$$

$$V_{DS2} = 5 + 1.32 = 6.32 \text{ V} \quad | \quad V_{DS3} = 5 - 1.63 = 3.37 \text{ V} \quad | \quad V_{DS4} = 5 - V_O = 5.00 \text{ V}$$

$(0.5 \text{ mA}, 4.82 \text{ V}), (0.5 \text{ mA}, 6.32 \text{ V}), (0.51 \text{ mA}, 3.37 \text{ V}), (2 \text{ mA}, 5.0 \text{ V})$

**Page 1235**

$$R_i \text{ appears in parallel with } r_\pi: r_\pi' = r_\pi \parallel R_i = 4.69k\Omega \parallel 10k\Omega = 3.19 \text{ k}\Omega$$

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

$$T = 8.17 \quad | \quad A_{vr} = A_{vr}^{ideal} \frac{T}{1+T} = -50k\Omega \frac{8.17}{1+8.17} = -44.5 \text{ k}\Omega$$

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

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

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

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

**Page 1236**

$$A_v = -\left(\frac{R_F}{R_i + R_{in}}\right)\left(\frac{R_L}{R_{out} + R_L}\right) = -\left(\frac{45.1k\Omega}{2k\Omega + 340\Omega}\right)\left(\frac{10k\Omega}{336\Omega + 10k\Omega}\right) = -18.6$$

$$A_v = -\left(\frac{R_F}{R_i + R_{in}}\right)\left(\frac{R_L}{R_{out} + R_L}\right) = -\left(\frac{45.1k\Omega}{10k\Omega + 340\Omega}\right)\left(\frac{2k\Omega}{336\Omega + 2k\Omega}\right) = -3.73$$

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$$T = \frac{-A_v}{R_F + A_v} = \frac{48.5k\Omega}{50k\Omega - 48.5k\Omega} = 32.3 \quad | \quad g_{m3} = \frac{1}{R_{out}}\left(\frac{1}{1+T}\right) = \frac{1}{12\Omega}\left(\frac{1}{1+32.3}\right) = 2.50 \text{ mS}$$

$$R_{in} = \left(R_F + \frac{1}{g_{m3}}\right)\left(\frac{1}{1+T}\right) = \left(50k\Omega + \frac{1}{2.5mS}\right)\left(\frac{1}{1+32.3}\right) = 1.51 \text{ k}\Omega$$

**Page 1240**

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

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

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

**Page 1241**

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

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

Note: The impedance looking in the source of a transistor with a high resistance load of  $r_o$  is  $2/g_m$  rather than  $1/g_m$ .

$$T_{SC} = -\frac{g_{m2}}{2} (2r_{o2} \parallel r_{o4}) \frac{g_{m5} R_F}{1 + g_{m5} R_F} = -\frac{3.16mS}{2} (400k\Omega \parallel 200k\Omega) \frac{3.16mS(10k\Omega)}{1 + 3.16mS(10k\Omega)} = -204$$

$$R_{out} = 500\Omega \frac{1+204}{1+306} = 334 \Omega$$

**Page 1244**

$$T \text{ is the same: } |T| = 152 \quad | \quad A_v^{Ideal} = -\frac{R_2}{R_1} = -1 \quad | \quad A_v = A_{tr}^{Ideal} \frac{T}{1+T} = -1 \left( \frac{152}{1+152} \right) = -0.993$$

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

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

**Page 1246**

$$\text{There are approximately 15 cycles in } 0.8 \mu\text{sec: } f \cong \frac{15 \text{ cycles}}{0.8 \mu\text{s}} = 18.8 \text{ MHz}$$

**Page 1246**

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

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

**Page 1256**

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

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

$$f_B = \frac{1}{2\pi} \left[ \frac{1}{R_o C_C (1 + A_{v2})} \right] = \frac{1}{2\pi} \left[ \frac{1}{R_o C_C (1 + \mu_{f2})} \right] \cong \frac{1}{2\pi} \left[ \frac{1}{500 \text{ k}\Omega (20 \text{ pF}) \left[ 1 + \frac{1}{0.02} \sqrt{\frac{2(0.001)}{5 \times 10^{-4}}} \right]} \right] = 158 \text{ Hz}$$

**Page 1257**

$$f_z \cong \frac{1}{2\pi} \frac{g_{m5}}{C_C} = \frac{1}{2\pi} \frac{\sqrt{2(0.001)5 \times 10^{-4}}}{20 \times 10^{-12}} = 7.96 \text{ MHz} \quad | \quad R = \frac{1}{g_{m5}} = \frac{1}{\sqrt{2(0.001)5 \times 10^{-4}}} = 1.00 \text{ k}\Omega$$

---

$$G_m = g_{m2} = 40(5 \times 10^{-5}) = 2.00 \text{ mS} \quad | \quad R_o = r_{\pi 5} \cong \frac{100V}{40(5.5 \times 10^{-4} A)} = 4.54 \text{ k}\Omega$$

$$f_T = \frac{1}{2\pi} \left( \frac{G_m}{C_C} \right) = \frac{1}{2\pi} \left( \frac{2.00 \text{ mS}}{30 \text{ pF}} \right) = 10.6 \text{ MHz} \quad | \quad f_z = \frac{1}{2\pi} \left( \frac{g_{m5}}{C_C} \right) = \frac{1}{2\pi} \left[ \frac{40(5 \times 10^{-4})}{3 \times 10^{-11}} \right] = 106 \text{ MHz}$$

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

**Page 1260**

$$SR = \frac{100 \mu A}{20 \text{ pF}} = 5.00 \times 10^6 \frac{V}{s} = 5.00 \frac{V}{\mu s}$$

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$$SR = \frac{100 \mu A}{20 \text{ pF}} = 5.00 \times 10^6 \frac{V}{s} = 5.00 \frac{V}{\mu s}$$

**Page 1264**

$$G_m = g_{m2} = 40(2.5 \times 10^{-4}) = 10.0 \text{ mS} \quad | \quad f_T = \frac{1}{2\pi} \left( \frac{G_m/2}{C_C + C_{\mu 3}} \right) = \frac{1}{4\pi} \left( \frac{10.0 \text{ mS}}{50.8 \text{ pF}} \right) = 15.7 \text{ MHz}$$

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

**Page 1268**

$$SR \cong \frac{I_1}{C_C + C_{GD5}} = \frac{1mA}{65pF} = 15.4 \times 10^6 \frac{V}{s} = 15.4 \frac{V}{\mu s}$$

---

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

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

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

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

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

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

**Page 1272**

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

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

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

**Page 1273**

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

**Page 1276**

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