Chapter 1

Exercise Solutions

EX1.1

$$n_i = BT^{3/2}\exp\left(\frac{-E_g}{2kT}\right)$$

GaAs: $n_i = \left(2.1\times10^{14}\right)(300)^{3/2}\exp\left(\frac{-1.4}{2\left(86\times10^{-6}\right)(300)}\right)$ or $\underline{n_i = 1.8\times10^{6}\ cm^{-3}}$

Ge: $n_i = \left(1.66\times10^{15}\right)(300)^{3/2}\exp\left(\frac{-0.66}{2\left(86\times10^{-6}\right)(300)}\right)$ or $\underline{n_i = 2.40\times10^{13}\ cm^{-3}}$

EX1.2

(a) (i) $n_o = N_d = 2\times10^{16}\ \text{cm}^{-3}$

$$p_o = \frac{n_i^2}{n_o} = \frac{\left(1.5\times10^{10}\right)^2}{2\times10^{16}} = 1.125\times10^{4}\ \text{cm}^{-3}$$

(ii) $p_o = N_a = 10^{15}\ \text{cm}^{-3}$

$$n_o = \frac{n_i^2}{p_o} = \frac{\left(1.5\times10^{10}\right)^2}{10^{15}} = 2.25\times10^{5}\ \text{cm}^{-3}$$

(b) (i) $n_o = N_d = 2\times10^{16}\ \text{cm}^{-3}$

$$p_o = \frac{n_i^2}{n_o} = \frac{\left(1.8\times10^{6}\right)^2}{2\times10^{16}} = 1.62\times10^{-4}\ \text{cm}^{-3}$$

(ii) $p_o = N_a = 10^{15}\ \text{cm}^{-3}$

$$n_o = \frac{n_i^2}{p_o} = \frac{\left(1.8\times10^{6}\right)^2}{10^{15}} = 3.24\times10^{-3}\ \text{cm}^{-3}$$

EX1.3

(a) For n-type;

$$\rho = \frac{1}{e\mu_n N_d} = \frac{1}{\left(1.6\times10^{-19}\right)(6800)\left(2\times10^{16}\right)} = 0.046\ \text{ohm-cm}$$

(b) $J = \frac{1}{\rho}\cdot \text{E} \Rightarrow \text{E} = \rho J = (0.046)(175) = 8.04\ \text{V/cm}$

EX1.4

Diffusion current density due to holes:

$$J_p = -eD_p\frac{dp}{dx}$$

$$= -eD_p\left(10^{16}\right)\left(\frac{-1}{L_p}\right)\exp\left(\frac{-x}{L_p}\right)$$

(a) At $x = 0$

$$J_p = \frac{(1.6\times10^{-19})(10)(10^{16})}{10^{-3}} = 16\ A/cm^2$$

(b) At $x = 10^{-3}\ cm$

$$J_p = 16\exp\left(\frac{-10^{-3}}{10^{-3}}\right) = 5.89\ A/cm^2$$

EX1.5

(a) $$V_{bi} = (0.026)\ln\left[\frac{(10^{16})(10^{17})}{(1.8\times10^{6})^2}\right] = 1.23\ \text{V}$$

(b) $$V_{bi} = (0.026)\ln\left[\frac{(10^{16})(10^{17})}{(2.4\times10^{13})^2}\right] = 0.374\ \text{V}$$

EX1.6

$$C_j = C_{jo}\left(1+\frac{V_R}{V_{bi}}\right)^{-1/2}$$

and

$$V_{bi} = V_T\ \ln\left[\frac{N_a N_d}{n_i^2}\right]$$

$$= (0.026)\ln\left[\frac{(10^{17})(10^{16})}{(1.5\times10^{10})^2}\right] = 0.757\ V$$

Then $0.8 = C_{jo}\left(1+\frac{5}{0.757}\right)^{-1/2} = C_{jo}(7.61)^{-1/2}$

or

$$C_{jo} = 2.21\ pF$$

EX1.7

(a) $$V_D = V_T\ \ln\left(\frac{I_D}{I_S}\right)$$

(i) $$V_D = (0.026)\ln\left(\frac{50\times10^{-6}}{2\times10^{-14}}\right) = 0.563\ \text{V}$$

(ii) $$V_D = (0.026)\ln\left(\frac{10^{-3}}{2\times10^{-14}}\right) = 0.641\ \text{V}$$

(b) (i) $$V_D = (0.026)\ln\left(\frac{50\times10^{-6}}{2\times10^{-12}}\right) = 0.443\ \text{V}$$

(ii) $$V_D = (0.026)\ln\left(\frac{10^{-3}}{2\times10^{-12}}\right) = 0.521\ \text{V}$$

EX1.8

$$V_{PS} = I_D R + V_D \text{ and } I_D \cong I_S \exp\left(\frac{V_D}{V_T}\right)$$

so $4 = I_D\left(4\times10^3\right) + V_D \Rightarrow I_D = \dfrac{\left(4-V_D\right)}{4\times10^3}$

and

$$I_D = \left(10^{-12}\right)\exp\left(\frac{V_D}{0.026}\right)$$

By trial and error, we find $I_D \cong 0.866$ mA and $V_D \cong 0.535$ V.

EX1.9

(a) $I_D = \dfrac{V_{PS}-V_\gamma}{R} \Rightarrow R = \dfrac{8-0.7}{1.20} = 6.08\ \text{k}\Omega$

(b) $I_D = \dfrac{4-0.7}{3.5} = 0.9429\ \text{mA}$

$P_D = I_D V_D = (0.9429)(0.7) = 0.66\ \text{mW}$

EX1.10

PSpice Analysis

EX1.11

(a) $I_D = \dfrac{8-0.7}{20} = 0.365\ \text{mA}$

$r_d = \dfrac{V_T}{I_D} = \dfrac{0.026}{0.365} \Rightarrow 71.2\,\Omega$

$i_d = \dfrac{0.25\sin\omega t}{20+0.0712} \Rightarrow 12.5\sin\omega t\ \ (\mu\text{ A})$

(b) $I_D = \dfrac{8-0.7}{10} = 0.73\ \text{mA}$

$r_d = \dfrac{0.026}{0.73} \Rightarrow 35.6\,\Omega$

$i_d = \dfrac{0.25\sin\omega t}{10+0.0356} \Rightarrow 24.9\sin\omega t\ \ (\mu\text{ A})$

EX1.12

For the pn junction diode, $V_D \cong V_T \ln\left(\dfrac{I_D}{I_S}\right) = (0.026)\ln\left(\dfrac{1.2\times10^{-3}}{4\times10^{-15}}\right)$ or $V_D = 0.6871\ V$

The Schottky diode voltage will be smaller, so $V_D = 0.6871 - 0.265 = 0.4221\ V$

Now $I_D \cong I_S \exp\left(\dfrac{V_D}{V_T}\right)$

or

$$I_S = \frac{1.2\times10^{-3}}{\exp\left(\frac{0.4221}{0.026}\right)} \Rightarrow I_S = 1.07\times10^{-10}\ A$$

EX1.13

$$P = I\cdot V_Z \Rightarrow 10 = I(5.6) \Rightarrow I = 1.79\ mA$$

Also $I = \frac{10-5.6}{R} = 1.79 \Rightarrow R = 2.46\ k\Omega$

Test Your Understanding Solutions

TYU1.1

(a) $T = 400K$

Si: $n_i = BT^{3/2}\exp\left(\frac{-E_g}{2kT}\right)$

$$n_i = \left(5.23\times10^{15}\right)(400)^{3/2}\exp\left[\frac{-1.1}{2\left(86\times10^{-6}\right)(400)}\right]$$

or

$$n_i = 4.76\times10^{12}\ cm^{-3}$$

Ge: $n_i = \left(1.66\times10^{15}\right)(400)^{3/2}\exp\left[\frac{-0.66}{2\left(86\times10^{-6}\right)(400)}\right]$

or

$$n_i = 9.06\times10^{14}\ cm^{-3}$$

GaAs:

$$n_i = \left(2.1\times10^{14}\right)(400)^{3/2}\exp\left[\frac{-1.4}{2\left(86\times10^{-6}\right)(400)}\right]$$

or

$$n_i = 2.44\times10^{9}\ cm^{-3}$$

(b) $T = 250\ K$

Si: $n_i = \left(5.23\times10^{15}\right)(250)^{3/2}\exp\left[\frac{-1.1}{2\left(86\times10^{-6}\right)(250)}\right]$

or

$$n_i = 1.61\times10^{8}\ cm^{-3}$$

Ge: $n_i = \left(1.66\times10^{15}\right)(250)^{3/2}\exp\left[\frac{-0.66}{2\left(86\times10^{-6}\right)(250)}\right]$

or

$$n_i = 1.42\times10^{12}\ cm^{-3}$$

GaAs: $n_i = \left(2.10\times10^{14}\right)(250)^{3/2}\exp\left[\frac{-1.4}{2\left(86\times10^{-6}\right)(250)}\right]$

or

$$n_i = 6.02\times10^{3}\ cm^{-3}$$

TYU1.2

(a) $\sigma = e\mu_p N_a = \left(1.6\times10^{-19}\right)(480)\left(2\times10^{15}\right) = 0.154\ \text{(ohm-cm)}^{-1}$

$$\rho = \frac{1}{\sigma} = \frac{1}{0.1536} = 6.51\,\Omega\text{-cm}$$

(b) $\sigma = e\mu_n N_d = \left(1.6\times10^{-19}\right)(1350)\left(2\times10^{17}\right) = 43.2\ \text{(ohm-cm)}^{-1}$

$$\rho = \frac{1}{\sigma} = \frac{1}{43.2} = 0.0231\,\Omega\text{-cm}$$

TYU1.3

(a) $J = \sigma\mathrm{E} = (0.154)(4) = 0.616\ \text{A/cm}^2$

(b) $J = \sigma\mathrm{E} = (43.2)(4) = 172.8\ \text{A/cm}^2$

TYU1.4

(a) $J_n = eD_n\frac{dn}{dx} = eD_n\frac{\Delta n}{\Delta x}$ so $J_n = \left(1.6\times10^{-19}\right)(35)\left(\frac{10^{15}-10^{16}}{0-2.5\times10^{-4}}\right)$

or

$$J_n = 202\ A/cm^2$$

(b) $J_p = -eD_p\frac{dp}{dx} = -eD_p\frac{\Delta p}{\Delta x}$ so $J_p = -\left(1.6\times10^{-19}\right)(12.5)\left(\frac{10^{14}-5\times10^{15}}{0-4\times10^{-4}}\right)$

or

$$J_p = -24.5\ A/cm^2$$

TYU1.5

(a) $n_o = N_d = 8\times10^{15}\ cm^{-3}$

$$p_o = \frac{n_i^2}{n_o} = \frac{\left(1.5\times10^{10}\right)^2}{8\times10^{15}} = 2.81\times10^{4}\ cm^{-3}$$

(b) $n = n_o + \delta n = 8\times10^{15} + 0.1\times10^{15}$

or

$$n = 8.1\times10^{15}\ cm^{-3}$$

$$p = p_o + \delta p = 2.81\times10^{4} + 10^{14}$$

or

$$p \cong 10^{14}\ cm^{-3}$$

TYU1.6

(a) $V_{bi} = V_T \ln\left(\frac{N_a N_d}{n_i^2}\right) = (0.026)\ln\left[\frac{(10^{15})(5\times10^{16})}{(1.5\times10^{10})^2}\right] = 0.679 \text{ V}$

(b) $V_{bi} = (0.026)\ln\left[\frac{(10^{15})(5\times10^{16})}{(1.8\times10^{6})^2}\right] = 1.15 \text{ V}$

(c) $V_{bi} = (0.026)\ln\left[\frac{(10^{15})(5\times10^{16})}{(2.4\times10^{13})^2}\right] = 0.296 \text{ V}$

TYU1.7

(a) (i) $I_D = I_S \exp\left(\frac{V_D}{V_T}\right) = (10^{-16})\exp\left(\frac{0.55}{0.026}\right) \Rightarrow 0.154\ \mu\text{A}$

(ii) $I_D = (10^{-16})\exp\left(\frac{0.65}{0.026}\right) \Rightarrow 7.20\ \mu\text{A}$

(ii) $I_D = (10^{-16})\exp\left(\frac{0.75}{0.026}\right) \Rightarrow 0.337 \text{ mA}$

(b) (i) $I_D = -10^{-16} \text{ A}$

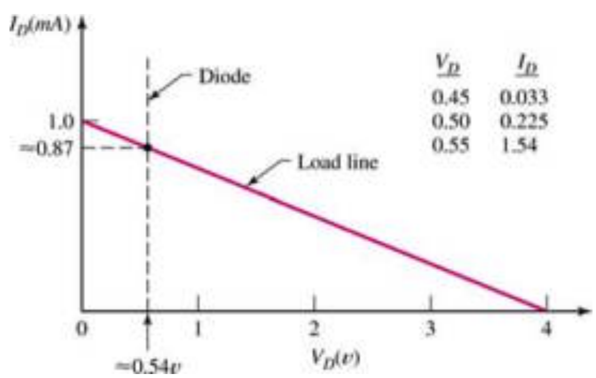
(ii) $I_D = -10^{-16} \text{ A}$

TYU1.8

$\Delta T = 100C$ so $\Delta V_D \cong 2\times100 = 200\ mV$

Then $V_D = 0.650 - 0.20 = 0.450\ V$

TYU1.9



TYU1.10

(a) $I_D = 0$

(b) $I_D = \dfrac{2-0.7}{4} = 0.325 \text{ mA}$

(c) $I_D = \dfrac{5-0.7}{4} = 1.075 \text{ mA}$

(d) $I_D = 0$

(e) $I_D = 0$

TYU1.11

$P = I_D V_D \Rightarrow 1.05 = I_D(0.7)$ so $I_D = 1.5\ mA$

Now $R = \dfrac{V_{PS} - V_\gamma}{I_D} = \dfrac{10-0.7}{1.5} \Rightarrow R = 6.2\ k\Omega$

TYU1.12

$$g_d = \frac{I_D}{V_T} = \frac{0.8}{0.026} = 30.8\ mS$$

TYU1.13

$$r_d = \frac{V_T}{I_D} = \frac{0.026}{0.010} = 2.6\ \text{k}\Omega$$

$$r_d = \frac{0.026}{0.10} \Rightarrow 260\,\Omega$$

$$r_d = \frac{0.026}{1} \Rightarrow 26\,\Omega$$

TYU1.14

$$r_d = \frac{V_T}{I_D} \Rightarrow 50 = \frac{0.026}{I_D} \Rightarrow I_D = \frac{0.026}{50}$$

or

$$I_D = 0.52\ mA$$

TYU1.15

For the pn junction diode,

$$I_D = \frac{4-0.7}{4} = 0.825\ mA$$

For the Schottky diode, $I_D = \dfrac{4-0.3}{4} = 0.925\ mA$

TYU1.16

$$V_z = V_{zo} + I_z r_z \Rightarrow V_{zo} = V_z - I_z r_z \text{ so } V_{zo} = 5.20 - \left(10^{-3}\right)\left(20\right) = 5.18\ V$$

Then $V_z = 5.18 + \left(10 \times 10^{-3}\right)\left(20\right) \Rightarrow V_z = 5.38\ V$

TYU1.17

$$P = I_Z V_Z \Rightarrow I_Z = \frac{P}{V_Z} = \frac{6.5}{3.6} = 1.81 \text{ mA}$$

$$V_{PS} = I_Z R + V_Z = (1.81)(4) + 3.6 = 10.8 \text{ V}$$

Chapter 2

Exercise Solutions

EX2.1

$$i_D(peak) = \frac{V_S - V_B - V_\gamma}{R} = \frac{12 - 4.5 - 0.6}{0.25} = 27.6 \text{ mA}$$

$$\upsilon_R(\max) = V_S + V_B = 12 + 4.5 = 16.5 \text{ V}$$

Conduction cycle:

$$\upsilon_I = 12\sin\omega t_1 = 4.5 + 0.6 = 5.1\,\text{V}$$

or

$$\omega t_1 = \sin^{-1}\left(\frac{5.1}{12}\right) = 25.15°$$

$$\omega t_2 = 180 - 25.15 = 154.85°$$

$$\text{Percent time } = \frac{154.85 - 25.15}{360} \times 100\% = 36.0\%$$

EX2.2

(a) $v_O = 12\sin\theta_1 - 1.4 = 0$

or $\sin\theta_1 = \frac{1.4}{12} = 0.1166$

which yields

$$\theta_1 = 6.7°$$

By symmetry, $\theta_2 = 180 - 6.7 = 173.3°$

Then

$$\%\text{ time} = \frac{173.3 - 6.7}{360} \times 100\% = 46.3\%$$

(b) $\sin\theta_1 = \frac{1.4}{4} = 0.35$

which yields

$$\theta_1 = 20.5°$$

By symmetry, $\theta_2 = 180 - 20.5 = 159.5°$

Then

$$\%\text{ time} = \frac{159.5 - 20.5}{360} \times 100\% = 38.6\%$$

EX2.3

(a) $C = \frac{V_M}{2fRV_r} = \frac{12}{2(60)(2\times 10^3)(0.4)} \Rightarrow 125\,\mu\text{F}$

(b) $C = \frac{V_M}{fRV_r} = \frac{12}{(60)(2\times 10^3)(0.4)} \Rightarrow 250\,\mu\text{F}$

EX2.4

$$V_r = \frac{V_M}{f\ RC} \Rightarrow R = \frac{V_M}{f\ CV_r} \quad \text{or} \quad R = \frac{75}{(60)(50\times10^{-6})(4)}$$

Then $R = 6.25\ k\Omega$

EX2.5

$10 \le V_{PS} \le 14\ V,\ \ V_Z = 5.6\ V,\ \ 20 \le R_L \le 100\ \Omega$

$$I_L(\max) = \frac{5.6}{20} = 0.28\ A,$$

$$I_L(\min) = \frac{5.6}{100} = 0.056\ A$$

$$I_Z(\max) = \frac{[V_{PS}(\max) - V_Z]\cdot I_L(\max)}{V_{PS}(\min) - 0.9V_Z - 0.1V_{PS}(\max)} - \frac{[V_{PS}(\min) - V_Z]\cdot I_L(\min)}{V_{PS}(\min) - 0.9V_Z - 0.1V_{PS}(\max)}$$

or

$$I_L(\max) = \frac{(14-5.6)(280)-(10-5.6)(56)}{10-(0.9)(5.6)-(0.1)(14)}$$

or $I_L(\max) = 591.5\ mA$

$\text{Power(min)} = I_Z(\max)\cdot V_Z = (0.5915)(5.6)$

So $\text{Power(min)} = 3.31\ W$

Now $R_i = \dfrac{V_{PS}(\max) - V_Z}{I_Z(\max) + I_L(\min)} = \dfrac{14-5.6}{0.5915+0.056}$ or $R_i \cong 13\ \Omega$

EX2.6

For $v_{PS} = 13.6\ V,\ I_Z = \dfrac{13.6-9}{15.3+4} = 0.2383\ A$

$$v_{L,\max} = 9 + (4)(0.2383) = 9.9532\ V$$

For $v_{PS} = 11\ V,\ I_Z = \dfrac{11-9}{15.3+4} = 0.1036\ A$

$$v_{L,\min} = 9 + (4)(0.1036) = 9.4144\ V$$

$$\text{Source Reg} = \frac{\Delta v_L}{\Delta v_{PS}}\times100\% = \frac{9.9532-9.4144}{13.6-11}\times100\%$$

or $\text{Source Reg} = 20.7\%$

For $I_L = 0,\ I_Z = \dfrac{13.6-9}{15.3+4} = 0.2383\ A$

$$v_{L,noload} = 9 + (4)(0.2383) = 9.9532\ V$$

For $I_L = 100\ mA,\quad I_Z = \dfrac{13.6 - [9 + I_Z(4)]}{15.3} - 0.10$

which yields

$$I_Z = 0.1591\ A$$

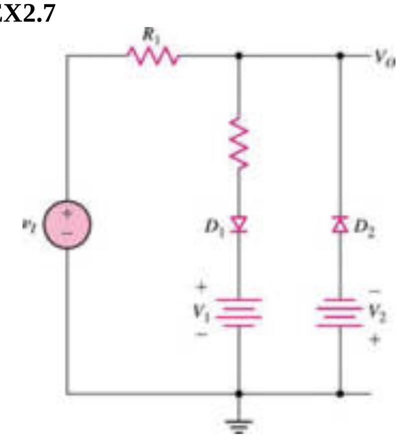
$$v_{L,\,full\ load} = 9 + (4)(0.1591A) = 9.6363\ V$$

$$\text{Load Reg} = \frac{v_{L,noload} - v_{L,\,full\ load}}{v_{L,\,full\ load}} \times 100\%$$

$$= \frac{9.9532 - 9.6363}{9.6363} \times 100\%$$

or $\text{Load Reg} = 3.29\%$

EX2.7



For $v_I < 5\ V$, D_2 on $\Rightarrow V_O = -5\ V$
Then, $V_2 = 4.3\ V$.
D_1 turns on when $v_1 = 2.5\ V$,
Then, $V_1 = 1.8\ V$.
For $v_I > 2.5\ V, \dfrac{\Delta v_O}{\Delta v_I} = \dfrac{1}{3} \Rightarrow \dfrac{R_2}{R_1 + R_2} = \dfrac{1}{3}$
So that $R_1 = 2R_2$

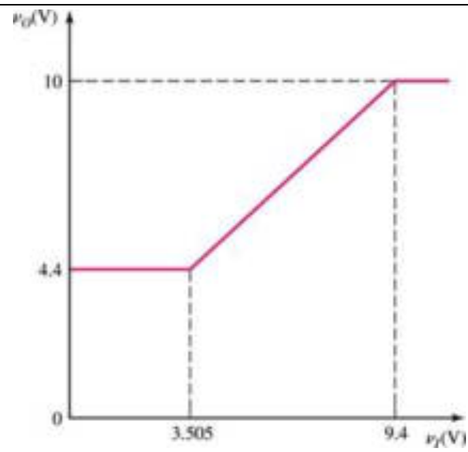
EX2.8

For $\upsilon_O = +2$ V, D is on. $\Delta\upsilon_I = 10$ V, so $\Delta\upsilon_O = 10$ V.
Output = Square wave between +2 and -8 V.

EX2.9

$$v_O = 4.4\ V,\ I = \frac{10 - 4.4}{9.5} = 0.5895\ mA$$

Set $I = I_{D1}$, then $v_I = 4.4 - 0.6 - (0.5895)(0.5) = 3.505\ V$
Summary: For $0 \le v_I \le 3.5\ V$, $v_O = 4.4\ V$
For $v_I > 3.5\ V$, D_2 turns on and when $v_I \ge 9.4\ V$, $v_O = 10\ V$



EX2.10

(a) If D_1 is on, $\upsilon_O = \upsilon_I - V_\gamma - V_B = 5 - 0.7 - 1 = 3.3$ V.

Then $I_{D2} = \dfrac{3.3 - 0.7}{4} = 0.65$ mA

Now $I_{R1} = \dfrac{5 - 3.3}{1.7} = 1.0$ mA, but $I_{D2} < I_{R1}$ is impossible.

D_1 is cutoff and $I_{D1} = 0$

Then $I_{R1} = I_{D2} = \dfrac{5 - 0.7}{1.7 + 4} = 0.754$ mA

$\upsilon_O = 0.7 + (0.754)(4) = 3.72$ V

(b) $\upsilon_I = 10$ V, Both D_1 and D_2 are on.

$\upsilon_O = 10 - 0.7 - 1 \Rightarrow \upsilon_O = 8.3$ V

$I_{D2} = \dfrac{8.3 - 0.7}{4} = 1.9$ mA

$I_{R1} = \dfrac{1.7}{1.7} = 1.0$ mA

$I_{D1} = 1.9 - 1.0 = 0.9$ mA

EX2.11

D_2 cutoff, $I_{D2} = 0$

$V_B = -0.7$ V, $I_{D3} = \dfrac{-0.7 - (-5)}{2} = 2.15$ mA

$I_{D1} = \dfrac{5 - 0.7 - (-10)}{R_1 + R_2} = \dfrac{14.3}{8 + 4} = 1.19$ mA

$V_A = 5 - (1.19)(8) = -4.53$ V

$V_A < V_B$ so that D_2 is cutoff.

EX2.12

(a) $I_{ph} = \eta e \Phi$

so

$$I = (0.8)\left(1.6\times10^{-19}\right)\left[\frac{6.4\times10^{-2}}{(2)\left(1.6\times10^{-19}\right)}\right](0.5)$$

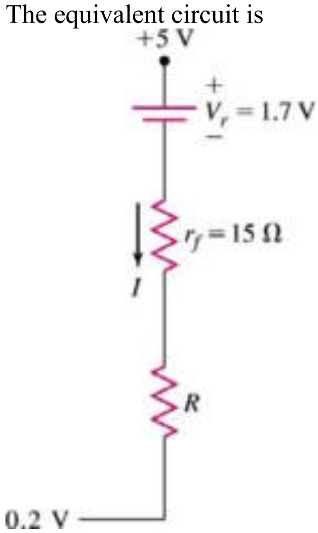
or $I_{ph} = 12.8\ mA$

(b) We have $v_O = (12.8)(1) = 12.8\ V$.

The diode must be reverse biased so that $V_{PS} > 12.8\ V$

EX2.13

The equivalent circuit is



So

$$I = \frac{5-1.7-0.2}{r_f + R} = 15\ mA$$

Or

$$r_f + R = \frac{15-1.7-0.2}{15} = \frac{3.1}{15} = 0.207\ k\Omega$$

Then $R = 207 - 15 \Rightarrow R = 192\ \Omega$

Test Your Understanding Solutions

TYU2.1

(a) $i_D(peak)$ for $V_B = 4$ V.

$$i_D(peak) = 18 = \frac{15 - 0.7 - 4}{R} \Rightarrow R = 572\,\Omega$$

(b) $i_D = \dfrac{15 - 0.7 - 8}{0.572} = 11.0$ mA

Then

$$11.0 \le i_D(peak) \le 18 \text{ mA}$$

For $V_B = 4$ V,

$$15\sin\omega t_1 = 4.7 \Rightarrow \omega t_1 = \sin^{-1}\left(\frac{4.7}{15}\right) = 18.26°$$

$$\omega t_2 = 180 - 18.26 = 161.74°$$

$$\text{duty cycle} = \frac{161.74 - 18.26}{360} \times 100\% = 39.9\%$$

For $V_B = 8$ V,

$$15\sin\omega t_1 = 8.7 \Rightarrow \omega t_1 = \sin^{-1}\left(\frac{8.7}{15}\right) = 35.45°$$

$$\omega t_2 = 180 - 35.45 = 144.55°$$

$$\text{duty cycle} = \frac{144.55 - 35.45}{360} \times 100\% = 30.3\%$$

Then

$$30.3 \le \text{duty cycle} \le 39.9\%$$

TYU2.2

$v_I = 120\sin(2\pi 60t)$, $V_\gamma = 0.7\ V$, and $R = 2.5\ k\Omega$

Full-wave rectifier: Turns ratio 1:2 so that

$$v_S = v_I$$

$$V_M = 120 - 0.7 = 119.3\ V$$

$$V_r = 119.3 - 100 = 19.3\ V$$

So $C = \dfrac{V_M}{2f\ RV_r} = \dfrac{119.3}{2(60)(2.5x10^3)(19.3)}$ or $C = 20.6\ \mu F$

TYU2.3

$v_I = 50\sin(2\pi 60t)$, $V_\gamma = 0.7\ V$, and $R = 10\ k\Omega$. Full-wave rectifier

$$C = \frac{V_M}{2f\ RV_r} = \frac{(50 - 1.4)}{2(60)(10\times10^3)(2)}$$

or $C = 20.3\ \mu F$

TYU2.4

Using Equation (2.16)

(a)

$$\omega \Delta t = \sqrt{\frac{2V_r}{V_M}} = \sqrt{\frac{2(4)}{75}} = 0.327$$

$$\text{Percent time} = \left(\frac{0.327}{2\pi}\right) \times 100\% = 5.2\%$$

(b)

$$\omega \Delta t = \sqrt{\frac{2V_r}{V_M}} = \sqrt{\frac{2(19.3)}{119.3}} = 0.569$$

$$\text{Percent time} = \left(\frac{0.569}{\pi}\right) \times 100\% = 18.1\%$$

(c)

$$\omega \Delta t = \sqrt{\frac{2V_r}{V_M}} = \sqrt{\frac{2(2)}{48.6}} = 0.287$$

$$\text{Percent time} = \left(\frac{0.287}{\pi}\right) \times 100\% = 9.14\%$$

TYU2.5

(a) $P = I_Z V_Z$

$$1 = I_Z(6.2 + 3I_Z) = 3I_Z^2 + 6.2I_Z$$

$$3I_Z^2 + 6.2I_Z - 1 = 0 \Rightarrow I_Z(\text{max}) = 150 \text{ mA}$$

$$V_Z = 6.2 + 3(0.15) = 6.65 \text{ V}$$

$$R_i = \frac{12 - 6.65}{0.15} \Rightarrow R_i = 35.7\,\Omega$$

(b) For $I_Z = (0.1)(150) = 15$ mA

$$V_Z = V_O = 6.2 + 3(0.015) = 6.245 \text{ V}$$

$$I_L = I_i - I_Z \Rightarrow I_i = \frac{12 - 6.245}{0.0357} = 161.2 \text{ mA}$$

$$I_L = 161.2 - 15 = 146.2 \text{ mA}$$

$$R_L = \frac{6.245}{0.1462} = 42.7\,\Omega$$

$$\text{Load Regulation} = \frac{\upsilon_L(no\,load) - \upsilon_L(full\,load)}{\upsilon_L(no\,load)} \times 100\%$$

$$= \frac{6.65 - 6.245}{6.65} \times 100\% = 6.09\%$$

TYU2.6

$$I_Z = \frac{V_{PS} - V_Z}{R_i} - I_L$$

For V_{PS} (min) and I_L (max), then $I_Z(\text{min}) = \dfrac{11 - 9}{20} - 0.1 = 0$ (Minimum Zener current is zero.)

For V_{PS} (max) and I_L (min), then $I_Z(\text{max}) = \dfrac{13.6 - 9}{20} - 0 \Rightarrow I_Z(\text{max}) = 230\ mA$

The characteristic of the minimum Zener current being one-tenth of the maximum value is violated. The proper circuit operation is questionable.

TYU2.7

$$I_Z(\min) = \frac{V_{PS}(\min) - V_Z}{R_i} - I_L(\max)$$

so $30 = \dfrac{10-9}{0.0153} - I_L(\max)$ which yields $I_L(\max) = 35.4\ mA$

TYU2.8

For $\upsilon_I \le -3.7$ V, D_2 on $\Rightarrow \upsilon_O = -3.7$ V

D_1 turns on when $\upsilon_I = 1.7$ V so

$$-3.7 \le \upsilon_I \le 1.7 \text{ V} \Rightarrow \upsilon_O = \upsilon_I$$

For $\upsilon_I > 1.7$ V,

$$i_1 = \frac{\upsilon_I - 1.7}{R_1 + R_2} = \frac{\upsilon_I - 1.7}{7}$$

$$\upsilon_O = i_1 R_2 + 1.7 = \left(\frac{\upsilon_I - 1.7}{7}\right)(2) + 1.7$$

Or

$$\upsilon_O = 0.286\upsilon_I + 1.21$$

TYU2.9

As v_S goes negative, D turns on and $v_O = +5\ V$. As v_S goes positive, D turns off. Output is a square wave oscillating between +5 and +35 volts.

TYU2.10

$$V_1 = 3 - 0.7 = 2.3 \text{ V}$$

$$V_2 = 2 - 0.7 = 1.3 \text{ V}$$

For $\upsilon_I > 3$ V, slope $= \dfrac{1}{2} \Rightarrow R_1 = R_2$

Put resistor in series with D_2,

For $\upsilon_I < 2$ V, slope $= \dfrac{1}{3} = \dfrac{R_3}{R_1 + R_3} \Rightarrow R_1 = 2R_3$

TYU2.11

D_2 and D_3 cutoff so that $I_{D2} = I_{D3} = 0$

$$I_{D1} = \frac{14 - 0.7 - (-5)}{R_1 + R_2 + R_3} = \frac{18.3}{5+5+5} = 1.22 \text{ mA}$$

$$V_A = 14 - 0.7 - (1.22)(5) = 7.2 \text{ V} \Rightarrow D_2 \text{ cutoff}$$

$$V_B = (1.22)(5) - 5 = 1.1 \text{ V} \Rightarrow D_3 \text{ cutoff}$$

TYU2.12

D_2 cutoff, $I_{D2} = 0$

$V_B = -0.7$ V

$$I_{D1} = \frac{14 - 0.7 - (-0.7)}{R_1 + R_2} = \frac{14}{8+12} = 0.7 \text{ mA}$$

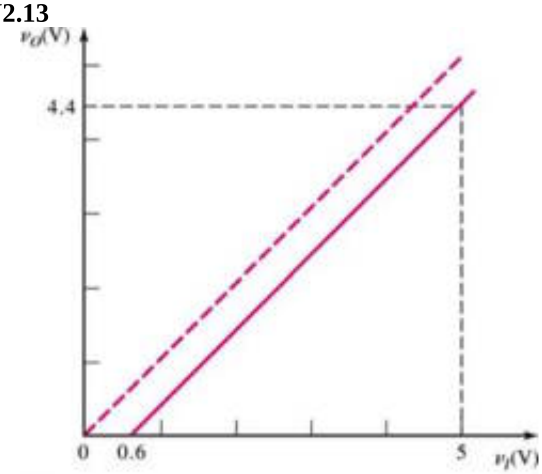
$V_A = 14 - 0.7 - (0.7)(8) = 7.7 \text{ V} \Rightarrow D_2$ cutoff

$$I_{R3} = \frac{-0.7 - (-5)}{2.5} = 1.72 \text{ mA}$$

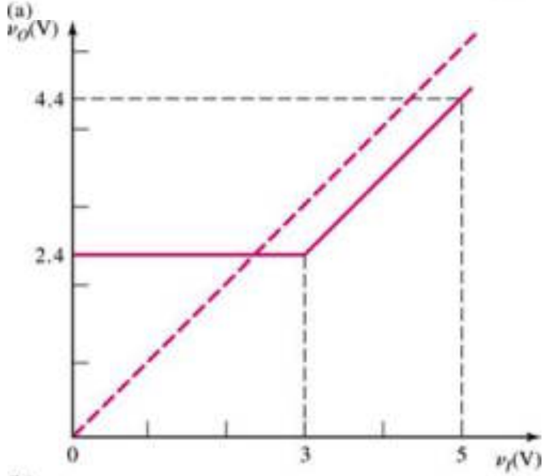
$I_{D1} + I_{D3} = I_{R3}$

$I_{D3} = I_{R3} - I_{D1} = 1.72 - 0.7 = 1.02$ mA

TYU2.13



(a)

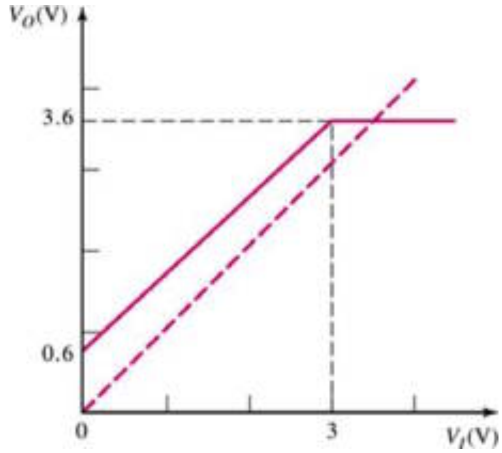


(b)

TYU2.14

(a) $V_O = 0.6\ V$ for all V_1.

(b)



Chapter 3

Exercise Solutions

EX3.1

$V_{TN} = 1\ V,\ V_{GS} = 3\ V,\ V_{DS} = 4.5\ V$

$V_{DS} = 4.5 > V_{DS}(sat) = V_{GS} - V_{TN} = 3 - 1 = 2\ V$

Transistor biased in the saturation region

$I_D = K_n(V_{GS} - V_{TN})^2 \Rightarrow 0.8 = K_n(3-1)^2 \Rightarrow K_n = 0.2\ mA/V^2$

(a) $V_{GS} = 2\ V$, $V_{DS} = 4.5\ V$

Saturation region:

$I_D = (0.2)(2-1)^2 \Rightarrow \underline{I_D = 0.2\ mA}$

(b) $V_{GS} = 3\ V$, $V_{DS} = 1\ V$

Nonsaturation region:

$I_D = (0.2)\left[2(3-1)(1)-(1)^2\right] \Rightarrow \underline{I_D = 0.6\ mA}$

EX3.2

$0.5 = K_p(3-1.2)^2 \Rightarrow K_p = 0.154\ \text{mA/V}^2$

(a) $i_D = K_p(\upsilon_{SG} + V_{TP})^2 = 0.154(2-1.2)^2 = 0.0986\ \text{mA}$

(b) $i_D = K_p\left[2(\upsilon_{SG} + V_{TP})\upsilon_{SD} - \upsilon_{SD}^2\right] = 0.154\left[2(5-1.2)(2)-(2)^2\right] = 1.72\ \text{mA}$

EX3.3

$$V_{GS} = \left(\frac{R_2}{R_1 + R_2}\right)\cdot V_{DD} = \left(\frac{245}{245+355}\right)(2.2) = 0.8983\ \text{V}$$

$I_D = (25)(0.8983 - 0.35)^2 = 7.52\ \mu\text{A}$

$V_{DS} = 2.2 - (0.00752)(100) = 1.45\ \text{V}$

EX3.4

$I_{DQ} = 0.5\ \text{mA},\ V_{SDQ} = 2.0\ \text{V}$

$$R_D = \frac{3.3 - 2.0}{0.5} = 2.6\ \text{k}\Omega$$

$I_D = K_p(V_{SGQ} + V_{TP})^2$

$0.5 = 0.2(V_{SGQ} - 0.6)^2 \Rightarrow V_{SGQ} = 2.18\ \text{V}$

$V_G = 3.3 - 2.18 = 1.12\ \text{V}$

$$V_G = \left(\frac{R_2}{R_1 + R_2}\right)\cdot V_{DD} = \frac{1}{R_1}(R_1 \| R_2)(3.3)$$

$$1.12 = \frac{1}{R_1}(300)(3.3) \Rightarrow R_1 = 884\ \text{k}\Omega$$

Then

$$\frac{884R_2}{884+R_2}=300 \Rightarrow R_2=454 \text{ k}\Omega$$

EX3.5

(a) $V_{GSQ}=\left(\frac{30}{30+60}\right)(5)=1.667 \text{ V}$

$I_{DQ}=(0.5)(1.667-0.6)^2=0.5689 \text{ mA}$

$V_{DSQ}=5-(0.5689)(4)=2.724 \text{ V}$

(b) $K_n(+5\%)=0.525 \text{ mA/V}^2$, $V_{TN}(-5\%)=0.57 \text{ V}$

$I_D=0.525(1.667-0.57)^2=0.6314 \text{ mA}$

$V_{DS}=5-(0.6314)(4)=2.474 \text{ V}$

$K_n(-5\%)=0.475 \text{ mA/V}^2$, $V_{TN}(+5\%)=0.63 \text{ V}$

$I_D=0.475(1.667-0.63)^2=0.5105 \text{ mA}$

$V_{DS}=5-(0.5105)(4)=2.958 \text{ V}$

Then

$$0.5105 \le I_D \le 0.6314 \text{ mA}$$

$$2.474 \le V_{DS} \le 2.958 \text{ V}$$

EX3.6

(a) $V_G=\left(\frac{345}{345+255}\right)(4.4)-2.2=0.330 \text{ V}$

$2.2=I_{DQ}R_S+V_{SGQ}+V_G$

$2.2=K_pR_S(V_{SGQ}+V_{TP})^2+V_{SGQ}+0.330$

$1.87=(0.035)(6)(V_{SGQ}^2-0.6V_{SGQ}+0.09)+V_{SGQ}$

$0.21V_{SGQ}^2+0.874V_{SGQ}-1.8511=0 \Rightarrow V_{SGQ}=1.545 \text{ V}$

We find

$I_{DQ}=35(1.545-0.3)^2=54.22\,\mu\text{A}$

$V_{SDQ}=4.4-(0.05422)(6+42)=1.797 \text{ V}$

(b)

For $V_{TP}=-0.315 \text{ V}$

We have

$1.87=(0.035)(6)(V_{SGQ}^2-0.63V_{SGQ}+0.099225)+V_{SGQ}$

$0.21V_{SGQ}^2+0.8677V_{SGQ}-1.849=0 \Rightarrow V_{SGQ}=1.550 \text{ V}$

Then

$I_{DQ}=35(1.550-0.315)^2=53.36\,\mu\text{A}$

For $V_{TP}=-0.285 \text{ V}$

We have

$1.87=(0.035)(6)(V_{SGQ}^2-0.57V_{SGQ}+0.081225)+V_{SGQ}$

$0.21V_{SGQ}^2+0.8803V_{SGQ}-1.8529=0 \Rightarrow V_{SGQ}=1.5395 \text{ V}$

Then

$$I_{DQ} = 35(1.5395 - 0.285)^2 = 55.08\,\mu\text{ A}$$

Therefore

$$53.36 \le I_{DQ} \le 55.08\,\mu\text{ A}$$

EX3.7

$$4.4 = V_{SD}(sat) + I_D(6 + 42)$$

$$4.4 = V_{SG} + V_{TP} + (0.035)(48)(V_{SG} + V_{TP})^2$$

$$4.4 = V_{SG} - 0.3 + 1.68(V_{SG}^2 - 0.6V_{SG} + 0.09)$$

$$1.68V_{SG}^2 - 0.008V_{SG} - 4.5488 = 0 \Rightarrow V_{SG} = 1.648\text{ V}$$

We find

$$I_D = 35(1.648 - 0.3)^2 = 63.59\,\mu\text{ A}$$

$$V_{SD} = 4.4 - (0.0636)(48) = 1.348\text{ V}$$

Note: $V_{SD}(sat) = 1.648 - 0.3 = 1.348\text{ V}$

EX3.8

(a) $I_{DQ} = 60 = 30(V_{SGQ} - 0.4)^2 \Rightarrow V_{SGQ} = 1.814\text{ V}$

$$I_{DQ} = \frac{3 - 1.814}{R_S} = 0.060 \Rightarrow R_S = 19.77\text{ k}\Omega$$

$$V_D = 1.814 - 2.5 = -0.686\text{ V}$$

$$R_D = \frac{-0.686 - (-3)}{0.060} = 38.57\text{ k}\Omega$$

(b) $|V_{TP}|(+5\%) = 0.42\text{ V},\quad K_p(-5\%) = 28.5\,\mu\text{ A/V}^2$

$$3 = I_D R_S + V_{SG} = (0.0285)(19.77)(V_{SG}^2 - 0.84V_{SG} + 0.1764) + V_{SG}$$

which yields

$$V_{SG} = 1.849\text{ V}$$

$$I_D = (28.5)(1.849 - 0.42)^2 = 58.2\,\mu\text{ A}$$

$$V_{SD} = 6 - (0.0582)(19.77 + 38.57) = 2.605\text{ V}$$

$|V_{TP}|(-5\%) = 0.38\text{ V},\quad K_p(+5\%) = 31.5\,\mu\text{ A/V}^2$

$$3 = (0.0315)(19.77)(V_{SG}^2 - 0.76V_{SG} + 0.1444) + V_{SG}$$

which yields

$$V_{SG} = 1.780\text{ V}$$

$$I_D = 31.5(1.780 - 0.38)^2 = 61.72\,\mu\text{ A}$$

$$V_{SD} = 6 - (0.06172)(19.77 + 38.57) = 2.399\text{ V}$$

Then

$$58.2 \le I_D \le 61.72\,\mu\text{ A}$$

$$2.399 \le V_{SD} \le 2.605\text{ V}$$

EX3.9

(a) $V_I = 4$ V, Driver in Non · Sat.

$$K_{nD}\left[2(V_I - V_{TND})V_O - V_O^2\right] = K_{nL}\left[V_{DD} - V_O - V_{TNL}\right]^2$$

$$5\left[2(4-1)V_D - V_D^2\right] = (5 - V_D - 1)^2 = (4 - V_O)^2 = 16 - 8V_O + V_O^2$$

$$6V_D^2 - 38V_O + 16 = 0$$

$$V_D = \frac{38 \pm \sqrt{1444 - 384}}{2(6)}$$

$$V_D = 0.454 \text{ V}$$

(b) $V_I = 2$ V Driver: Sat

$$K_{nD}\left[V_I - V_{TND}\right]^2 = K_{nL}\left[V_{DD} - V_O - V_{TNL}\right]^2$$

$$5[2-1]^2 = [5 - V_O - 1]^2$$

$$\sqrt{5} = 4 - V_O \Rightarrow V_O = 1.76 \text{ V}$$

EX3.10

(a) For $V_I = 5$ V, Load in saturation and driver in nonsaturation.

$$I_{DD} = I_{DL}$$

$$K_{nD}\left[2(V_I - V_{TND})V_O - V_O^2\right] = K_{nL}(-V_{TNL})^2$$

$$\frac{K_{nD}}{K_{nL}}\left[2(5-1)(0.25) - (0.25)^2\right] = 4 \Rightarrow \frac{K_{nD}}{K_{nL}} = 2.06$$

(b)

$$I_{DL} = K_{nL}(-V_{TNL})^2 \Rightarrow 0.2 = K_{nL}\left[-(-2)\right]^2$$

$\underline{K_{nL} = 50\ \mu A/V^2}$ and $\underline{K_{nD} = 103\ \mu A/V^2}$

EX3.11

For M_N

$$I_{DN} = I_{DP}$$

$$K_n(V_{GSN} - V_{TN})^2 = K_p(V_{scop} + V_{TP})^2$$

$$V_{GSN} = 1 + (5 - 3.25 - 1) = \underline{1.75\ V = V_I}$$

$$V_o = V_{DSN}(\text{sat}) = 1.75 - 1 \Rightarrow V_o = 0.75 \text{ V}$$

For M_P: $V_I = 1.75$ V

$$V_{DD} - V_O = V_{SD}(\text{sat}) = V_{SGP} + V_{TP} = (5 - 3.25) - 1 = 0.75 \text{ V}$$

So $V_{ot} = 5 - 0.75 \Rightarrow V_{ot} = 4.25$ V

EX3.12

Transistor in nonsaturation

(a) $V_{DS} = 0.2$ V, $V_{GS} = 5$ V

$$V_O = V_{DD} - I_D R_D = V_{DD} - K_n R_D\left[2(V_{GS} - V_{TN})V_{DS} - V_{DS}^2\right]$$

$$0.2 = 5 - K_n(0.5)\left[2(5-1)(0.2) - (0.2)^2\right] \Rightarrow K_n = 6.154 \text{ mA/V}^2$$

(b) $I_D = (6.154)\left[2(5-1)(0.2)-(0.2)^2\right] = 9.60 \text{ mA}$

$P = I_D V_{DS} = (9.60)(0.2) = 1.92 \text{ mW}$

EX3.13

a. $V_1 = 5 \text{ V}, \quad V_2 = 0, \quad M_2 \text{ cutoff} \Rightarrow \underline{I_{D2} = 0}$

$$I_D = K_n\left[2(V_I - V_{TN})V_O - V_O^2\right] = \frac{5 - V_O}{R_D}$$

$$(0.05)(30)\left[2(5-1)V_0 - V_0^2\right] = 5 - V_0$$

$$1.5V_0^2 - 13V_0 + 5 = 0$$

$$V_0 = \frac{13 \pm \sqrt{(13)^2 - 4(1.5)(5)}}{2(1.5)} \Rightarrow \underline{V_0 = 0.40 \text{ V}}$$

$$I_R = I_{D1} = \frac{5 - 0.40}{30} \Rightarrow \underline{I_R = I_{D1} = 0.153 \text{ mA}}$$

b. $V_1 = V_2 = 5 \text{ V}$

$$\frac{5 - V_O}{R_D} = 2\left\{K_n\left[2(V_I - V_{TN})V_O - V_O^2\right]\right\}$$

$$5 - V_0 = 2(0.05)(30)\left[2(5-1)V_0 - V_0^2\right]$$

$$3V_0^2 - 25V_0 + 5 = 0$$

$$V_0 = \frac{25 \pm \sqrt{(25)^2 - 4(3)(5)}}{2(3)} \Rightarrow \underline{V_0 = 0.205 \text{ V}}$$

$$I_R = \frac{5 - 0.205}{30} \Rightarrow \underline{I_R = 0.160 \text{ mA}}$$

$$\underline{I_{D1} = I_{D2} = 0.080 \text{ mA}}$$

EX3.14

$$V_{GS3} = \sqrt{\frac{I_{REF1}}{K_{n3}}} + V_{TN} = \sqrt{\frac{120}{60}} + 0.4 = 1.814 \text{ V}$$

$$V_{GS2} = V_{GS3} = 1.814 \text{ V}$$

$$I_{Q1} = K_{n2}(V_{GS2} - V_{TN})^2 = 30(1.814 - 0.4)^2 = 60\,\mu\text{A}$$

$$V_{GS1} = \sqrt{\frac{I_{Q1}}{K_{n1}}} + V_{TN} = \sqrt{\frac{60}{50}} + 0.4 = 1.495 \text{ V}$$

EX3.15

$$0.1=\left(\frac{0.04}{2}\right)(15)(V_{SGC}-0.6)^2$$

$$V_{SGC}=1.177\ V=V_{SGB}$$

$$0.2=\left(\frac{0.04}{2}\right)\left(\frac{W}{L}\right)_B(1.177-0.6)^2$$

$$\left(\frac{W}{L}\right)_B=30$$

$$0.2=\left(\frac{0.04}{2}\right)(25)(V_{SGA}-0.6)^2$$

$$V_{SGA}=1.23\text{ V}$$

EX3.16

$$I_{REF}=K_{n3}(V_{GS3}-V_{TN})^2=K_{n4}(V_{GS4}-V_{TN})^2$$

$$V_{GS3}=2\ V\Rightarrow V_{GS4}=3\ V$$

(a) $$(2-1)^2=\frac{K_{n4}}{K_{n3}}(3-1)^2\Rightarrow \underline{\frac{K_{n4}}{K_{n3}}=\frac{1}{4}}$$

$$I_Q=K_{n2}(V_{GS2}-V_{TN})^2$$

But $V_{GS2}=V_{GS3}=2\ V$

(b) $$0.1=K_{n2}(2-1)^2\Rightarrow \underline{K_{n2}=0.1\ mA/V^2}$$

$$0.2=K_{n3}(2-1)^2\Rightarrow \underline{K_{n3}=0.2\ mA/V^2}$$

(c) $$0.2=K_{n4}(3-1)^2\Rightarrow \underline{K_{n4}=0.05\ mA/V^2}$$

EX3.17

$$V_{S2}=5-5=0\qquad R_{S2}=\frac{5}{0.3}=16.7\text{ K}$$

$$I_{D2}=K_{n2}(V_{GS2}-V_{TN2})^2$$

$$0.3=0.2(V_{GS2}-1.2)^2\Rightarrow V_{GS2}=2.425\text{ V}\Rightarrow V_{G2}=V_{GS2}+V_S=2.425\text{ V}$$

$$R_{D1}=\frac{5-2.425}{0.1}=25.8\text{ K}$$

$$V_{S1}=V_{G2}-V_{DSQ1}=2.425-5=-2.575\text{ V}$$

$$R_{S1}=\frac{-2.575-(-5)}{0.1}\Rightarrow R_{S1}=24.3\text{ K}$$

$$I_{D1}=K_{n1}(V_{GS1}-V_{TN1})^2$$

$$0.1=0.5(V_{GS1}-1.2)^2\Rightarrow V_{GS1}=1.647\text{ V}$$

$$V_{G1}=V_{GS1}+V_{S1}=1.647+(-2.575)\Rightarrow V_{G1}=-0.928\text{ V}$$

$$V_{G1}=\left(\frac{R_2}{R_1+R_2}\right)(10)-5=\frac{1}{R_1}\cdot R_{TN}\cdot(10)-5$$

$$-0.928=\frac{1}{R_1}(200)(10)-5 \Rightarrow R_1=491\text{ K}$$

$$\frac{491\,R_2}{491+R_2}=200 \Rightarrow R_2=337\text{ K}$$

EX3.18

$$V_{S1}=I_D R_S-5=(0.25)(16)-5=-1\text{ V}$$

$$I_{DQ}=K_n(V_{GS1}-V_{TN})^2 \Rightarrow 0.25=0.5(V_{GS1}-0.8)^2 \Rightarrow V_{GS1}=1.507\text{ V}$$

$$V_{G1}=V_{GS1}+V_{S1}=1.507-1=0.507\text{ V}$$

$$V_{G1}=\left(\frac{R_3}{R_1+R_2+R_3}\right)(5) \Rightarrow 0.507=\frac{R_3}{500}(5) \Rightarrow \underline{R_3=50.7\text{ K}}$$

$$V_{S2}=V_{S1}+V_{DS1}=-1+2.5=1.5\text{ V}$$

$$V_{G2}=V_{S2}+V_{GS}=1.5+1.507=3.007\text{ V}$$

$$V_{G2}=\left(\frac{R_2+R_3}{R_1+R_2+R_3}\right)(5) \Rightarrow 3.007=\left(\frac{R_2+R_3}{500}\right)(5)$$

$$R_2+R_3=300.7$$

$$R_2=300.7-50.7 \Rightarrow \underline{R_2=250\text{ K}}$$

$$R_1=500-250-50.7 \Rightarrow R_1=199.3\text{ K}$$

$$V_{D2}=V_{S2}+V_{DS2}=1.5+2.5=4\text{ V}$$

$$R_D=\frac{5-4}{0.25} \Rightarrow R_D=4\text{ K}$$

EX3.19

$$V_{DS}(\text{sat})=V_{GS}-V_P=-1.2-(-4.5) \Rightarrow \underline{V_{DS}(\text{sat})=3.3\text{ V}}$$

$$I_D=I_{DSS}\left(1-\frac{V_{GS}}{V_P}\right)^2=12\left(1-\frac{(-1.2)}{(-4.5)}\right)^2 \Rightarrow \underline{I_D=6.45\text{ mA}}$$

EX3.20

$$I_D = 2.5 \text{ mA}$$

$$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2$$

$$2.5 = 6\left(1 - \frac{V_{GS}}{(-4)}\right)^2 \Rightarrow V_{GS} = -1.42 \text{ V}$$

$$V_S = I_D R_S - 5 = (2.5)(0.25) - 5$$

$$V_S = -4.375$$

$$V_{DS} = 6 \Rightarrow V_D = 6 - 4.375 = 1.625$$

$$R_D = \frac{5 - 1625}{2.5} \Rightarrow \underline{R_D = 1.35 \text{ k}\Omega}$$

$$\frac{(20)^2}{R_1 + R_2} = 2 \Rightarrow R_1 + R_2 = 200 \text{ k}\Omega$$

$$V_G = V_{GS} + V_S = -1.42 - 4.375 = -5.795$$

$$V_G = \left(\frac{R_2}{R_1 + R_2}\right)(20) - 10$$

$$-5.795 = \left(\frac{R_2}{200}\right)(20) - 10 \Rightarrow \underline{R_2 = 42.05 \text{ k}\Omega} \to \underline{42 \text{ k}\Omega}$$

$$\underline{R_1 = 157.95 \text{ k}\Omega} \to \underline{158 \text{ k}\Omega}$$

EX3.21

$$V_S = -V_{GS}. \quad I_D = \frac{0 - V_S}{R_S} = \frac{V_{GS}}{R_S}$$

$$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2$$

$$\frac{V_{GS}}{1} = 6\left(1 - \frac{V_{GS}}{4}\right)^2 = 6\left(1 - \frac{V_{GS}}{2} + \frac{V_{GS}^2}{16}\right)$$

$$0.375V_{GS}^2 - 4V_{GS} + 6 = 0$$

$$V_{GS} = \frac{4 \pm \sqrt{16 - 4(0.375)(6)}}{2(0.375)}$$

$$\underbrace{V_{GS} = 8.86}_{\text{impossible}} \text{ or } \underline{V_{GS} = 1.806 \text{ V}}$$

$$\underline{I_D = \frac{V_{GS}}{R_S} = 1.806 \text{ mA}}$$

$$V_D = I_D R_D - 5 = (1.81)(0.4) - 5 = -4.278$$

$$V_{SD} = V_S - V_0 = -1.81 - (-4.276) \Rightarrow \underline{V_{SD} = 2.47 \text{ V}}$$

$$V_{SD}(\text{sat}) = V_P - V_{GS} = 4 - 1.81 = 2.19$$

So $V_{SD} > V_{SD}(\text{sat})$

EX3.22

$$R_{ib} = R_1 \| R_2 = \frac{R_1 R_2}{R_1 + R_2} = 100\ \text{k}\Omega$$

$$I_{DQ} = 5\,\text{mA},\ \ V_S = -I_{DQ} R_S = -(5)(1.2) = -6\ \text{V}$$

$$V_{SDQ} = 12\ \text{V},\ \ V_D = V_S - V_{SDQ}$$

$$= -6 - 12 = -18\ \text{V}$$

$$R_D = \frac{-18-(-20)}{5} \Rightarrow \underline{R_D = 0.4\ \text{k}\Omega}$$

$$I_{DQ} = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2 \Rightarrow 5 = 8\left(1 - \frac{V_{GS}}{4}\right)^2$$

$$V_{GS} = 0.838\ \text{V}$$

$$V_G = V_{GS} + V_S = 0.838 - 6 = -5.162$$

$$V_G = \left(\frac{R_2}{R_1 + R_2}\right)(-20)$$

$$-5.162 = \frac{1}{R_1}(100)(-20) \Rightarrow \underline{R_1 = 387\ \text{k}\Omega}$$

$$\frac{R_1 R_2}{R_1 + R_2} = 100 \Rightarrow (387)R_2 = 100(387) + 100\ R_2$$

$$(387-100)R_2 = (100)(387) \Rightarrow \underline{R_2 = 135\ \text{k}\Omega}$$

Test Your Understanding Solutions

TYU3.1

$$V_{TN} = 1.2\ V,\ \ V_{GS} = 2\ V$$

(a) $V_{DS}(sat) = V_{GS} - V_{TN} = 2 - 1.2 = 0.8\ V$

(i) $V_{DS} = 0.4 \Rightarrow$ Nonsaturation

(ii) $V_{DS} = 1 \Rightarrow$ Saturation

(iii) $V_{DS} = 5 \Rightarrow$ Saturation

$$V_{TN} = -1.2\ V,\ \ V_{GS} = 2\ V$$

(b) $V_{DS}(sat) = V_{GS} - V_{TN} = 2 - (-1.2) = 3.2\ V$

(i) $V_{DS} = 0.4 \Rightarrow$ Nonsaturation

(ii) $V_{DS} = 1 \Rightarrow$ Nonsaturation

(iii) $V_{DS} = 5 \Rightarrow$ Saturation

TYU3.2

(a) $K_n = \dfrac{W\mu_n \in_{ox}}{2Lt_{ox}} = \dfrac{(20\times10^{-4})(500)(3.9)(8.85\times10^{-14})}{2(0.8\times10^{-4})(200\times10^{-8})} \Rightarrow 1.08\ \text{mA/V}^2$

(b)

(i) $i_D = (1.08)\left[2(2-1.2)(0.4)-(0.4)^2\right] = 0.518\ \text{mA}$

(ii) $i_D = (1.08)(2-1.2)^2 = 0.691\ \text{mA}$

(iii) $i_D = (1.08)(2-1.2)^2 = 0.691\ \text{mA}$

(i) $i_D = (1.08)\left[2(2+1.2)(0.4)-(0.4)^2\right] = 2.59\ \text{mA}$

(ii) $i_D = (1.08)\left[2(2+1.2)(1)-(1)^2\right] = 5.83\ \text{mA}$

(iii) $i_D = (1.08)(2+1.2)^2 = 11.1\ \text{mA}$

TYU3.3

(a) $V_{SD}(\text{sat}) = V_{SG} + V_{TP} = 2-1.2 = 0.8\ \text{V}$

(i) Non Sat (ii) Sat (iii) Sat

(b) $V_{SD}(\text{sat}) = 2+1.2 = 3.2\ \text{V}$

(i) Non Sat (ii) Non Sat (iii) Sat

TYU3.4

(a) $K_p = \dfrac{W\mu_p \in_{ox}}{2Lt_{ox}} = \dfrac{(10\times10^{-4})(300)(3.9)(8.85\times10^{-14})}{2(0.8\times10^{-4})(200\times10^{-8})} \Rightarrow 0.324\ \text{mA/V}^2$

(b)

(i) $i_D = (0.324)\left[2(2-1.2)(0.4)-(0.4)^2\right] = 0.156\ \text{mA}$

(ii) $i_D = (0.324)(2-1.2)^2 = 0.207\ \text{mA}$

(iii) $i_D = (0.324)(2-1.2)^2 = 0.207\ \text{mA}$

(i) $i_D = (0.324)\left[2(2+1.2)(0.4)-(0.4)^2\right] = 0.778\ \text{mA}$

(ii) $i_D = (0.324)\left[2(2+1.2)(1)-(1)^2\right] = 1.75\ \text{mA}$

(iii) $i_D = (0.324)(2+1.2)^2 = 3.32\ \text{mA}$

TYU3.5

(a), (i) (ii)

$$i_D = (10)(0.5-0.25)^2 = 0.625\ \mu\text{A}$$

(b)

(i) $i_D = K_n(\upsilon_{GS} - V_{TN})^2(1+\lambda\upsilon_{DS})$

$i_D = (10)(0.5-0.25)^2[1+(0.03)(0.5)] = 0.6344\ \mu\text{A}$

(ii) $i_D = (10)(0.5-0.25)^2[1+(0.03)(1.2)] = 0.6475\ \mu\text{A}$

(c) For (a),

$$r_o = \infty$$

For (b), $$r_o = \frac{1}{\lambda I_{DQ}} = \frac{1}{(0.03)(0.625)} = 53.3 \text{ M}\Omega$$

TYU3.6

(a) $V_{TN} = V_{TNO} = 0.4$ V

(b) $$V_{TN} = V_{TNO} + \gamma\left[\sqrt{2\phi_f + \upsilon_{SB}} - \sqrt{2\phi_f}\right]$$

$$= 0.4 + 0.15\left[\sqrt{2(0.35)+0.5} - \sqrt{2(0.35)}\right] \Rightarrow V_{TN} = 0.439 \text{ V}$$

(c) $$V_{TN} = 0.4 + 0.15\left[\sqrt{2(0.35)+1.5} - \sqrt{2(0.35)}\right] \Rightarrow V_{TN} = 0.497 \text{ V}$$

TYU3.7

$$V_{DS} = 2.2 - (0.07)R_D = 1.2 \Rightarrow R_D = 14.3\,\text{k}\Omega$$

$$V_{GS} = \sqrt{\frac{I_{DQ}}{K_n}} + V_{TN} = \sqrt{\frac{70}{30}} + 0.25 = 1.778 \text{ V}$$

$$V_{GS} = 1.778 = \left(\frac{R_2}{R_1 + R_2}\right) \cdot V_{DD} = \left(\frac{R_2}{500}\right)(2.2)$$

We find

$$R_2 = 404 \text{ k}\Omega, \quad R_1 = 96 \text{ k}\Omega$$

TYU3.8

$$I_D = \frac{3.3 - 1.6}{10} = 0.17 \text{ mA}$$

$$0.17 = \left(\frac{0.1}{2}\right)\left(\frac{W}{L}\right)(1.6 - 0.4)^2 \Rightarrow \frac{W}{L} = 2.36$$

TYU3.9

(a) The transition point is

$$V_{It} = \frac{V_{DD} - V_{TNL} + V_{TND}\left(1 + \sqrt{K_{nD}/K_{nL}}\right)}{1 + \sqrt{K_{nD}/K_{nL}}}$$

$$= \frac{5 - 1 + 1\left(1 + \sqrt{0.05/0.01}\right)}{1 + \sqrt{0.05/0.01}}$$

$$= \frac{7.236}{3.236} \Rightarrow \underline{V_{It} = 2.236 \text{ V}}$$

$$V_{Ot} = V_{It} - V_{TND} = 2.24 - 1 \Rightarrow \underline{V_{Ot} = 1.24\ V}$$

(b) We may write

$$I_D = K_{nD}\left(V_{GSD} - V_{TND}\right)^2 = (0.05)(2.236 - 1)^2 \Rightarrow \underline{I_D = 76.4\ \mu A}$$

TYU3.10

(a) $V_{DS} > [0-(-1.2)] \Rightarrow$ Saturation

$$I_D = \frac{3.3-1.8}{8} = 0.1875 \text{ mA}$$

$$0.1875 = \left(\frac{0.08}{2}\right)\left(\frac{W}{L}\right)[0-(-1.2)]^2 \Rightarrow \frac{W}{L} = 3.26$$

(b) $V_{DS} < [0-(-1.2)] \Rightarrow$ Nonsaturation

$$I_D = \frac{3.3-0.8}{8} = 0.3125 \text{ mA}$$

$$0.3125 = \left(\frac{0.08}{2}\right)\left(\frac{W}{L}\right)\left[2(0-(-1.2))(0.8)-(0.8)^2\right] \Rightarrow \frac{W}{L} = 6.10$$

TYU3.11

(a) Transition point for the load transistor – Driver is in the saturation region.

$$I_{DD} = I_{DL}$$

$$K_{nD}\left(V_{GSD}-V_{TND}\right)^2 = K_{nL}\left(V_{GSL}-V_{TNL}\right)^2$$

$$V_{DSL}(sat) = V_{GSL}-V_{TNL} = -V_{TNL} \Rightarrow V_{DSL} = V_{DD}-V_{Ot} = 2\ V$$

Then $V_{Ot} = 5-2 = 3\ V$, $\underline{V_{Ot} = 3\ V}$

$$\sqrt{\frac{K_{nD}}{K_{nL}}}\left(V_{It}-1\right) = \left(-V_{TNL}\right)$$

$$\sqrt{\frac{0.08}{0.01}}\left(V_{It}-1\right) = 2 \Rightarrow \underline{V_{It} = 1.89\ V}$$

(b) For the driver:

$$V_{Ot} = V_{It}-V_{TND}$$

$$\underline{V_{It} = 1.89\ V,\ V_{Ot} = 0.89\ V}$$

TYU3.12

Transistor biased in nonsaturation

$$I_D = K_n\left[2(V_{GS}-V_{TN})V_{DS}-V_{DS}^2\right] = (4)\left[2(10-0.7)(0.2)-(0.2)^2\right] = 14.72 \text{ mA}$$

$$R_D = \frac{10-0.2}{14.72} = 0.666 \text{ k}\Omega$$

TYU3.13

(a) Transistor biased in the nonsaturation region

$$I_D = \frac{5-1.5-V_{DS}}{R} = 12$$

$$I_D = K_n\left[2\left(V_{GS}-V_{TN}\right)V_{DS}-V_{DS}^2\right]$$

$$12 = 4\left[2(5-0.8)V_{DS}-V_{DS}^2\right]$$

$$4V_{DS}^2-33.6V_{DS}+12 = 0 \Rightarrow \underline{V_{DS} = 0.374\ V}$$

Then $R = \dfrac{5-1.5-0.374}{12} \Rightarrow \underline{R = 261\ \Omega}$

TYU3.14

$$I_D = \frac{5 - V_O}{R_D} = K_n\left[2\left(V_2 - V_{TN}\right)V_O - V_O^2\right]$$

a.

$$\frac{5 - (0.10)}{25} = K_n\left[2(5-1)(0.10) - (0.10)^2\right] \Rightarrow \underline{K_n = 0.248\ mA/V^2}$$

$$\frac{5 - V_0}{25} = 2(0.248)\left[2(5-1)V_0 - V_0^2\right]$$

$$5 - V_0 = 12.4\left[8V_0 - V_0^2\right]$$

$$12.4V_0^2 - 100.2V_0 + 5 = 0$$

$$V_0 = \frac{100.2 \pm \sqrt{(100.2)^2 - 4(12.4)(5)}}{2(12.4)} \Rightarrow \underline{V_0 = 0.0502\ \text{V}}$$

b.

TYU3.15

$$V_{SGC} = \sqrt{\frac{I_{REF2}}{K_{pC}}} - V_{TP} = \sqrt{\frac{40}{40}} + 0.3 \Rightarrow V_{SGC} = V_{SGB} = 1.30\ \text{V}$$

$$I_{Q2} = K_{pB}\left(V_{SGB} + V_{TP}\right)^2 = 60(1.30 - 0.3)^2 = 60\,\mu\text{A}$$

$$V_{SGA} = \sqrt{\frac{I_{Q2}}{K_{pA}}} - V_{TP} = \sqrt{\frac{60}{75}} + 0.3 = 1.19\ \text{V}$$

TYU3.16

$$I_Q = K_{n1}\left(V_{GS1} - V_{TN}\right)^2$$

$$120 = K_{n1}(1.5 - 0.7)^2 \Rightarrow K_{n1} = 187.5\,\mu\text{A/V}^2$$

$$V_{GS2} = V_{GS3} = 2\ \text{V}$$

$$120 = K_{n2}(2 - 0.7)^2 \Rightarrow K_{n2} = 71.0\,\mu\text{A/V}^2$$

$$I_{REF} = K_{n3}\left(V_{GS3} - V_{TN}\right)^2$$

$$80 = K_{n3}(2 - 0.7)^2 \Rightarrow K_{n3} = 47.3\,\mu\text{A/V}^2$$

$$V_{GS4} = 5 - 2 = 3\ \text{V}$$

$$80 = K_{n4}(3 - 0.7)^2 \Rightarrow K_{n4} = 15.12\,\mu\text{A/V}^2$$

TYU3.17

$$I_{DQ} = K\left(V_{GS} - V_{TN}\right)^2 \Rightarrow 5 = 50\left(V_{GS} - 0.15\right)^2 \Rightarrow \underline{V_{GS} = 0.466\ \text{V}}$$

$$V_S = (0.005)(10) = 0.050\ \text{V} \Rightarrow V_{GG} = V_{GS} + V_S = 0.466 + 0.050 \Rightarrow \underline{V_{GG} = 0.516\ \text{V}}$$

$$V_D = 5 - (0.005)(100) \Rightarrow V_D = 4.5\ \text{V}$$

$$V_{DS} = V_D - V_S = 4.5 - 0.050 \Rightarrow \underline{V_{DS} = 4.45\ \text{V}}$$

TYU3.18

$$I_D = K\left[2\left(V_{GS} - V_{TN}\right)V_{DS} - V_{DS}^2\right]$$

$$= 100\left[2\left(0.7 - 0.2\right)\left(0.1\right) - \left(0.1\right)^2\right]$$

$$I_D = 9\ \mu\text{A}$$

$$R_D = \frac{2.5 - 0.1}{0.009} \Rightarrow \underline{R_D = 267\ \text{k}\Omega}$$

Chapter 4

Exercise Solutions

EX4.1

$$g_m = 2\sqrt{\left(\frac{k_n'}{2}\right)\left(\frac{W}{L}\right)I_{DQ}}$$

$$1.8 = 2\sqrt{\left(\frac{0.1}{2}\right)\left(\frac{W}{L}\right)(0.8)} \Rightarrow \frac{W}{L} = 20.25$$

EX4.2

(a) $K_n = \left(\frac{k_n'}{2}\right)\left(\frac{W}{L}\right) = \left(\frac{0.1}{2}\right)(50) = 2.5 \text{ mA/V}^2$

$$I_{DQ} = K_n(V_{GSQ} - V_{TN})^2$$

$$0.25 = 2.5(V_{GSQ} - 0.4)^2 \Rightarrow V_{GSQ} = 0.716V$$

$$V_{DSQ} = V_{DD} - I_{DQ}R_D = 3.3 - (0.25)(10) = 0.8 \text{ V}$$

$$V_{DS}(sat) = V_{GS} - V_{TN} = 0.717 - 0.4 = 0.316 \text{ V} \Rightarrow V_{DS} > V_{DS}(sat)$$

(b)

$$g_m = 2\sqrt{K_n I_{DQ}} = 2\sqrt{(2.5)(0.25)} = 1.58 \text{ mA/V}$$

$$r_o = \frac{1}{\lambda I_{DQ}} = \frac{1}{(0.025)(0.25)} = 160 \text{ k}\Omega$$

(c) $A_\upsilon = -g_m(r_o \| R_D) = -(1.58)(160\|10) = -14.9$

EX4.3

$$V_{GS} = \left(\frac{R_2}{R_1 + R_2}\right)V_{DD} = \left(\frac{320}{520+320}\right)(5) = 1.905 \text{ V}$$

$$I_{DQ} = 0.20(1.905 - 0.8)^2 = 0.244 \text{ mA}$$

$$g_m = 2\sqrt{K_n I_{DQ}} = 2\sqrt{(0.2)(0.244)} = 0.442 \text{ mA/V}$$

(a) $r_o = \infty$

(b) $A_v = -g_m R_D = -(0.422)(10) = -4.22$

(c) $R_i = R_1 \| R_2 = 520\|320 = 198 \text{ k}\Omega$

(d) $R_O = R_D = 10 \text{ K}$

EX4.4

At transition point, $I_D = 1 \text{ mA}$

$$I_D = K_n(V_{GSt} - V_{TN})^2 = K_n(V_{DS}(\text{sat}))^2$$

$$1 = 0.2(V_{DS}(\text{sat}))^2 \Rightarrow V_{DS}(\text{sat}) = 2.236 \text{ V}$$

Want $V_{DSQ} = \dfrac{5-2.236}{2} + 2.236 = 3.62\text{ V}$

$$R_D = \frac{5-3.62}{0.5} = 2.76\text{ k}\Omega$$

$$0.5 = 0.2(V_{GSQ} - 0.8)^2 \Rightarrow V_{GSQ} = 2.38\text{ V}$$

$$V_{GSQ} = \left(\frac{R_2}{R_1+R_2}\right)V_{DD} = \frac{1}{R_1}(R_1 \| R_2)V_{DD}$$

So $2.38 = \dfrac{1}{R_1}(200)(5) \Rightarrow R_1 = 420\text{ K}$ and $R_2 = 382\text{ K}$

$$A_v = -g_m R_D$$

$$g_m = 2\sqrt{K_n I_{DQ}} = 2\sqrt{(0.2)(0.5)} = 0.6325\text{ mA/V}$$

$$A_v = -(0.6325)(2.76)$$

$$= -1.75$$

EX4.5

(a) $V_G = \left(\dfrac{35}{35+165}\right)(10) - 5 = -3.25\text{ V}$

$$V_G = V_{GS} + I_D R_S - 5$$

So

$$5 - 3.25 = V_{GS} + K_n R_S (V_{GS} - V_{TN})^2$$

$$1.75 = V_{GS} + (1)(0.5)(V_{GS}^2 - 1.6V_{GS} + 0.64)$$

or

$$0.5V_{GS}^2 + 0.2V_{GS} - 1.43 = 0 \Rightarrow V_{GS} = 1.503\text{ V}$$

Then

$$I_{DQ} = (1)(1.503 - 0.8)^2 = 0.4942\text{ mA}$$

$$V_{DSQ} = 10 - (0.4942)(7 + 0.5) = 6.29\text{ V}$$

(b)

$$g_m = 2\sqrt{K_n I_{DQ}} = 2\sqrt{(1)(0.4942)} = 1.406\text{ mA/V}$$

$$A_\upsilon = \frac{-g_m R_D}{1 + g_m R_S} = \frac{-(1.406)(7)}{1 + (1.406)(0.5)} = -5.78$$

EX4.6

(a) $K_p = \left(\dfrac{k_p'}{2}\right)\left(\dfrac{W}{L}\right) = \left(\dfrac{0.04}{2}\right)(40) = 0.80\text{ mA/V}^2$

$$3 = K_p R_S (V_{SGQ} + V_{TP})^2 + V_{SGQ}$$

$$3 = (0.8)(1.2)(V_{SGQ}^2 - 0.8V_{SGQ} + 0.16) + V_{SGQ}$$

or

$$0.96V_{SGQ}^2 + 0.232V_{SGQ} - 2.846 = 0 \Rightarrow V_{SGQ} = 1.605\text{ V}$$

$$I_{DQ} = (0.8)(1.605 - 0.4)^2 = 1.162\text{ mA}$$

$$V_{SDQ} = 6 - (1.162)(1.2 + 2) = 2.283\text{ V}$$

(b)

$$g_m = 2\sqrt{K_p I_{DQ}} = 2\sqrt{(0.8)(1.162)} = 1.928 \text{ mA/V}$$

$$r_o = \frac{1}{\lambda I_{DQ}} = \frac{1}{(0.02)(1.162)} = 43.03 \text{ k}\Omega$$

$$A_\upsilon = -g_m (r_o \| R_D) = -(1.928)(43.03 \| 2) = -3.68$$

EX4.7

$$V_{DSQ} = V_{DD} - I_{DQ} R_S$$

$$5 = 10 - (1.5) R_S \Rightarrow \underline{R_S = 3.33 \text{ k}\Omega}$$

$$I_{DQ} = K_n (V_{GS} - V_{TN})^2 \Rightarrow 1.5 = (1)(V_{GS} - 0.8)^2$$

$$V_{GS} = 2.025 \text{ V} = V_G - V_S = V_G - 5 \Rightarrow V_G = 7.025 \text{ V} = \left(\frac{R_2}{R_1 + R_2}\right) V_{DD} = \frac{R_2}{400} \cdot 10$$

So $\underline{R_2 = 281 \text{ k}\Omega,}$ $\underline{R_1 = 119 \text{ k}\Omega}$

Neglecting R_{Si}, $A_\upsilon = \dfrac{g_m (R_S \| r_o)}{1 + g_m (R_S \| r_o)}$

$$r_o = [\lambda I_{DQ}]^{-1} = [(0.015)(1.5)]^{-1} = 44.4 \text{ k}\Omega$$

$$R_S \| r_o = 3.33 \| 44.4 = 3.1 \text{ k}\Omega$$

$$g_m = 2\sqrt{K_n I_{DQ}} = 2\sqrt{(1)(1.5)} = 2.45 \text{ mA/V}$$

$$A_\upsilon = \frac{(2.45)(3.1)}{1 + (2.45)(3.1)} \Rightarrow A_\upsilon = 0.884$$

EX4.8

(a) $V_{SG} = V_{DD} - I_D R_S = 5 - (1.5)(2) = 2 \text{ V}$

$$I_D = \left(\frac{k_p'}{2}\right)\left(\frac{W}{L}\right)(V_{SG} + V_{TP})^2$$

$$1.5 = \left(\frac{0.04}{2}\right)\left(\frac{W}{L}\right)(2 - 1.2)^2 \Rightarrow \frac{W}{L} = 117$$

(b) $K_p = \left(\dfrac{k_p'}{2}\right)\left(\dfrac{W}{L}\right) = \left(\dfrac{0.04}{2}\right)(117) = 2.344 \text{ mA/V}^2$

$$g_m = 2\sqrt{K_p I_D} = 2\sqrt{(2.344)(1.5)} = 3.75 \text{ mA/V}$$

$$A_\upsilon = \frac{g_m R_S}{1 + g_m R_S} = \frac{(3.75)(2)}{1 + (3.75)(2)} = 0.882$$

(c) $A_\upsilon = \dfrac{g_m (R_S \| R_L)}{1 + g_m (R_S \| R_L)} = (0.9)(0.882) = 0.794$

Then

$$(0.794)[1 + (3.75)(R_S \| R_L)] = (3.75)(R_S \| R_L) \Rightarrow R_S \| R_L = 2 \| R_L = 1.028$$

So

$$R_L = 2.12 \text{ k}\Omega$$

EX4.9

$$V_G = \left(\frac{R_2}{R_1 + R_2}\right) V_{DD} = \left(\frac{9.3}{70.7 + 9.3}\right)(5)$$
$$= 0.581 \text{ V}$$
$$I_{DQ} = K_p \left(V_{SG} - |V_{TP}|\right)^2 = K_P \left(V_S - V_G - |V_{TP}|\right)^2$$
$$= \frac{5 - V_S}{R_S}$$

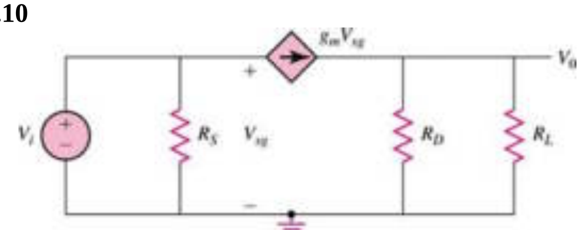
Then $(0.4)(5)(V_S - 0.581 - 0.8)^2 = 5 - V_S$

$$2(V_S - 1.381)^2 = 5 - V_S$$
$$2(V_S^2 - 2.762V_S + 1.907) = 5 - V_S$$
$$2V_S^2 - 4.52V_S - 1.19 = 0$$
$$V_S = \frac{4.52 \pm \sqrt{(4.52)^2 + 4(2)(1.19)}}{2(2)}$$
$$V_S = 2.50 \text{ V} \Rightarrow I_{DQ} = \frac{5 - 2.5}{5} = 0.5 \text{ mA}$$
$$g_m = 2\sqrt{K_p I_{DQ}} = 2\sqrt{(0.4)(0.5)} = 0.894 \text{ mA/V}$$
$$A_\upsilon = \frac{g_m R_S}{1 + g_m R_S} \cdot \frac{R_1 \| R_2}{R_1 \| R_2 + R_{Si}}$$
$$= \frac{(0.894)(5)}{1 + (0.894)(5)} \cdot \frac{70.7 \| 9.3}{70.7 \| 9.3 + 0.5} \Rightarrow A_\upsilon = 0.770$$

Neglecting R_{Si}, $A_v = 0.817$

$$R_o = R_S \left\| \frac{1}{g_m} = 5 \right\| \frac{1}{0.894} = 5 \| 1.12 \Rightarrow R_o = 0.915 \text{ k}\Omega$$

EX4.10



$$V_O = g_m V_{sg}\left(R_D \| R_L\right) \text{ and } V_{sg} = V_i$$
$$A_\upsilon = g_m \left(R_D \| R_L\right)$$
$$I_{DQ} = \frac{5 - V_{SG}}{R_S} = K_p \left(V_{SG} - |V_{TP}|\right)^2$$
$$5 - V_{SG} = (1)(4)(V_{SG} - 0.8)^2$$
$$5 - V_{SG} = 4(V_{SG}^2 - 1.6V_{SG} + 0.64)$$
$$4V_{SG}^2 - 5.4V_{SG} - 2.44 = 0$$

$$V_{SG} = \frac{5.4 \pm \sqrt{(5.4)^2 + (4)(4)(2.44)}}{2(4)}$$

$$V_{SG} = 1.71 \text{ V}$$

$$I_{DQ} = \frac{5 - 1.71}{4} = 0.822 \text{ mA}$$

$$g_m = 2\sqrt{K_p I_{DQ}} = 2\sqrt{(1)(0.822)} = 1.81 \text{ mA/V}$$

$$A_\upsilon = (1.81)(2\|4) = (1.81)(1.33) \Rightarrow A_\upsilon = 2.41$$

$$R_{in} = R_S \left\| \frac{1}{g_m} = 4 \right\| \frac{1}{1.81} = 4\|0.552 \Rightarrow R_{in} = 0.485 \text{ k}\Omega$$

EX4.11

(a) $$|A_\upsilon| = 8 = \sqrt{\frac{(W/L)_D}{(W/L)_L}} = \sqrt{\frac{(W/L)_D}{1.2}} \Rightarrow \left(\frac{W}{L}\right)_D = 76.8$$

(b) $$V_{GSDt} = \frac{(V_{DD} - V_{TNL}) + V_{TND}\left(1 + \sqrt{\frac{K_{nD}}{K_{nL}}}\right)}{1 + \sqrt{\frac{K_{nD}}{K_{nL}}}} = \frac{(3.3 - 0.4) + (0.4)(1 + 8)}{1 + 8}$$

or $V_{GSDt} = 0.7222$ V

So

$$V_{GSDQ} = \frac{0.7222 - 0.4}{2} + 0.4 = 0.561 \text{ V}$$

EX4.12

$$A_\upsilon = -g_{mD}(r_{oD}\|r_{oL})$$

$$r_{oD} = r_{oL} = \frac{1}{\lambda I_{DQ}} = \frac{1}{(0.02)(0.1)} = 500 \text{ k}\Omega$$

$$g_{mD} = 2\sqrt{K_{nD} I_{DQ}} = 2\sqrt{(0.25)(0.1)} = 0.3162 \text{ mA/V}$$

Then

$$A_\upsilon = -(0.3162)(500\|500) = -79.1$$

EX4.13

$$A_\upsilon = -g_m(r_{on}\|r_{op})$$

$$r_{on} = r_{op} = \frac{1}{(0.015)(0.1)} = 666.7 \text{ k}\Omega$$

$$-250 = -g_m(666.7\|666.7)$$

$$g_m = 0.75 \text{ mA/V} = 2\sqrt{K_n I_{DQ}} = 2\sqrt{K_n(0.1)}$$

$$K_n = 1.406 \text{ mA/V}^2 = \frac{k_n'}{2}\left(\frac{W}{L}\right) = \left(\frac{0.080}{2}\right)\left(\frac{W}{L}\right) \Rightarrow \left(\frac{W}{L}\right)_1 = 35.2$$

EX4.14

(a)

$$R_O = \frac{1}{g_{m1}} \| r_{o2} \| r_{o1} \approx \frac{1}{g_{m1}}$$

So $g_{m1} = \frac{1}{R_0} = \frac{1}{2} = 0.5$ mA/V

$$g_{m1} = 2\sqrt{K_n I_D}$$

$$0.5 = 2\sqrt{(0.2) I_D} \Rightarrow \underline{I_D = 0.3125 \text{ mA}}$$

(b)

$$A_\upsilon = \frac{g_{m1}(r_{o1} \| r_{o2})}{1 + g_{m1}(r_{o1} \| r_{o2})}$$

$$r_{o1} = r_{o2} = \frac{1}{(0.01)(0.3125)} = 320 \text{ k}\Omega$$

$$A_\upsilon = \frac{(0.5)(320 \| 320)}{1 + (0.5)(320 \| 320)}$$

$$A_\upsilon = 0.988$$

EX4.15

(a)

$$A_v = \frac{g_{m1} + \frac{1}{r_{o1}}}{\frac{1}{r_{o2}} + \frac{1}{r_{o1}}} = \frac{2\sqrt{K_n I_D} + \lambda_1 I_D}{\lambda_2 I_D + \lambda_1 I_D}$$

$$120 = \frac{2\sqrt{0.2 I_D} + 0.01 I_D}{0.01 I_D + 0.01 I_D}$$

$$2.4 I_D - 0.01 I_D = 2\sqrt{0.2 I_D}$$

$$2.39\sqrt{I_D} = 2\sqrt{0.2} \Rightarrow \underline{I_D = 0.140 \text{ mA}}$$

$$g_{m1} = 2\sqrt{(0.2)(0.14)} \Rightarrow \underline{g_{m1} = 0.335 \text{ mA/V}}$$

(b)

$$R_o = r_{o1} \| r_{o2}$$

$$r_{o1} = r_{o2} = \frac{1}{(0.01)(0.14)} = 714 \text{ k}\Omega$$

$$R_o = 714 \| 714 = 357 \text{ k}\Omega$$

EX4.16

$$R_o = R_{S2} \left\| \frac{1}{g_{m2}} \right.$$

$$g_{m2} = 0.632 \text{ mA/V}, \quad R_{S2} = 8 \text{ k}\Omega$$

$$R_o = 8 \left\| \frac{1}{0.632} \right. = 8 \| 1.58 \Rightarrow R_o = 1.32 \text{ k}\Omega$$

EX4.17

(a) $$V_{G1} = \left(\frac{54.6}{54.6+150+95.4}\right)(5) = \left(\frac{54.6}{300}\right)(5) = 0.91 \text{ V}$$

$$V_{G2} = \left(\frac{54.6+150}{300}\right)(5) = 3.41 \text{ V}$$

$$V_{G1} = V_{GS1} + K_{n1}R_S\left(V_{GS1} - V_{TN}\right)^2 - 5$$

$$5.91 = V_{GS1} + (3)(10)\left(V_{GS1}^2 - 1.6V_{GS1} + 0.64\right)$$

or

$$30V_{GS1}^2 - 47V_{GS1} + 13.29 = 0 \Rightarrow V_{GS1} = 1.196 \text{ V}$$

Then

$$I_{DQ} = (3)(1.196 - 0.8)^2 = 0.471 \text{ mA}$$

$$V_{D1} = V_{G2} - V_{GS2} = 3.41 - 1.196 = 2.214 \text{ V}$$

$$V_{S1} = V_{G1} - V_{GS1} = 0.91 - 1.196 = -0.286 \text{ V}$$

Then

$$V_{DSQ1} = 2.214 - (-0.286) = 2.5 \text{ V}$$

$$V_{D2} = 5 - (0.471)(2.5) = 3.8225 \text{ V}$$

$$V_{DSQ2} = 3.8225 - 2.214 = 1.61 \text{ V}$$

(b)

$$g_{m1} = 2\sqrt{K_{n1}I_{DQ}} = 2\sqrt{(3)(0.471)} = 2.377 \text{ mA/V}$$

$$A_\upsilon = -g_{m1}R_D = -(2.377)(2.5) = -5.94$$

EX4.18

$$V_S = I_{DQ}R_S = (1.2)(2.7) = 3.24 \text{ V}$$

$$V_D = V_S + V_{DSQ} = 3.24 + 12 = 15.24 \text{ V}$$

$$R_D = \frac{20 - 15.24}{1.2} \Rightarrow R_D = 3.97 \text{ k}\Omega$$

$$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2$$

$$1.2 = 4\left(1 - \frac{V_{GS}}{V_P}\right)^2 \Rightarrow \frac{V_{GS}}{V_P} = 0.4523$$

$$V_{GS} = (0.4523)(-3) = -1.357 \text{ V}$$

$$V_G = V_S + V_{GS} = 3.24 - 1.357 = 1.883 \text{ V}$$

$$V_G = \left(\frac{R_2}{R_1+R_2}\right)(20) = \left(\frac{R_2}{500}\right)(20) = 1.88 \Rightarrow R_2 = 47 \text{ k}\Omega, \quad R_1 = 453 \text{ k}\Omega$$

$$r_o = \frac{1}{\lambda I_{DQ}} = \frac{1}{(0.005)(1.2)} = 167 \text{ k}\Omega$$

$$g_m = \frac{2I_{DSS}}{(-V_P)}\left(1 - \frac{V_{GS}}{V_P}\right) = \frac{2(4)}{(3)}\left(1 - \frac{1.357}{3}\right) = 1.46 \text{ mA/V}$$

$$A_\upsilon = -g_m\left(r_o \| R_D \| R_L\right) = -(1.46)(167 \| 3.97 \| 4) \Rightarrow A_\upsilon = -2.87$$

EX4.19

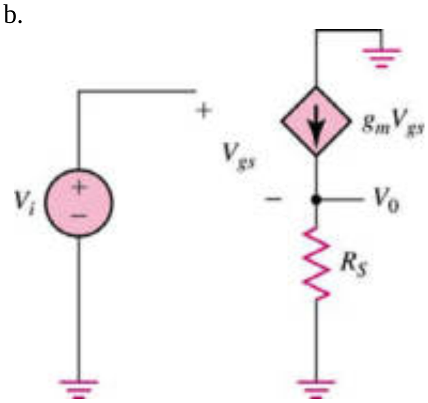
a.

$$I_{DQ} = I_{DSS}\left(1-\frac{V_{GS}}{V_P}\right)^2 \quad 2 = 8\left(1-\frac{V_{GS}}{V_P}\right)^2 \Rightarrow \frac{V_{GS}}{V_P} = 0.5$$

$$V_{GS} = (0.5)(-3.5) \Rightarrow V_{GS} = -1.75$$

$$\text{Also } I_{DQ} = \frac{-V_{GS}-(-10)}{R_S}\, 2 = \frac{1.75+10}{R_S} \Rightarrow \underline{R_S = 5.88 \text{ k}\Omega}$$

b.



$$g_m = \frac{2I_{DSS}}{|V_P|}\left(1-\frac{V_{GS}}{V_P}\right) = \frac{2(8)}{3.5}\left(1-\frac{1.75}{3.5}\right) = 2.29 \text{ mA/V}$$

$$r_o = \frac{1}{(0.01)(2)} = 50 \text{ k}\Omega$$

$$V_i = V_{gs} + g_m R_S V_{gs} \Rightarrow V_{gs} = \frac{V_i}{1+g_m R_S}$$

$$A_\upsilon = \frac{V_o}{V_i} = \frac{g_m (R_S \| r_o)}{1+g_m (R_S \| r_o)} = \frac{(2.29)(5.88\|50)}{1+(2.29)(5.88\|50)} \Rightarrow A_\upsilon = 0.9234$$

c.

$$A_\upsilon = \frac{g_m (R_S \| R_L \| r_o)}{1+g_m (R_S \| R_L \| r_o)} = (0.80)(0.9234) = 0.7387$$

$$0.7387 = \frac{(2.29)(R_S \| R_L \| r_o)}{1+(2.29)(R_S \| R_L \| r_o)} \Rightarrow R_S \| R_L \| r_o = 1.235 \text{ k}\Omega$$

$$R_S \| r_o = 5.261 \text{ k}\Omega$$

$$\text{Then} \quad \frac{(5.261)R_L}{5.261+R_L} = 1.235 \Rightarrow R_L = 1.61 \text{ k}\Omega$$

Test Your Understanding Solutions

TYU4.1

(a) $g_m = 2\sqrt{\left(\frac{k_n'}{2}\right)\left(\frac{W}{L}\right)I_{DQ}}$

$(2.5)^2 = 4\left[\left(\frac{0.1}{2}\right)\left(\frac{W}{L}\right)(1.2)\right] \Rightarrow \frac{W}{L} = 26.0$

(b) $r_o = \frac{1}{\lambda I_{DQ}} = \frac{1}{(0.015)(1.2)} = 55.6\ \text{k}\Omega$

TYU4.2

(a) $I_{DQ} = K_n\left(V_{GSQ} - V_{TN}\right)^2$

$0.15 = 0.5\left(V_{GSQ} - 0.4\right)^2 \Rightarrow V_{GSQ} = 0.948\ \text{V}$

$V_{DSQ} = 3.3 - (0.15)(8) = 2.1\ \text{V}$

(b)

$g_m = 2\sqrt{K_n I_{DQ}} = 2\sqrt{(0.5)(0.15)} = 0.548\ \text{mA/V}$

$r_o = \frac{1}{\lambda I_{DQ}} = \frac{1}{(0.02)(0.15)} = 333\ \text{k}\Omega$

$A_\upsilon = -g_m\left(r_o \| R_D\right) = -(0.548)(333\|8) = -4.28$

TYU4.3

$i_D = I_{DQ} + i_d = I_{DQ} + g_m \upsilon_{gs}$

$i_D = 0.15 + (0.548)(0.025)\sin\omega t$

or

$i_D = 0.15 + 0.0137\sin\omega t\ (\text{mA})$

Also

$\upsilon_{DS} = V_{DSQ} + \upsilon_d = 2.1 - (0.0137)(8)\sin\omega t$

or

$\upsilon_{DS} = 2.1 - (0.11)\sin t\ \ (\text{V})$

TYU4.4

(a) $V_{SDQ} = V_{DD} - I_{DQ}R_D$

$3 = 5 - I_{DQ}(5) \Rightarrow I_{DQ} = 0.4\ \text{mA}$

$I_{DQ} = K_p\left(V_{SGQ} + V_{TP}\right)^2$

$0.4 = 0.4\left(V_{SGQ} - 0.4\right)^2 \Rightarrow V_{SGQ} = 1.4\ \text{V}$

(b) $g_m = 2\sqrt{K_p I_{DQ}} = 2\sqrt{(0.4)(0.4)} = 0.8\ \text{mA/V}$

$A_\upsilon = -g_m R_D = -(0.8)(5) = -4$

TYU4.5

$$\eta = \frac{\gamma}{2\sqrt{2\phi_f + v_{SB}}}$$

(a)

$$\eta = \frac{0.40}{2\sqrt{2(0.35)+1}} \Rightarrow \underline{\eta = 0.153}$$

$$\eta = \frac{0.40}{2\sqrt{2(0.35)+3}} \Rightarrow \underline{\eta = 0.104}$$

(b) $g_m = 2\sqrt{K_n I_{DQ}} = 2\sqrt{(0.5)(0.75)} = 1.22\ mA/V$

For (a), $g_{mb} = g_m \eta = (1.22)(0.153) \Rightarrow \underline{g_{mb} = 0.187\ mA/V}$

For (b), $g_{mb} = (1.22)(0.104) \Rightarrow \underline{g_{mb} = 0.127\ mA/V}$

TYU4.6

a. With $R_G \Rightarrow V_{GS} = V_{DS} \Rightarrow$ transistor biased in sat. region

$$I_D = K_n(V_{GS} - V_{TN})^2 = K_n(V_{DS} - V_{TN})^2$$

$$V_{DS} = V_{DD} - I_D R_D = V_{DD} - K_n R_D (V_{DS} - V_{TN})^2$$

$$V_{DS} = 15 - (0.15)(10)(V_{DS} - 1.8)^2$$

$$= 15 - 1.5(V_{DS}^2 - 3.6V_{DS} + 3.24)$$

$$1.5V_{DS}^2 - 4.4V_{DS} - 10.14 = 0$$

$$V_{DS} = \frac{4.4 \pm \sqrt{(4.4)^2 + (4)(1.5)(10.14)}}{2(1.5)} \Rightarrow \underline{V_{DSQ} = 4.45\text{ V}}$$

$$I_{DQ} = (0.15)(4.45 - 1.8)^2 \Rightarrow \underline{I_{DQ} = 1.05\text{ mA}}$$

b. Neglecting effect of R_G:

$$A_\upsilon = -g_m (R_D \| R_L)$$

$$g_m = 2K_n(V_{GS} - V_{TN}) = 2(0.15)(4.45 - 1.8) \Rightarrow g_m = 0.795\text{ mA/V}$$

$$A_\upsilon = -(0.795)(10\|5) \Rightarrow A_\upsilon = -2.65$$

c. $R_G \Rightarrow$ establishes $V_{GS} = V_{DS} \Rightarrow$ essentially no effect on small-signal voltage gain.

TYU4.7

a.

$$5 = I_{DQ}R_S + V_{SG} \text{ and } I_{DQ} = K_p\ (V_{SG} + V_{TP})^2$$

$$0.8 = 0.5(V_{SG} + 0.8)^2 \Rightarrow V_{SG} = 0.465\text{ V}$$

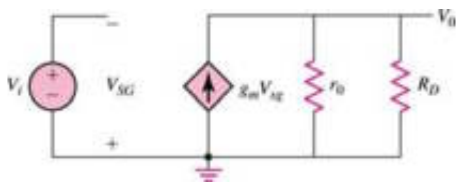
$$5 = (0.8)R_S + 0.465 \Rightarrow \underline{R_S = 5.67\text{ k}\Omega}$$

$$V_{SDQ} = 10 - I_{DQ}(R_S + R_D)$$

$$3 = 10 - (0.8)(5.67 + R_D)$$

$$R_D = \frac{10 - (0.8)(5.67) - 3}{0.8} \Rightarrow \underline{R_D = 3.08\text{ k}\Omega}$$

b.



$$V_o = g_m V_{sg}\left(R_D \| r_o\right) = -g_m V_i\left(R_D \| r_o\right)$$

$$A_\upsilon = \frac{V_o}{V_i} = -g_m\left(R_D \| r_o\right)$$

$$g_m = 2K_p\left(V_{SG} + V_{TP}\right) = 2(0.5)(0.465 + 0.8) = 1.265 \text{ mA/V}$$

$$r_o = \frac{1}{\lambda I_O} = \frac{1}{(0.02)(0.8)} = 62.5 \text{ k}\Omega$$

$$A_\upsilon = -(1.265)(3.08 \| 62.5) \Rightarrow A_\upsilon = -3.71$$

TYU4.8

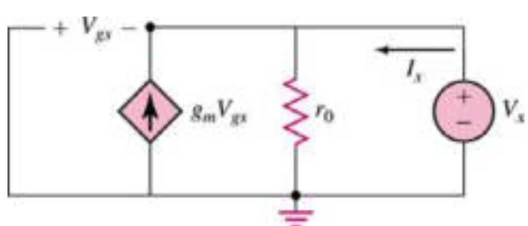
(a)

$$V_0 = g_m V_{gs} r_0$$

$$V_i = V_{gs} + V_0 \Rightarrow V_{gs} = V_i - V_0$$

$$\text{So } V_0 = g_m r_0\left(V_i - V_0\right)$$

$$A_v = \frac{V_0}{V_i} = \frac{g_m r_0}{1 + g_m r_0} = \frac{(4)(50)}{1 + (4)(50)} \Rightarrow \underline{A_v = 0.995}$$



$$I_x + g_m V_{gs} = \frac{V_x}{r_0} \text{ and } V_{gs} = -V_x$$

$$I_x = g_m V_x + \frac{V_x}{r_0} \Rightarrow R_0 = r_0 \left\| \frac{1}{g_m} \right. = 50 \left\| \frac{1}{4} \right. \Rightarrow \underline{R_0 \cong 0.25 \text{ k}\Omega}$$

(b) With $R_S = 4\,\text{k}\Omega \Rightarrow A_\upsilon = \dfrac{g_m\left(r_o \| R_S\right)}{1 + g_m\left(r_o \| R_S\right)}$

$$r_0 \| R_s = 50 \| 4 = 3.7 \text{ k}\Omega \Rightarrow A_v = \frac{(4)(3.7)}{1 + (4)(3.7)} \Rightarrow \underline{A_v = 0.937}$$

TYU4.9

(a)

$$g_m = 2\sqrt{K_n I_{DQ}} \Rightarrow 2 = 2\sqrt{K_n(0.8)} \Rightarrow K_n = 1.25\ mA/V^2$$

$$K_n = \frac{\mu_n C_{ox}}{2}\cdot\frac{W}{L} \Rightarrow 1.25 = (0.020)\left(\frac{W}{L}\right)$$

So $\underline{\frac{W}{L} = 62.5}$

$$I_{DQ} = K_n(V_{GS} - V_{TN})^2 \Rightarrow 0.8 = 1.25(V_{GS} - 2)^2 \Rightarrow \underline{V_{GS} = 2.8\text{ V}}$$

b.

$$r_o = [\lambda I_{DQ}]^{-1} = [(0.01)(0.8)]^{-1} = 125\text{ k}\Omega$$

$$A_\upsilon = \frac{g_m(r_o \| R_L)}{1 + g_m(r_o \| R_L)}$$

$$r_o \| R_L = 125 \| 4 = 3.88\text{ k}\Omega$$

$$A_\upsilon = \frac{(2)(3.88)}{1 + (2)(3.88)} \Rightarrow A_\upsilon = 0.886$$

$$R_o = \frac{1}{g_m} \| r_o = \frac{1}{2} \| 125 \Rightarrow R_o \cong 0.5\text{ k}\Omega$$

TYU4.10

$$R_{in} = \frac{1}{g_m} = 0.35\text{ k}\Omega \Rightarrow g_m = 2.86\text{ mA/V}$$

$$\frac{V_o}{I_i} = R_D \| R_L = 2.4 = R_D \| 4 \Rightarrow R_D = 6\text{ k}\Omega$$

$$g_m = 2\sqrt{K_n I_{DQ}}$$

$$2.86 = 2\sqrt{K_n(0.5)} \Rightarrow K_n = 4.09\text{ mA/V}^2$$

$$I_{DQ} = K_n(V_{GS} - V_{TN})^2$$

$$0.5 = 4.09(V_{GS} - 1)^2 \Rightarrow V_{GS} = 1.35\text{ V} \Rightarrow V_S = -1.35\text{ V}$$

$$V_D = 5 - (0.5)(6) = 2\text{ V}$$

$$V_{DS} = V_D - V_S = 2 - (-1.35) = 3.35\text{ V}$$

We have $V_{DS} = 3.35 > V_{GS} - V_{TN} = 1.35 - 1 = 0.35\ V \Rightarrow$ Biased in the saturation region

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TYU4.11

$$K_{n1} = \frac{\mu_n C_{ox}}{2}\cdot\left(\frac{W}{L}\right)_1 = (0.020)(80) = 1.6\ mA/V^2$$

$$K_{n2} = \frac{\mu_n C_{ox}}{2}\cdot\left(\frac{W}{L}\right)_2 = (0.020)(1) = 0.020\ mA/V^2$$

$$A_v = -\sqrt{\frac{K_{n1}}{K_{n2}}} = -\sqrt{\frac{1.6}{0.020}} \Rightarrow \underline{A_v = -8.94}$$

The transition point is determined from $v_{GSt} - V_{TND} = V_{DD} - V_{TNL} - \sqrt{\dfrac{K_{n1}}{K_{n2}}}\left(v_{GSt} - V_{TND}\right)$

$$v_{GSt} - 0.8 = (5 - 0.8) - (8.94)(v_{GSt} - 0.8)$$

$$v_{GSt} = \frac{(5-0.8)+(8.94)(0.8)+0.8}{1+8.94}$$

$$v_{GSt} = 1.22 \text{ V}$$

For Q-point in middle of saturation region $V_{GS} = \dfrac{1.22-0.8}{2} + 0.8 \Rightarrow \underline{V_{GS} = 1.01 \text{ V}}$

TYU4.12

(a) $$V_{G1} = \left(\frac{R_2}{R_1+R_2}\right)(10) - 5 = \left(\frac{135}{135+383}\right)(10) - 5 = -2.394 \text{ V}$$

$$V_{G1} = V_{GS1} + K_{n1}R_{S1}\left(V_{GS1} - V_{TN}\right)^2 - 5$$

or

$$5 - 2.394 = V_{GS1} + (1.5)(3.9)\left(V_{GS1}^2 - 1.2V_{GS1} + 0.36\right)$$

so

$$5.85V_{GS1}^2 - 6.02V_{GS1} - 0.5 = 0 \Rightarrow V_{GS1} = 1.106 \text{ V}$$

Then

$$I_{DQ1} = (1.5)(1.106 - 0.6)^2 = 0.3845 \text{ mA}$$

$$V_{DSQ1} = 10 - (0.3845)(3.9 + 16.1) = 2.31 \text{ V}$$

$$V_{G2} = 5 - (0.3845)(16.1) = -1.190 \text{ V}$$

$$V_{G2} = V_{GS2} + K_{n2}R_{S2}\left(V_{GS2} - V_{TN}\right)^2 - 5$$

or

$$5 - 1.19 = V_{GS2} + (2)(8)\left(V_{GS2}^2 - 1.2V_{GS2} + 0.36\right)$$

so

$$16V_{GS2}^2 - 18.2V_{GS2} + 1.95 = 0 \Rightarrow V_{GS2} = 1.018 \text{ V}$$

Then

$$I_{DQ2} = (2)(1.018 - 0.6)^2 = 0.349 \text{ mA}$$

$$V_{DSQ2} = 10 - (0.349)(8) = 7.208 \text{ V}$$

(b)

$$g_{m1} = 2\sqrt{K_{n1}I_{DQ1}} = 2\sqrt{(1.5)(0.3845)} = 1.519 \text{ mA/V}$$

$$g_{m2} = 2\sqrt{K_{n2}I_{DQ2}} = 2\sqrt{(2)(0.349)} = 1.671 \text{ mA/V}$$

From Example 4.16

$$A_\upsilon = \frac{-g_{m1}g_{m2}R_{D1}\left(R_{S2}\|R_L\right)}{1+g_{m2}\left(R_{S2}\|R_L\right)} \cdot \frac{R_i}{R_i + R_{Si}}$$

$$= \frac{-(1.519)(1.671)(16.1)(8\|4)}{1+(1.671)(8\|4)} \cdot \frac{99.8}{99.8+4}$$

or

$$A_\upsilon = -19.2$$

(c)

$$R_o = \frac{1}{g_{m2}} \| R_{S2} = \frac{1}{1.671} \| 8 = 0.5984 \| 8 \Rightarrow R_o = 557\,\Omega$$

TYU4.13

From Example 6.18

$$g_m = 3.0 \text{ mA/V}, \quad r_o = 41.7 \text{ k}\Omega$$

$$R_1 \| R_2 = 420 \| 180 = 126 \text{ k}\Omega$$

$$V_{gs} = \frac{R_1 \| R_2}{R_1 \| R_2 + R_i} \cdot V_i = \left(\frac{126}{126 + 20}\right) \cdot V_i = 0.863 \cdot V_i$$

$$A_\upsilon = \frac{-g_m V_{gs} \left(r_o \| R_D \| R_L\right)}{V_i}$$

$$= -(3.0)(0.863)(41.7 \| 2.7 \| 4) = -(2.589)(1.55) \Rightarrow A_\upsilon = -4.01$$

TYU4.14

a.

$$V_{G1} = \left(\frac{R_2}{R_1 + R_2}\right)(V_{DD})$$

$$V_{G1} = \left(\frac{430}{430 + 70}\right)(20) = 17.2 \text{ V}$$

$$I_{DQ1} = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2 = 6\left(1 - \frac{V_{G1} - V_{S1}}{2}\right)^2$$

$$= 6\left(1 - \frac{17.2}{2} + \frac{V_{S1}}{2}\right)^2 = 6\left(\frac{V_{S1}}{2} - 7.6\right)^2 \text{ and } I_{DQ1} = \frac{20 - V_{S1}}{4}$$

$$\text{Then } \frac{20 - V_{S1}}{4} = 6\left(\frac{V_{S1}}{2} - 7.6\right)^2$$

$$20 - V_{S1} = 24\left(\frac{V_{S1}^2}{4} - 7.6V_{S1} + 57.76\right)$$

$$= 6V_{S1}^2 - 182.4V_{S1} + 1386.24$$

$$6V_{S1}^2 - 181.4V_{S1} + 1366.24 = 0$$

$$V_{S1} = \frac{181.4 \pm \sqrt{(181.4)^2 - 4(6)(1366.24)}}{2(6)}$$

$$V_{S1} = 14.2 \text{ V} \Rightarrow V_{GS1} = 17.2 - 14.2 = 3 \text{ V} > V_P$$

$$\text{So } V_{S1} = 16.0 \Rightarrow V_{GS1} = 17.2 - 16 = 1.2 < V_P - Q$$

$$\text{on } I_{DQ1} = \frac{20 - 16}{4} \Rightarrow \underline{I_{DQ1} = 1 \text{ mA}}$$

$$V_{SDQ1} = 20 - I_{DQ1}\left(R_{S1} + R_{D1}\right)$$

$$= 20 - (1)(8) \Rightarrow \underline{V_{SDQ1} = 12 \text{ V}}$$

$$V_{D1} = I_{DQ1}R_{D1} = (1)(4) = 4 \text{ V} = V_{G2}$$

$$I_{DQ2} = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2 = 6\left(1 - \frac{V_{G2} - V_{S2}}{(-2)}\right)^2$$

$$= 6\left(1 + \frac{4}{2} - \frac{V_{S2}}{2}\right)^2 = 6\left(3 - \frac{V_{S2}}{2}\right)^2 \text{ and } I_{DQ2} = \frac{V_{S2}}{R_{S2}} = \frac{V_{S2}}{4}$$

Then $\dfrac{V_{S2}}{4} = 6\left(3 - \dfrac{V_{S2}}{2}\right)^2$

$$V_{S2} = 24\left(9 - 3V_{S2} + \frac{V_{S2}^2}{4}\right)$$

$$6V_{S2}^2 - 73V_{S2} + 216 = 0$$

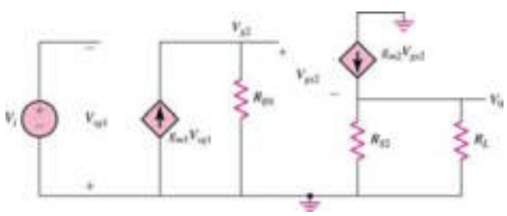
$$V_{S2} = \frac{73 \pm \sqrt{(73)^2 - 4(6)(216)}}{2(6)} \Rightarrow V_{S2} = 7.09 \text{ V or } = 5.08 \text{ V}$$

For $V_{S2} = 5.08\text{ V} \Rightarrow V_{GS2} = 4 - 5.08 = -1.08$ transistor biased ON

$$I_{DQ2} = \frac{5.08}{4} \Rightarrow \underline{I_{DQ2} = 1.27 \text{ mA}}$$

$$V_{DS2} = 20 - V_{S2} = 20 - 5.08 \Rightarrow \underline{V_{DS2} = 14.9 \text{ V}}$$

b.



$$V_{g2} = g_{m1}V_{sg1}R_{D1} = -g_{m1}V_iR_{D1}$$

$$V_o = g_{m2}V_{gs2}\left(R_{S2}\|R_L\right)$$

$$V_{g2} = V_{gs2} + V_o \Rightarrow V_{gs2} = \frac{V_{g2}}{1 + g_{m2}\left(R_{S2}\|R_L\right)}$$

$$A_\upsilon = \frac{V_o}{V_i} = \frac{-g_{m1}R_{D1}}{1 + g_{m2}\left(R_{S2}\|R_L\right)}$$

$$g_{m1} = \frac{2I_{DSS}}{|V_P|}\left(1 - \frac{V_{GS}}{V_P}\right)$$

$$= \frac{2(6)}{2}\left(1 - \frac{1.2}{2}\right) = 2.4 \text{ mA/V}$$

$$g_{m2} = \frac{2(6)}{2}\left(1 - \frac{1.08}{2}\right) = 2.76 \text{ mA/V}$$

Then $A_\upsilon = \dfrac{-(2.4)(4)}{1 + (2.76)(4\|2)} = -2.05$

Chapter 5

Exercise Solutions

EX5.1

$$I_E = (1+\beta)I_B$$

$$1+\beta = \frac{I_E}{I_B} = \frac{1.20}{0.0085} = 141.2 \Rightarrow \beta = 140.2$$

$$\alpha = \frac{\beta}{1+\beta} = \frac{140.2}{141.2} = 0.9929$$

$$I_C = I_E - I_B = 1.20 - 0.0085 = 1.1915 \text{ mA}$$

EX5.2

$$BV_{CEO} = \frac{BV_{CBO}}{\sqrt[n]{\beta}} = \frac{200}{\sqrt[3]{120}} \text{ or } BV_{CEO} = 40.5\ V$$

EX5.3

$$I_B = \frac{V_{BB} - V_{BE}(on)}{R_B} = \frac{2-0.7}{430} \Rightarrow I_B = 3.02\,\mu\text{A}$$

$$I_C = \beta I_B = (150)(3.02)\,\mu\text{A} \Rightarrow I_C = 0.453 \text{ mA}$$

$$V_{CE} = V_{CC} - I_C R_C = 3.3 - (0.453)(3.2) = 1.85 \text{ V}$$

$$P \cong I_C V_{CE} = (0.453)(1.85) = 0.838 \text{ mW}$$

EX5.4

$$I_B = \frac{V^+ - V_{EB}(on) - V_{BB}}{R_B} = \frac{3.3-0.7-1.2}{400} \Rightarrow I_B = 3.5\,\mu\text{A}$$

$$I_C = \beta I_B = (80)(3.5)\,\mu\text{A} \Rightarrow I_C = 0.28 \text{ mA}$$

$$V_{EC} = V^+ - I_C R_C = 3.3 - (0.28)(5.25) = 1.83 \text{ V}$$

EX5.5

(a) $$I_B = \frac{V^+ - V_{EB}(on) - V_{BB}}{R_B} = \frac{3.3-0.7-2}{150} \Rightarrow I_B = 4\,\mu\text{A}$$

$$I_C = \beta I_B = (110)(4)\,\mu\text{A} \Rightarrow I_C = 0.44 \text{ mA}$$

$$V_{EC} = V^+ - I_C R_C = 3.3 - (0.44)(5) = 1.1 \text{ V}$$

(b)

$$I_B = \frac{3.3-0.7-1}{150} \Rightarrow I_B = 10.7\,\mu\text{A}$$

$$I_C = \frac{V^+ - V_{EC}(sat)}{R_C} = \frac{3.3-0.2}{5} = 0.62 \text{ mA}$$

$$V_{EC} = 0.2 \text{ V}$$

EX5.6

For $0 \le V_I < 0.7\ V$, Q_n is cutoff, $V_O = 9\ V$

When Q_n is biased in saturation, we have

$$0.2 = 9 - \frac{(100)(V_I - 0.7)(4)}{200} \Rightarrow V_I = 5.1\ V$$

So, for $V_I \ge 5.1\ V$, $V_O = 0.2\ V$

EX5.7

$$V_{BB} = I_B R_B + V_{BE}(on) + I_E R_E + V^-$$

$$I_E = (1+\beta) I_B$$

So

$$I_B = \frac{3.3 - 0.7}{640 + (81)(2.4)} \Rightarrow I_B = 3.116\ \mu\text{A}$$

$$I_C = \beta I_B = (80)(3.116)\ \mu\text{A} \Rightarrow I_C = 0.249\ \text{mA}$$

$$I_E = \left(\frac{1+\beta}{\beta}\right) I_C = \left(\frac{81}{80}\right)(0.249) = 0.252\ \text{mA}$$

$$V_{CE} = [3.3 - (-3.3)] - (0.249)(10) - (0.252)(2.4) = 3.51\ \text{V}$$

EX5.8

$$I_{EQ} = \frac{V^+ - V_{EB}(on)}{R_E} \Rightarrow R_E = \frac{3 - 0.7}{0.125} = 18.4\ \text{k}\Omega$$

$$V_C = V_{EB}(on) - V_{ECQ} = 0.7 - 2.2 = -1.5\ \text{V}$$

$$I_{CQ} = \left(\frac{\beta}{1+\beta}\right) I_{EQ} = \left(\frac{110}{111}\right)(0.125) = 0.1239\ \text{mA}$$

$$R_C = \frac{V_C - V^-}{I_{CQ}} = \frac{-1.5 - (-3)}{0.1239} = 12.1\ \text{k}\Omega$$

EX5.9

$$5 = I_E R_E + V_{EB}(\text{on}) + I_B R_B - 2$$

(a)

$$5 + 2 - 0.7 = I_E\left(2 + \frac{180}{41}\right) \quad I_E = 0.9859\ \text{mA}$$

$$\underline{I_C = 0.962\ \text{mA}}$$

(b)

$$6.3 = I_E\left(2 + \frac{180}{61}\right) \quad I_E = 1.2725\ \text{mA}$$

$$\underline{I_C = 1.25\ \text{mA}}$$

(c)

$$6.3 = I_E\left(2 + \frac{180}{101}\right) \quad I_E = 1.6657\ \text{mA}$$

$$I_C = 1.64\ \text{mA}$$

(d)

$$6.3 = I_E\left(2 + \frac{180}{151}\right) \quad I_E = 1.97365\ \text{mA}$$

$$I_C = 1.94\ \text{mA}$$

EX5.10

$$I_E = \frac{V_{BB} - V_{EB}(on)}{R_E} \Rightarrow R_E = \frac{4-0.7}{1.0}$$

or $R_E = 3.3\ k\Omega$

$$I_C = \alpha I_E = (0.992)(1) = 0.992\ mA$$

$$I_B = I_E - I_C = 1.0 - 0.992 \text{ or } I_B = 8\ \mu A$$

$$V_{CB} = I_C R_C - V_{CC} = (0.992)(1) - 5$$

or $V_{CB} = -4.01\ V$

EX5.11

(a) $$R_1 = \frac{V^+ - V_\gamma - V_{CE}(sat)}{I_{C1}} = \frac{5-1.5-0.2}{15} \Rightarrow R_1 = 220\ \Omega$$

$$I_{B1} = \frac{I_{C1}}{50} = \frac{15}{50} = 0.30\ \text{mA}$$

$$R_{B1} = \frac{5-0.7}{0.3} = 14.3\ \text{k}\Omega$$

(b)

$$I_{B2} = \frac{I_{C2}}{25} = \frac{2}{25} = 0.08\ \text{A}$$

$$R_{B2} = \frac{12-0.7-0}{0.08} = 141\ \Omega$$

EX5.12

(a) For $V_1 = V_2 = 0$, All currents are zero and $V_O = 5\ V$.

(b) For $V_1 = 5\ V$, $V_2 = 0$; $I_{B2} = I_{C2} = 0$,

$$I_{B1} = \frac{5-0.7}{0.95} = 4.53\ mA$$

$$I_{C1} = \frac{5-0.2}{0.6} \Rightarrow I_{C1} = I_R = 8\ mA$$

$$V_O = 0.2\ V$$

(c) For $V_1 = V_2 = 5\ V$, $I_{B1} = I_{B2} = 4.53\ mA$; $I_R = 8\ mA$, $I_{C1} = I_{C2} = I_R/2 = 4\ mA$, $V_O = 0.2\ V$

EX5.13

In active region,

$$\upsilon_O = m\upsilon_I + b \Rightarrow m = -6.5$$

At $\upsilon_I = 0.7\ \text{V}$, $\upsilon_O = 5\ \text{V}$

$$5 = -6.5(0.7) + b \Rightarrow b = 9.55$$

Then

$$\upsilon_O = -6.5\upsilon_I + 9.55$$

When

$$\upsilon_O = 0.2 = -6.5\upsilon_I + 9.55 \Rightarrow \upsilon_I = 1.438\ \text{V}$$

Q-point

$$\upsilon_{IQ} = \frac{1.438-0.7}{2} + 0.7 = 1.069\ \text{V}$$

$$\upsilon_{OQ} = \frac{5-0.2}{2} + 0.2 = 2.6 \text{ V}$$

Now

$$I_{BQ} = \frac{1.069-0.7}{80} \Rightarrow 4.61 \mu \text{ A}$$

$$I_{CQ} = \beta I_{BQ} = (120)(4.61) \mu \text{ A} \Rightarrow I_{CQ} = 0.5535 \text{ mA}$$

At Q-point

$$\upsilon_{OQ} = 5 - I_{CQ} R_C$$

$$2.6 = 5 - (0.5535) R_C \Rightarrow R_C = 4.34 \text{ k}\Omega$$

EX5.14

$$R_C = \frac{V_{CC} - V_{CEQ}}{I_{CQ}} = \frac{2.8-1.4}{0.12} = 11.7 \text{ k}\Omega$$

$$I_{BQ} = \frac{I_{CQ}}{\beta} = \frac{0.12}{150} \Rightarrow I_{BQ} = 0.80 \mu \text{ A}$$

$$R_B = \frac{V_{CC} - V_{BEQ}}{I_{BQ}} = \frac{2.8-0.7}{0.80} = 2.625 \text{ M}\Omega$$

EX5.15

(a) $R_{TH} = R_1 \| R_2 = 85 \| 35 = 24.8 \text{ k}\Omega$

$$V_{TH} = \left(\frac{R_2}{R_1 + R_2}\right)(V_{CC}) = \left(\frac{35}{35+85}\right)(3.3) = 0.9625 \text{ V}$$

(b) $V_{TH} = I_{BQ} R_{TH} + V_{BE}(on) + (1+\beta) I_{BQ} R_E$

so

$$I_{BQ} = \frac{V_{TH} - V_{BE}(on)}{R_{TH} + (1+\beta) R_E} = \frac{0.9625-0.7}{24.8 + (151)(0.5)} \Rightarrow I_{BQ} = 2.617 \mu \text{ A}$$

$$I_{CQ} = \beta I_{BQ} = (150)(0.002617) = 0.3926 \text{ mA}$$

$$I_{EQ} = \left(\frac{1+\beta}{\beta}\right) I_{CQ} = \left(\frac{151}{150}\right)(0.3926) = 0.3952 \text{ mA}$$

$$V_{CEQ} = 3.3 - (0.3926)(4) - (0.3952)(0.5) = 1.53 \text{ V}$$

(c) $I_{BQ} = \dfrac{0.9625-0.7}{24.8 + (76)(0.5)} \Rightarrow I_{BQ} = 4.18 \mu \text{ A}$

Then $I_{CQ} = (75)(0.00418) = 0.3135 \text{ mA}$

$$I_{EQ} = (76)(0.00418) = 0.3177 \text{ mA}$$

$$V_{CEQ} = 3.3 - (0.3135)(4) - (0.3177)(0.5) = 1.89 \text{ V}$$

EX5.16

$V_{CEQ} \cong V_{CC} - I_{CQ}\left(R_C + R_E\right)$

or $2.5 \cong 5 - I_{CQ}\left(1+0.2\right)$

which yields

$I_{CQ} = 2.08\ mA,$

$I_{BQ} = \dfrac{I_{CQ}}{\beta} = \dfrac{2.08}{150} = 0.0139\ mA$

$R_{TH} = (0.1)(1+\beta)R_E = (0.1)(151)(0.2)$

or $R_{TH} = 3.02\ k\Omega$

Now $V_{TH} = \left(\dfrac{R_2}{R_1+R_2}\right)\cdot V_{CC} = \dfrac{1}{R_1}\cdot R_{TH}\cdot V_{CC}$

so $V_{TH} = \dfrac{1}{R_1}(3.02)(5)$

We can write $V_{TH} = I_{BQ}R_{TH} + V_{BE}(on) + (1+\beta)I_{BQ}R_E$

or

$\dfrac{1}{R_1}(3.02)(5) = (0.0139)(3.02) + 0.7 + (151)(0.0139)(0.2)$

We obtain $R_1 = 13\ k\Omega$ and then $R_2 = 3.93\ k\Omega$

EX5.17

$I_{CQ} = \dfrac{V^+ - V_O}{R_C} = \dfrac{5-0}{10} = 0.5\ \text{mA}$

$I_{EQ} = \left(\dfrac{1+\beta}{\beta}\right)I_{CQ} = \left(\dfrac{151}{150}\right)(0.5) = 0.5033\ \text{mA}$

$V_{CEQ} = \left(V^+ - V^-\right) - I_{CQ}R_C - I_{EQ}R_E$

$= 10 - (0.5)(10) - (0.5033)(2) = 3.99\ \text{V}$

Now

$I_{BQ} = \dfrac{I_{CQ}}{\beta} = \dfrac{0.5}{150} \Rightarrow I_{BQ} = 3.33\,\mu\text{A}$

$R_{TH} = (0.1)(1+\beta)R_E = (0.1)(151)(2) = 30.2\ \text{k}\Omega$

$V_{TH} = \left(\dfrac{R_2}{R_1+R_2}\right)(10) - 5 = \dfrac{1}{R_1}(R_{TH})(10) - 5 = \dfrac{1}{R_1}(30.2)(10) - 5$

Also

$V_{TH} = I_{BQ}R_{TH} + V_{BE}(on) + I_{EQ}R_E - 5$

$= (0.00333)(30.2) + 0.7 + (0.5033)(2) - 5 = -3.193\ \text{V}$

Then

$\dfrac{1}{R_1}(30.2)(10) - 5 = -3.193$

or $R_1 = 167\ \text{k}\Omega$ and $167 \| R_2 = 30.2 \Rightarrow R_2 = 36.9\ \text{k}\Omega$

EX5.18

$$V_{EO} = -0.7 \text{ V}, \quad V_{CO} = -0.7 + 1.6 = 0.9 \text{ V}$$

$$R_C = \frac{V^+ - V_{CO}}{I_{CQO}} = \frac{3.3 - 0.9}{0.12} = 20 \text{ k}\Omega$$

$$I_Q = \left(\frac{1+\beta}{\beta}\right) I_{CQO} = \left(\frac{61}{60}\right)(0.12) = 0.122 \text{ mA}$$

$$I_1 = \left(1 + \frac{2}{\beta}\right) I_Q = \left(1 + \frac{2}{60}\right)(0.122) = 0.126 \text{ mA}$$

$$I_1 = 0.126 = \frac{0 - V_{BE}(on) - (-3.3)}{R_1} = \frac{3.3 - 0.7}{R_1} \Rightarrow R_1 = 20.6 \text{ k}\Omega$$

EX5.19

$$R_{TH} 50 \| 100 = 33.3 \, k\Omega$$

$$V_{TH} = V_{TH} = \left(\frac{50}{50+100}\right)(10) - 5 = -1.67 \, V$$

$$I_{B1} = \frac{-1.67 - 0.7 - (-5)}{33.3 + (101)(2)} \Rightarrow 11.2 \, \mu A$$

$$I_{C1} = 1.12 \, mA, \; I_{E1} = 1.13 \, mA$$

$$V_{E1} = I_{E1} R_{E1} - 5 = (1.13)(2) - 5 = -2.74 \, V$$

$$V_{CE1} = 3.25 \, V \Rightarrow V_{C1} = 0.51 \, V$$

Now $V_{E2} = 0.51 + 0.7 = 1.21 \, V$

$$I_{E2} = \frac{5 - 1.21}{2} = 1.90 \, mA \Rightarrow I_{B2} = 18.8 \, \mu A$$

$$I_{C2} = 1.88 \, mA$$

$$I_{R1} = I_{C1} - I_{B2} = 1.12 - 0.0188 = 1.10 \, mA$$

$$R_{C1} = \frac{5 - 0.51}{1.10} = 4.08 \, k\Omega$$

$$\begin{aligned} V_{EC2} = 2.5 \Rightarrow V_{C2} &= V_{E2} - V_{EC2} \\ &= 1.21 - 2.5 = -1.29 \, V \end{aligned}$$

$$R_{C2} = \frac{-1.29 - (-5)}{1.88} = 1.97 \, k\Omega$$

EX5.20

We find $\dfrac{12}{0.05} = 240 \, k\Omega = R_1 + R_2 + R_3$

Then $V_{B1} = (0.5)(2) + 0.7 = 1.7 \, V$

$$R_3 = \frac{1.7}{0.05} = 34 \, k\Omega$$

Also $V_{B2} = (0.5)(2) + 4 + 0.7 = 5.7 \, V$

$\Delta V_{R2} = 5.7 - 1.7 = 4 \, V$

so $R_2 = \dfrac{4}{0.05} = 80 \, k\Omega$

and $R_1 = 240 - 80 - 34 = 126\ k\Omega$

$V_{C2} = 1 + 4 + 4 = 9\ V$

Then $R_C = \dfrac{V^+ - V_{C2}}{I_{CQ}} = \dfrac{12-9}{0.5} = 6\ k\Omega$

Test Your Understanding Solutions

TYU5.1

(a) $\alpha = \dfrac{\beta}{1+\beta} = \dfrac{60}{61} = 0.9836$

$\alpha = \dfrac{150}{151} = 0.9934$

(b) $\beta = \dfrac{\alpha}{1-\alpha} = \dfrac{0.982}{1-0.982} = 54.6$

$\beta = \dfrac{0.9925}{1-0.9925} = 132.3$

TYU5.2

$I_E = I_C + I_B = 0.620 + 0.005 = 0.625\ \text{mA}$

$\beta = \dfrac{I_C}{I_B} = \dfrac{0.620}{0.005} = 124$

$\alpha = \dfrac{\beta}{1+\beta} = \dfrac{124}{125} = 0.992$

TYU5.3

$I_C = \alpha I_E = (0.9915)(1.20) = 1.19\ \text{mA}$

$\beta = \dfrac{\alpha}{1-\alpha} = \dfrac{0.9915}{1-0.9915} = 116.6$

$I_B = \dfrac{I_E}{1+\beta} = \dfrac{1.20}{117.6} \Rightarrow I_B = 10.2\ \mu\text{A}$

TYU5.4

(a) $r_o = \dfrac{V_A}{I_C} \Rightarrow V_A = (225)(0.8) = 180\ \text{V}$

(b) (i) $r_o = \dfrac{180}{0.08} \Rightarrow 2.25\ \text{M}\Omega$

(ii) $r_o = \dfrac{180}{8} = 22.5\ \text{k}\Omega$

TYU5.5

$$I_C = I_O\left(1+\frac{V_{CE}}{V_A}\right)$$

At $V_{CE} = 1\ V,\ I_C = 1\ mA$

(a) For $V_A = 75\ V,$ $I_C = 1 = I_O\left(1+\frac{1}{75}\right) \Rightarrow I_O = 0.9868\ mA$

Then, at $V_{CE} = 10\ V$

$$I_C = (0.9868)\left(1+\frac{10}{75}\right) = 1.12\ mA$$

(b) For $V_A = 150\ V,$ $I_C = 1 = I_O\left(1+\frac{1}{150}\right) \Rightarrow I_O = 0.9934\ mA$

At $V_{CE} = 10\ V,$ $I_C = (0.9934)\left(1+\frac{10}{150}\right) = 1.06\ mA$

TYU5.6

$BV_{CEO} = \dfrac{BV_{CBO}}{n\sqrt{\beta}}$ so $BV_{CBO} = \sqrt[3]{100}\,(30) = 139\ V$

TYU5.7

(a) For $V_I = 0.2\ V < V_{BE}(on) \Rightarrow I_B = I_C = 0,\ \ V_O = 5\ V$ and $P = 0$

(c) For $V_I = 3.6\ V,$ transistor is driven into saturation, so $I_B = \dfrac{V_I - V_{BE}(on)}{R_B} = \dfrac{3.6-0.7}{0.64} = 4.53\ mA$

and $I_C = \dfrac{V^+ - V_{CE}(sat)}{R_C} = \dfrac{5-0.2}{0.440} = 10.9\ mA$

Note that $\dfrac{I_C}{I_B} = \dfrac{10.9}{4.53} = 2.41 < \beta$ which shows that the transistor is indeed driven into saturation. Now,

$$P = I_B V_{BE}(on) + I_C V_{CE}(sat)$$
$$= (4.53)(0.7) + (10.9)(0.2) = 5.35\ mW$$

TYU5.8

For $V_{BC} = 0 \Rightarrow V_O = 0.7\ V$

Then $I_C = \dfrac{5-0.7}{0.44} = 9.77\ mA$ and $I_B = \dfrac{I_C}{\beta} = \dfrac{9.77}{50} = 0.195\ mA$

Now $V_I = I_B R_B + V_{BE}(on) = (0.195)(0.64) + 0.7$ or $V_I = 0.825\ V$

Also $P = I_B V_{BE}(on) + I_C V_{CE}$

$$= (0.195)(0.7) + (9.77)(0.7) = 6.98\ mW$$

TYU5.9

$$I_C = \frac{3.3 - V_C}{R_C} = \frac{3.3 - 2.27}{4} = 0.2575 \text{ mA}$$

$$I_E = \frac{-V_{BE}(on) - (-3.3)}{R_E} = \frac{3.3 - 0.7}{10} = 0.260 \text{ mA}$$

$$I_B = I_E - I_C = 0.260 - 0.2575 \Rightarrow I_B = 2.5\,\mu\text{ A}$$

$$\beta = \frac{I_C}{I_B} = \frac{0.2575}{0.0025} = 103$$

$$\alpha = \frac{\beta}{1+\beta} = \frac{103}{104} = 0.99038$$

TYU5.10

$$I_E = \frac{5 - V_{EB}(on)}{R_E} = \frac{5 - 0.7}{8} = 0.5375 \text{ mA}$$

$$I_C = \left(\frac{\beta}{1+\beta}\right) I_E = \left(\frac{85}{86}\right)(0.5375) = 0.531 \text{ mA}$$

$$I_B = \frac{I_E}{1+\beta} = \frac{0.5375}{86} \Rightarrow I_B = 6.25\,\mu\text{ A}$$

$$V_{EC} = 10 - (0.531)(4) - (0.5375)(8) = 3.575 \text{ V}$$

TYU5.11

$$V_{BB} = I_B R_B + V_{BE}(on) + I_E R_E$$

or $V_{BB} = I_B R_B + V_{BE}(on) + (1+\beta) I_B R_E$

Then $I_B = \dfrac{V_{BB} - V_{BE}(on)}{R_B + (1+\beta) R_E} = \dfrac{2 - 0.7}{10 + (76)(1)}$

or $I_B = 15.1\,\mu A$

Also $I_C = (75)(15.1\,\mu A) = 1.13\,mA$ and $I_E = (76)(15.1\,\mu A) = 1.15\,mA$

Now $V_{CE} = V_{CC} + V_{BB} - I_C R_C - I_E R_E$

$$= 8 + 2 - (1.13)(2.5) - (1.15)(1) = 6.03\,V$$

TYU5.12

$$V_E = 5 - V_{CE} = 5 - 2.2 = 2.8 \text{ V}$$

$$I_B = \frac{V_{BB} - V_{BE}(on) - V_E}{R_B} = \frac{5 - 0.7 - 2.8}{10} = 0.15 \text{ mA}$$

$$I_E = (1+\beta) I_B = (121)(0.15) = 18.15 \text{ mA}$$

$$R_E = \frac{V_E}{I_E} = \frac{2.8}{18.15} = 0.154 \text{ k}\Omega$$

TYU5.13

(a) $I_E = 1.2 \text{ mA}, \quad I_B = \dfrac{I_E}{1+\beta} = \dfrac{1.2}{91} = 0.01319 \text{ mA}$

$$V_{BB} = I_E R_E + V_{EB}(on) + I_B R_B$$
$$= (1.2)(1) + 0.7 + (0.01319)(50) = 2.56 \text{ V}$$

(b) $I_C = \left(\dfrac{\beta}{1+\beta}\right) I_E = \left(\dfrac{90}{91}\right)(1.2) = 1.187 \text{ mA}$

$$V_{EC} = 5 - I_E R_E = 5 - (1.2)(1) = 3.8 \text{ V}$$

TYU5.14

(a) For $v_I = 0, \quad i_B = i_C = 0, \; v_O = 12\,V, \; P = 0$

(b) For $v_I = 12\ V$, $\quad i_B = \dfrac{v_I - V_{BE}(on)}{R_B} = \dfrac{12 - 0.7}{0.24} = 47.1\ mA$

$$i_C = \frac{V_{CC} - V_{CE}(sat)}{R_C} = \frac{12 - 0.1}{5} = 2.38\ A$$

$$v_O = 0.1\ V$$

and

$$P = i_B V_{BE}(on) + i_C V_{CE}(sat)$$
$$= (0.0471)(0.7) + (2.38)(0.1) = 0.271\ W$$

TYU5.15

(a) $I_{CQ} = \dfrac{5 - V_{CEQ}}{R_C} = \dfrac{5 - 2.5}{2} = 1.25 \text{ mA}$

$$I_{BQ} = \frac{I_{CQ}}{\beta} = \frac{1.25}{120} \Rightarrow I_{BQ} = 10.42\,\mu\text{A}$$

$$R_B = \frac{5 - V_{BE}(on)}{I_{BQ}} = \frac{5 - 0.7}{0.01042} = 413 \text{ k}\Omega$$

(b) $I_{BQ} = 10.42\,\mu\text{A}$

For $\beta = 80 \Rightarrow I_{CQ} = 0.8336 \text{ mA}$

For $\beta = 160 \Rightarrow I_{CQ} = 1.667 \text{ mA}$

Now

$$V_{CEQ} = 5 - I_{CQ}(2)$$

For $\beta = 80 \Rightarrow V_{CEQ} = 5 - (0.8336)(2) = 3.33 \text{ V}$

For $\beta = 160 \Rightarrow V_{CEQ} = 5 - (1.667)(2) = 1.67 \text{ V}$

So $\quad 1.67 \le V_{CEQ} \le 3.33 \text{ V}$

TYU5.16

$$I_{BQ} = \frac{5-0.7}{800} = 0.005375\ mA$$

For $\beta = 75,\ I_{CQ} = \beta I_{BQ} = (75)(0.005375)$

Or $I_{CQ} = 0.403\ mA$

For $\beta = 150,\ I_{CQ} = (150)(0.005375)$

Or $I_{CQ} = 0.806\ mA$

Largest $I_{CQ} \Rightarrow \text{Smallest } V_{CEQ}$

For $\beta = 150,\ R_C = \dfrac{5-1}{0.806} = 4.96\ k\Omega$

For $\beta = 75,\ R_C = \dfrac{5-4}{0.403} = 2.48\ k\Omega$

For a nominal $I_{CQ} = 0.604\ mA$ and $V_{CEQ} = 2.5\ V,\ R_C = \dfrac{5-2.5}{0.604} = 4.14\ k\Omega$

Now for $I_{CQ} = 0.403\ mA,\ V_{CEQ} = 5-(0.403)(4.14) = 3.33\ V$

For $I_{CQ} = 0.806\ mA,\ V_{CEQ} = 5-(0.806)(4.14) = 1.66\ V$

So, for $R_C = 4.14\ k\Omega,\ 1.66 \le V_{CEQ} \le 3.33\ V$

TYU5.17

(a) $R_{TH} = R_1 \| R_2 = 440 \| 230 = 151\ \text{k}\Omega$

$$V_{TH} = \left(\frac{R_2}{R_1+R_2}\right)\cdot V_{CC} = \left(\frac{230}{440+230}\right)(5) = 1.716\ \text{V}$$

(b) $I_{BQ} = \dfrac{V_{TH}-V_{BE}(on)}{R_{TH}+(1+\beta)R_E} = \dfrac{1.716-0.7}{151+(151)(1)} \Rightarrow I_{BQ} = 3.364\,\mu\text{A}$

$I_{CQ} = \beta I_{BQ} = 0.5046\ \text{mA};\quad I_{EQ} = (1+\beta)I_{BQ} = 0.508\ \text{mA}$

$$V_{CEQ} = V_{CC} - I_{CQ}R_C - I_{EQ}R_E$$
$$= 5-(0.5046)(4)-(0.508)(1) = 2.47\ \text{V}$$

(c) $R_{TH} = 151\ \text{k}\Omega;\quad V_{TH} = 1.716\ \text{V}$

$$I_{BQ} = \frac{1.716-0.7}{151+(91)(1)} \Rightarrow I_{BQ} = 4.2\,\mu\text{A}$$

$I_{CQ} = \beta I_{BQ} = 0.378\ \text{mA};\quad I_{EQ} = (1+\beta)I_{BQ} = 0.382\ \text{mA}$

$$V_{CEQ} = 5-(0.378)(4)-(0.382)(1) = 3.11\ \text{V}$$

TYU5.18

(a) $R_{TH} = (0.1)(1+\beta)R_E = (0.1)(151)(1) = 15.1\ \text{k}\Omega$

$$I_{BQ} = \frac{I_{CQ}}{\beta} = \frac{0.4}{150} \Rightarrow I_{BQ} = 2.667\,\mu\text{A}$$

$$I_{EQ} = \left(\frac{1+\beta}{\beta}\right)I_{CQ} = \left(\frac{151}{150}\right)(0.4) = 0.4027\ \text{mA}$$

$$V_{CEQ} = V_{CC} - I_{CQ}R_C - I_{EQ}R_E$$
$$2.7 = 5 - (0.4)R_C - (0.4027)(1) \Rightarrow R_C = 4.74 \text{ k}\Omega$$

Now

$$V_{TH} = \frac{1}{R_1}(R_{TH})V_{CC} = I_{BQ}R_{TH} + V_{BE}(on) + I_{EQ}R_E$$
$$\frac{1}{R_1}(15.1)(5) = (0.002667)(15.1) + 0.7 + (0.4027)(1)$$

yields $R_1 = 66 \text{ k}\Omega$; $66 \| R_2 = 15.1 \Rightarrow R_2 = 19.6 \text{ k}\Omega$

(b) $V_{TH} = 1.143$ V; $R_{TH} = 15.1$ kΩ

$$I_{BQ} = \frac{V_{TH} - V_{BE}(on)}{R_{TH} + (1+\beta)R_E} = \frac{1.143 - 0.7}{15.1 + (91)(1)} \Rightarrow I_{BQ} = 4.175\,\mu\text{A}$$
$$I_{CQ} = \beta I_{BQ} = 0.376 \text{ mA}; \quad I_{EQ} = (1+\beta)I_{BQ} = 0.380 \text{ mA}$$
$$V_{CEQ} = 5 - (0.376)(4.74) - (0.380)(1) = 2.84 \text{ V}$$

TYU5.19

$$V_{ECQ} = 5 \cong 10 - I_{CQ}(R_C + R_E) = 10 - I_{CQ}(4.5 + 0.5) \Rightarrow I_{CQ} \cong 1 \text{ mA}$$
$$I_{BQ} = \frac{I_{CQ}}{\beta} = \frac{1}{120} \Rightarrow I_{BQ} = 8.33\,\mu\text{A}$$
$$I_{EQ} = \left(\frac{1+\beta}{\beta}\right)I_{CQ} = \left(\frac{121}{120}\right)(1) = 1.008 \text{ mA}$$
$$R_{TH} = (0.1)(1+\beta)R_E = (0.1)(121)(0.5) = 6.05 \text{ k}\Omega$$
$$V^+ = I_{EQ}R_E + V_{EB}(on) + I_{BQ}R_{TH} + V_{TH}$$
$$5 = (1.008)(0.5) + 0.7 + (0.00833)(6.05) + V_{TH} \Rightarrow V_{TH} = 3.746 \text{ V}$$
$$V_{TH} = \left(\frac{R_2}{R_1 + R_2}\right)(10) - 5 = \frac{1}{R_1}(R_{TH})(10) - 5$$

So

$$\frac{1}{R_1}(6.05)(10) - 5 = 3.746 \Rightarrow R_1 = 6.92 \text{ k}\Omega$$
$$6.92 \| R_2 = 6.05 \Rightarrow R_2 = 48.1 \text{ k}\Omega$$

TYU5.20

(a) $$I_{CQ} = \left(\frac{\beta}{1+\beta}\right)I_Q = \left(\frac{120}{121}\right)(0.25) = 0.2479 \text{ mA}$$
$$I_{CQ} = I_S e^{V_{BE}/V_T}$$

or

$$V_{BE} = V_T \ln\left(\frac{I_{CQ}}{I_S}\right) = (0.026)\ln\left(\frac{0.2479 \times 10^{-3}}{3 \times 10^{-14}}\right) = 0.5937 \text{ V}$$
$$I_{BQ} = \frac{I_{CQ}}{\beta} = \frac{0.2479}{120} \Rightarrow I_{BQ} = 2.066\,\mu\text{A}$$
$$V_B = -(0.002066)(75) = -0.155 \text{ V}$$
$$V_E = V_B - V_{BE} = -0.155 - 0.5937 = -0.7487 \text{ V}$$

$$V_C = V^+ - I_{CQ}R_C = 2.5 - (0.2479)(4) = 1.508 \text{ V}$$
$$V_{CEQ} = V_C - V_E = 1.508 - (-0.7487) = 2.26 \text{ V}$$

(b) $$I_{CQ} = \left(\frac{60}{61}\right)(0.25) = 0.2459 \text{ mA}$$
$$V_{BE} = (0.026)\ln\left(\frac{0.2459\times10^{-3}}{3\times10^{-14}}\right) = 0.5935 \text{ V}$$
$$I_{BQ} = \frac{I_{CQ}}{\beta} = \frac{0.2459}{60} \Rightarrow I_{BQ} = 4.098\,\mu\text{A}$$
$$V_B = -(0.004098)(75) = -0.307 \text{ V}$$
$$V_E = -0.307 - 0.5935 = -0.901 \text{ V}$$
$$V_C = 2.5 - (0.2459)(4) = 1.516 \text{ V}$$
$$V_{CEQ} = 1.516 - (-0.901) = 2.42 \text{ V}$$

Chapter 6

Exercise Solutions

EX6.1

(a) $$I_{BQ} = \frac{V_{BB} - V_{BE}(on)}{R_B} = \frac{0.85 - 0.7}{180} \Rightarrow I_{BQ} = 0.833\,\mu\text{ A}$$

$$I_{CQ} = \beta I_{BQ} = (120)(0.000833) = 0.10 \text{ mA}$$

$$V_{CEQ} = V_{CC} - I_{CQ}R_C = 3.3 - (0.1)(15) = 1.8 \text{ V}$$

(b) $$g_m = \frac{I_{CQ}}{V_T} = \frac{0.1}{0.026} = 3.846 \text{ mA/V}$$

$$r_\pi = \frac{\beta V_T}{I_{CQ}} = \frac{(120)(0.026)}{0.1} = 31.2 \text{ k}\Omega$$

(c) $$A_\upsilon = -g_m R_C\left(\frac{r_\pi}{r_\pi + R_B}\right) = -(3.846)(15)\left(\frac{31.2}{31.2 + 180}\right) = -8.52$$

EX6.2

(a) $$I_{BQ} = \frac{V_{BB} - V_{BE}(on)}{R_B} = \frac{1.025 - 0.7}{100} = 0.00325 \text{ mA}$$

$$I_{CQ} = \beta I_{BQ} = (150)(0.00325) = 0.4875 \text{ mA}$$

$$g_m = \frac{I_{CQ}}{V_T} = \frac{0.4875}{0.026} = 18.75 \text{ mA/V}$$

$$r_\pi = \frac{\beta V_T}{I_{CQ}} = \frac{(150)(0.026)}{0.4875} = 8 \text{ k}\Omega$$

$$r_o = \frac{V_A}{I_{CQ}} = \frac{150}{0.4875} = 308 \text{ k}\Omega$$

(b) $$A_\upsilon = -g_m(r_o \| R_C)\left(\frac{r_\pi}{r_\pi + R_B}\right) = -(18.75)(308\|6)\left(\frac{8}{8 + 100}\right) = -8.17$$

EX6.3

(a)

$$I_{BQ} = \frac{V_{BB} - V_{EB}(on)}{R_B} = \frac{1.145 - 0.7}{50}$$

or $I_{BQ} = 0.0089\ mA$

Then $I_{CQ} = \beta I_{BQ} = (90)(0.0089) = 0.801\ mA$

Now

$$g_m = \frac{I_{CQ}}{V_T} = \frac{0.801}{0.026} = 30.8\ mA/V$$

$$r_\pi = \frac{\beta V_T}{I_{CQ}} = \frac{(90)(0.026)}{0.801} = 2.92\ k\Omega$$

$$r_o = \frac{V_A}{I_{CQ}} = \frac{120}{0.801} = 150\ k\Omega$$

(b) We have $V_o = g_m V_\pi (r_o \| R_C)$

$$V_\pi = -\left(\frac{r_\pi}{r_\pi + R_B}\right) V_s$$

and so

$$A_\upsilon = \frac{V_o}{V_s} = -g_m \left(\frac{r_\pi}{r_\pi + R_B}\right)(r_o \| R_C)$$

$$= -(30.8)\left(\frac{2.92}{2.92 + 50}\right)(150 \| 2.5)$$

which yields $A_\upsilon = -4.18$

EX6.4

Using Figure 6.23

(a) For $I_{CQ} = 0.2\ mA,\ 7.8 < h_{ie} < 15\ k\Omega,\ 60 < h_{fe} < 125,\ 6.2\times10^{-4} < h_{re} < 50\times10^{-4},$
$5 < h_{oe} < 13\ \mu mhos$

(b) For $I_{CQ} = 5\ mA,\ 0.7 < h_{ie} < 1.1\ k\Omega,\ 140 < h_{fe} < 210,\ 1.05\times10^{-4} < h_{re} < 1.6\times10^{-4},$
$22 < h_{oe} < 35\ \mu mhos$

EX6.5

$$R_{TH} = R_1 \| R_2 = 250 \| 75 = 57.7\ \text{k}\,\Omega$$

$$V_{TH} = \left(\frac{R_2}{R_1 + R_2}\right)\cdot V_{CC} = \left(\frac{75}{75 + 250}\right)(5)$$

or

$$V_{TH} = 1.154\ V$$

$$I_{BQ} = \frac{V_{TH} - V_{BE}(on)}{R_{TH} + (1+\beta)R_E} = \frac{1.154 - 0.7}{57.7 + (121)(0.6)}$$

or

$$I_{BQ} = 3.48\ \mu A$$

$$I_{CQ} = \beta I_{BQ} = (120)(3.38\ \mu A) = 0.418\ mA$$

(a)

Now

$$g_m = \frac{I_{CQ}}{V_T} = \frac{0.418}{0.026} = 16.08\,mA/V$$

$$r_\pi = \frac{\beta V_T}{I_{CQ}} = \frac{(120)(0.026)}{0.418} = 7.46\,k\Omega$$

We have

$$V_o = -g_m V_\pi R_C$$

We find

$$R_{ib} = r_\pi + (1+\beta)R_E = 7.46 + (121)(0.6)$$

or

$$R_{ib} = 80.1\ k\Omega$$

Also

$$R_1 \| R_2 = 250 \| 75 = 57.7\ \text{k}\Omega$$

$$R_1 \| R_2 \| R_{ib} = 57.7 \| 80.1 = 33.54\ \text{k}\Omega$$

We find

$$V_s' = \left(\frac{R_1 \| R_2 \| R_{ib}}{R_1 \| R_2 \| R_{ib} + R_S}\right) \cdot V_s = \left(\frac{33.54}{33.54 + 0.5}\right) \cdot V_s$$

or

$$V_s' = (0.985)V_s$$

Now

$$V_s' = V_\pi \left[1 + \left(\frac{1+\beta}{r_\pi}\right) R_E\right] = V_\pi \left[1 + \left(\frac{121}{7.46}\right)(0.6)\right]$$

or

$$V_\pi = (0.0932)V_s' = (0.0932)(0.985)V_s$$

So

$$A_v = \frac{V_o}{V_s} = -(16.08)(0.0932)(0.985)(5.6)$$

or

$$A_v = -8.27$$

EX6.6

(a) $R_{TH} = R_1 \| R_2 = 14.4 \| 110 = 12.73\ \text{k}\Omega$

$$V_{TH} = \left(\frac{R_2}{R_1 + R_2}\right) V_{CC} = \left(\frac{110}{110 + 14.4}\right)(12) = 10.61\ \text{V}$$

$$12 = (101) I_{BQ}(0.3) + 0.7 + I_{BQ}(12.73) + 10.61$$

so

$$I_{BQ} = 0.0160\ \text{mA}$$

$$I_{CQ} = \beta I_{BQ} = 1.60\ \text{mA};\quad I_{EQ} = (1+\beta) I_{BQ} = 1.62\ \text{mA}$$

$$V_{ECQ} = 12 - (1.6)(4) - (1.62)(0.3) = 5.11\ \text{V}$$

(b) $g_m = \dfrac{I_{CQ}}{V_T} = \dfrac{1.60}{0.026} = 61.54\ \text{mA/V}$

$$r_\pi = \frac{\beta V_T}{I_{CQ}} = \frac{(100)(0.026)}{1.60} = 1.625\ \text{k}\Omega$$

$$r_o = \frac{V_A}{I_{CQ}} = \infty$$

(c) $A_\upsilon = \dfrac{-\beta (R_C \| R_L)}{r_\pi + (1+\beta) R_E} = \dfrac{-(100)(4 \| 10)}{1.625 + (101)(0.3)} = -8.95$

EX6.7

(a) $R_i = R_S + R_B \| r_\pi$

$$I_{BQ} R_B + 0.7 + (1+\beta) I_{BQ} R_E + V^- = 0$$

$$5 - 0.7 = I_{BQ}[100 + (121)(4)] \Rightarrow I_{BQ} = 0.007363 \text{ mA}$$

$$I_{CQ} = \beta I_{BQ} = 0.8836 \text{ mA}$$

$$g_m = \frac{I_{CQ}}{V_T} = \frac{0.8836}{0.026} = 33.98 \text{ mA/V}$$

$$r_\pi = \frac{\beta V_T}{I_{CQ}} = \frac{(120)(0.026)}{0.8836} = 3.53 \text{ k}\Omega$$

$$R_i = 0.5 + 100 \| 3.53 = 3.91 \text{ k}\Omega$$

(b) $r_o = \dfrac{V_A}{I_{CQ}} = \dfrac{80}{0.8836} = 90.5 \text{ k}\Omega$

$$V_\pi = \left(\frac{R_B \| r_\pi}{R_B \| r_\pi + R_S}\right) \cdot \upsilon_s = \left(\frac{100 \| 3.53}{100 \| 3.53 + 0.5}\right) \cdot \upsilon_s = (0.872)\upsilon_s$$

$$A_\upsilon = -g_m (R_C \| r_o) \frac{V_\pi}{\upsilon_s} = -(33.98)(4 \| 90.5)(0.872) = -114$$

EX6.8

(a)

$$g_m = \frac{I_{CQ}}{V_T} = \frac{0.25}{0.026} = 9.615 \text{ mA/V}$$

$$r_o = \frac{V_A}{I_{CQ}} = \frac{100}{0.25} = 400 \text{ k}\Omega$$

$$A_\upsilon = -g_m (r_o \| r_c) = -(9.615)(400 \| 100) = -769$$

(b)

$$A_\upsilon = -g_m (r_o \| r_c \| r_L) = -(9.615)(400 \| 100 \| 100)$$

$$A_\upsilon = -427$$

EX6.9

$$I_{BQ} = \frac{5 - 0.7}{10 + (126)(5)} = 0.00672 \ mA$$

$$I_{CQ} = 0.84 \ mA, \ I_{EQ} = 0.847 \ mA$$

$$V_{CEQ} = 10 - (0.84)(2.3) - (0.847)(5)$$

or

$$V_{CEQ} = 3.83 \ V$$

dc load line

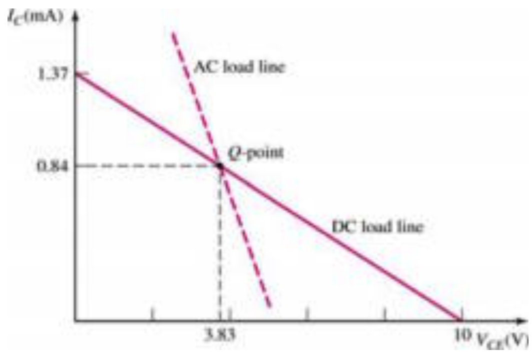
$$V_{CE} \cong (V^+ - V^-) - I_C (R_C + R_E)$$

or

$$V_{CE} = 10 - I_C (7.3)$$

ac load line (neglecting r_o)

$$\upsilon_{ce} = -i_c\left(R_C \| R_L\right) = -i_c\left(2.3\|5\right) = -i_c\left(1.58\right)$$



EX6.10

(b) $I_{BQ}R_B + 0.7 + (1+\beta)R_E - 5 = 0$

$\Rightarrow I_{BQ} = 0.007363$ mA; $I_{CQ} = \beta I_{BQ} = 0.884$ mA; $I_{EQ} = 0.8909$ mA

$V_{CEQ} = 10 - (0.8836)(4) - (0.8909)(4) = 2.90$ V

(c) $\Delta V_{CE} = -\Delta I_C\left(R_C \| r_o\right) = -\Delta I_C\left(4\|90.5\right) = -\Delta I_C(3.831)$

For $|\Delta V_{CE}| = 2.9 - 0.5 = 2.4$ V

Then $|\Delta I_C| = \dfrac{2.4}{3.831} = 0.626$ mA; $\Delta\upsilon_{ce} = 4.8$ V, peak-to-peak

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EX6.11

$$V_{TH} = \left(\frac{R_2}{R_1+R_2}\right)\cdot V_{CC} = \frac{1}{R_1}\cdot R_{TH}\cdot V_{CC}$$

(a) $R_{TH} = (0.1)(1+\beta)R_E = (0.1)(121)(1)$

so

$$R_{TH} = 12.1\ k\Omega,\ V_{TH} = \frac{1}{R_1}(12.1)(12)$$

We can write

$$V_{CC} = (1+\beta)I_{BQ}R_E + V_{EB}(on) + I_{BQ}R_{TH} + V_{TH}$$

We have

$$I_{CQ} = 1.6\ mA,\ I_{BQ} = \frac{1.6}{120} = 0.0133\ mA$$

Then

$$I_{BQ} = 0.0133 = \frac{12 - 0.7 - \frac{1}{R_1}(12.1)(12)}{12.1 + (121)(1)}$$

which yields

$$R_1 = 15.24\ k\Omega$$

Since $R_{TH} = R_1 \| R_2 = 12.1\ \text{k}\Omega$, we find $R_2 = 58.7\ k\Omega$

Also $V_{ECQ} = 12 - (1.6)(4) - (1.61)(1) = 3.99\ V$

(b) ac load line $\Delta\upsilon_{ec} = -i_c\left(R_C \| R_L\right)$

Want $\Delta i_c = I_{CQ} - 0.1 = 1.6 - 0.1 = 1.5\ mA$

Also $\Delta v_{ec} = 3.99 - 0.5 = 3.49\ V$

Now $\dfrac{\Delta\upsilon_{ec}}{\Delta i_c} = \dfrac{3.49}{1.5} = 2.327\ \text{k}\Omega = R_C \| R_L$

So $4 \| R_L = 2.327\ \text{k}\Omega$ which yields $R_L = 5.56\ k\Omega$

EX6.12

(a) $R_{TH} = R_1 \| R_2 = 1.3 \| 4.2 = 0.9927\ \text{k}\Omega$

$$V_{TH} = \left(\frac{R_2}{R_1 + R_2}\right) \cdot V_{CC} = \left(\frac{4.2}{1.3 + 4.2}\right)(12) = 9.1636\ \text{V}$$

$$I_{BQ} = \frac{9.1636 - 0.7}{0.9927 + (81)(0.03)} = 2.473\ \text{mA}$$

$I_{EQ} = (1+\beta)I_{BQ} = 0.20\ \text{A},\ I_{CQ} = \beta I_{BQ} = 0.1978\ \text{A}$

$V_{CEQ} = 12 - (0.20)(30) = 6.0\ \text{V}$

(b) $g_m = \dfrac{I_{CQ}}{V_T} = \dfrac{0.1978}{0.026} = 7.608\ \text{A/V}$

$r_\pi = 10.52\ \Omega$, $r_o = 379.2\ \Omega$

$$A_\upsilon = \frac{(1+\beta)(r_o \| R_E)}{r_\pi + (1+\beta)(r_o \| R_E)} = \frac{(81)(379.2 \| 30)}{10.52 + (81)(379.2 \| 30)} = 0.9953$$

(c) $R_{ib} = r_\pi + (1+\beta)(r_o \| R_E) = 10.52 + (81)(379.2 \| 30)$

or

$R_{ib} = 2.26\ \text{k}\Omega$

EX6.13

$$R_o = R_E \| r_o \left\| \frac{r_\pi}{1+\beta} \right. = 30 \| 379.2 \left\| \frac{10.52}{81} \right. = 0.129\ \Omega$$

EX6.14

(a) For $I_{CQ} = 1.25\ mA$ and $\beta = 100,$ we find

$I_{EQ} = 1.26\ mA$ and $I_{BQ} = 0.0125\ mA$

Now $V_{CEQ} = 10 - I_{EQ} R_E$

Or

$4 = 10 - (1.26) R_E$

which yields

$R_E = 4.76\ k\Omega$

Then

$R_{TH} = (0.1)(1+\beta) R_E = (0.1)(101)(4.76)$

or

$R_{TH} = 48.1\ k\Omega$

We have

$$V_{TH} = \left(\frac{R_2}{R_1 + R_2}\right)(10) - 5 = \frac{1}{R_1} \cdot R_{TH}(10) - 5$$

or

$$V_{TH} = \frac{1}{R_1}(481) - 5$$

We can write

$$I_{BQ} = \frac{V_{TH} - 0.7 - (-5)}{R_{TH} + (1+\beta)R_E}$$

Or

$$0.0125 = \frac{\frac{1}{R_1}(481) - 5 - 0.7 + 5}{48.1 + (101)(4.76)}$$

which yields

$$R_1 = 65.8\ k\Omega$$

Since $R_1 \| R_2 = 48.1\ \text{k}\Omega$, we obtain

$$R_2 = 178.8\ k\Omega$$

(b)

$$r_\pi = \frac{\beta V_T}{I_{CQ}} = \frac{(100)(0.026)}{1.25} = 2.08\ k\Omega$$

$$r_o = \frac{V_A}{I_{CQ}} = \frac{125}{1.25} = 100\ k\Omega$$

We may note that

$$g_m V_\pi = g_m(I_b r_\pi) = \beta I_b$$

Also

$$R_{ib} = r_\pi + (1+\beta)(R_E \| R_L \| r_o)$$

$$= 2.08 + (101)(4.76 \| 1 \| 100)$$

or

$$R_{ib} = 84.9\ k\Omega$$

Now

$$I_o = \left(\frac{R_E \| r_o}{R_E \| r_o + R_L}\right)(1+\beta) I_b$$

where

$$I_b = \left(\frac{R_1 \| R_2}{R_1 \| R_2 + R_{ib}}\right) \cdot I_s$$

We can then write

$$A_I = \frac{I_o}{I_s} = \left(\frac{R_E \| r_o}{R_E \| r_o + R_L}\right)(1+\beta)\left(\frac{R_1 \| R_2}{R_1 \| R_2 + R_{ib}}\right)$$

We have

$$R_E \| r_o = 4.76 \| 100 = 4.54\ k\Omega$$

so

$$A_I = \left(\frac{4.54}{4.54 + 1}\right)(101)\left(\frac{48.1}{48.1 + 84.9}\right)$$

or

$A_I = 29.9$

(c)

$$R_o = R_E \| r_o \| \frac{r_\pi}{1+\beta} = 4.76 \| 100 \| \frac{2.08}{101}$$

or

$$R_o = 20.5\ \Omega$$

EX6.15

(a)

$$R_{TH} = R_1 \| R_2 = 70 \| 6 = 5.53\ k\Omega$$

$$V_{TH} = \left(\frac{R_2}{R_1+R_2}\right)(10) - 5 = \left(\frac{6}{70+6}\right)(10) - 5$$

or

$$V_{TH} = -4.2105\ V$$

We find

$$I_{BQ1} = \frac{-4.2105 - 0.7 - (-5)}{5.53 + (126)(0.2)} \Rightarrow 2.91\ \mu A$$

and

$$I_{CQ1} = \beta I_{BQ1} = (125)(2.91\ \mu A) = 0.364\ mA$$

$$I_{EQ1} = (1+\beta) I_{BQ1} = 0.368\ mA$$

At the collector of Q_1,

$$\frac{5 - V_{C1}}{R_{C1}} = I_{CQ1} + \frac{V_{C1} - 0.7 - (-5)}{(1+\beta)(R_{E2})}$$

or

$$\frac{5 - V_{C1}}{5} = 0.364 + \frac{V_{C1} - 0.7 - (-5)}{(126)(1.5)}$$

which yields

$$V_{C1} = 2.99\ V$$

also

$$V_{E1} = I_{EQ1} R_{E1} - 5 = (0.368)(0.2) - 5$$

or

$$V_{E1} = -4.93\ V$$

Then

$$V_{CEQ1} = V_{C1} - V_{E1} = 2.99 - (-4.93) = 7.92\ V$$

We find

$$I_{EQ2} = \frac{V_{C1} - 0.7 - (-5)}{1.5} = 4.86\ mA$$

and

$$I_{CQ2} = \left(\frac{\beta}{1+\beta}\right) \cdot I_{EQ1} = \left(\frac{125}{126}\right)(4.86) = 4.82\ mA$$

We find

$$V_{E2} = V_{C1} - 0.7 = 2.99 - 0.7 = 2.29\ V$$

and

$$V_{CEQ2} = 5 - V_{E2} = 5 - 2.29 = 2.71\ V$$

(b)
The small-signal transistor parameters are:

$$r_{\pi 1} = \frac{\beta V_T}{I_{CQ1}} = \frac{(125)(0.026)}{0.364} = 8.93\ k\Omega$$

$$g_{m1} = \frac{I_{CQ1}}{V_T} = \frac{0.364}{0.026} = 14.0\ mA/V$$

$$r_{\pi 2} = \frac{\beta V_T}{I_{CQ2}} = \frac{(125)(0.026)}{4.82} = 0.674\ k\Omega$$

$$g_{m2} = \frac{I_{CQ2}}{V_T} = \frac{4.82}{0.026} = 185\ mA/V$$

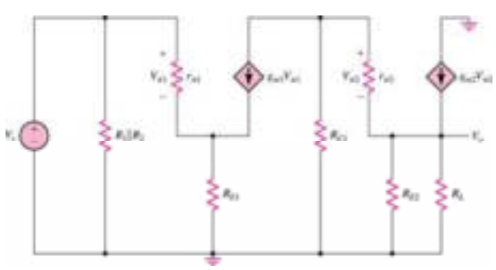
We find $R_{ib1} = r_{\pi 1} + (1+\beta)R_{E1} = 8.93 + (126)(0.2)$
Or

$$R_{ib1} = 34.1\ k\Omega$$

and

$$R_{ib} = r_{\pi 2} + (1+\beta)(R_{E2} \| R_L)$$
$$= 0.674 + (126)(1.5 \| 10) = 165\ \mathrm{k}\,\Omega$$

The small-signal equivalent circuit is:



We can write

$$V_o = (1+\beta) I_{b2} (R_{E2} \| R_L)$$

where

$$I_{b2} = \left(\frac{R_{C1}}{R_{C1} + R_{ib2}}\right)(-g_{m1} V_{\pi 1})$$

$$V_{\pi 1} = \frac{V_s}{R_{ib1}} \cdot r_{\pi 1}$$

Then

$$A_\upsilon = \frac{V_o}{V_i} = (1+\beta)(R_{E2} \| R_L)\left(\frac{R_{C1}}{R_{C1} + R_{ib2}}\right)\left(\frac{-g_{m1} r_{\pi 1}}{R_{ib1}}\right)$$

so

$$A_\upsilon = -(126)(1.5 \| 10)\left(\frac{5}{5+165}\right)\left(\frac{125}{34.1}\right)$$

or

$$A_v = -17.7$$

(c)

$$R_i = R_1 \| R_2 \| R_{ib1} = 70 \| 6 \| 34.1 = 4.76 \text{ k}\Omega$$

and

$$R_o = R_{E2} \left\| \left(\frac{r_{\pi 2} + R_{C1}}{1+\beta} \right) = 1.5 \right\| \left(\frac{0.676 + 5}{126} \right)$$

or

$$R_o = 43.7\ \Omega$$

Test Your Understanding Solutions

TYU6.1

$$i_b = \frac{\upsilon_s}{R_B + r_\pi} = \frac{\upsilon_s}{180 + 31.2} = \frac{\upsilon_s}{211.2}$$

$$i_b = \frac{0.065 \sin \omega t}{211.2} \Rightarrow i_b = 0.308 \sin \omega t \ \ (\mu \text{ A})$$

$$i_B = I_{BQ} + i_b = 0.833 + 0.308 \sin \omega t \ \ (\mu \text{ A})$$

$$\upsilon_{be} = \left(\frac{r_\pi}{r_\pi + R_B} \right) \cdot \upsilon_s = \left(\frac{31.2}{31.2 + 180} \right) (0.065 \sin \omega t) = 0.00960 \sin \omega t \ \ (\text{V})$$

$$\upsilon_{BE} = V_{BE}(on) + \upsilon_{be} = 0.7 + 0.00969 \sin \omega t \ \ (\text{V})$$

$$|\upsilon_{ce}| = |A_\upsilon| \cdot \upsilon_s = (8.52)(0.065 \sin \omega t) = 0.554 \sin \omega t \ \ (\text{V})$$

$$\upsilon_{CE} = V_{CEQ} + \upsilon_{ce} = 1.8 - 0.554 \sin \omega t \ \ (\text{V})$$

TYU6.2

(a) $$I_{BQ} = \frac{V^+ - V_{EB}(on) - V_{BB}}{R_B} = \frac{3.3 - 0.7 - 2.455}{80} \Rightarrow I_{BQ} = 1.8125 \,\mu \text{ A}$$

$$I_{CQ} = \beta I_{BQ} = 0.20 \text{ mA}$$

$$V_{ECQ} = 3.3 - (0.2)(7) = 1.9 \text{ V}$$

(b) $$g_m = \frac{I_{CQ}}{V_T} = \frac{0.2}{0.026} = 7.692 \text{ mA/V}$$

$$r_\pi = \frac{\beta V_T}{I_{CQ}} = \frac{(110)(0.026)}{0.20} = 14.3 \text{ k}\Omega$$

$$r_o = \frac{V_A}{I_{CQ}} = \frac{80}{0.20} = 400 \text{ k}\Omega$$

(c) $$A_\upsilon = -g_m (R_C \| r_o) \left(\frac{r_\pi}{r_\pi + R_B} \right) = -(7.692)(7 \| 400) \left(\frac{14.3}{14.3 + 80} \right) = -8.02$$

(d) $$R_i = R_B + r_\pi = 80 + 14.3 = 94.3 \text{ k}\Omega$$

$$R_o = R_C \| r_o = 7 \| 400 = 6.88 \text{ k}\Omega$$

TYU6.3

$$R_{TH} = R_1 \| R_2 = 100 \| 25 = 20 \text{ k}\Omega$$

$$V_{TH} = \left(\frac{R_2}{R_1 + R_2}\right) \cdot V_{CC} = \left(\frac{25}{100+25}\right)(5) = 1.0 \text{ V}$$

$$I_{BQ} = \frac{V_{TH} - V_{BE}(on)}{R_{TH} + (1+\beta)R_E} = \frac{1.0 - 0.7}{20 + (121)(0.25)} = 0.00597 \text{ mA}$$

$$I_{CQ} = \beta I_{BQ} = 0.7164 \text{ mA}$$

Now

$$g_m = \frac{I_{CQ}}{V_T} = \frac{0.7164}{0.026} = 27.55 \text{ mA/V}$$

$$r_\pi = \frac{\beta V_T}{I_{CQ}} = \frac{(120)(0.026)}{0.7164} = 4.355 \text{ k}\Omega$$

We find

$$R_{TH} \| [r_\pi + (1+\beta)R_E] = 20 \| [4.355 + (121)(0.25)] = 20 \| 34.605 = 12.67 \text{ k}\Omega$$

Then

$$A_\upsilon = \frac{-\beta R_C}{r_\pi + (1+\beta)R_E} \cdot \left(\frac{12.67}{12.67 + 0.25}\right) = \frac{-(120)(4)}{4.355 + (121)(0.25)} \cdot (0.9807)$$

or

$$A_\upsilon = -13.6$$

TYU6.4

As a first approximation, $A_v \cong -\dfrac{R_C}{R_E}$

Resulting gain is always smaller than this value. The effect of R_S is very small.

Set $\dfrac{R_C}{R_E} = 10$

Now $5 \cong I_C(R_C + R_E) + V_{CEQ}$

or $5 = (0.5)(R_C + R_E) + 2.5$

which yields $R_C + R_E = 5\ k\Omega$

We have $R_C = 10 R_E$

so $R_E = 0.454\ k\Omega$ and $R_C = 4.54\ k\Omega$

We have

$$I_{BQ} = \frac{I_{CQ}}{\beta} = \frac{0.5}{100} = 0.005\ mA$$

and

$$R_{TH} = (0.1)(1+\beta)R_E = (0.1)(101)(0.454) \text{ or } R_{TH} = 4.59\ k\Omega$$

Also

$$V_{TH} = \left(\frac{R_2}{R_1 + R_2}\right) \cdot V_{CC} = \frac{1}{R_1} \cdot R_{TH} \cdot V_{CC}$$

or

$$V_{TH} = \frac{1}{R_1}(4.59)(5) = \frac{23}{R_1}$$

Also $$V_{TH} = I_{BQ}R_{TH} + V_{BE}(on) + (1+\beta)I_{BQ}R_E$$

so that $$\frac{23}{R_1} = (0.005)(4.59) + 0.7 + (101)(0.005)(0.454)$$

which yields $R_1 = 24.1\ k\Omega$

Since $R_1 \| R_2 = 4.59\ \text{k}\Omega$, then $R_2 = 5.67\ k\Omega$

TYU6.5

As a first approximation
$$A_v \cong -\frac{R_C}{R_E}$$
Set
$$\frac{R_C}{R_E} = 9$$
Now
$$V_{CC} \cong I_{CQ}(R_C + R_E) + V_{ECQ}$$
$$7.5 = (0.6)(9R_E + R_E) + 3.75$$
which yields
$$R_E = 0.625\ k\Omega \quad \text{and} \quad R_C = 5.62\ k\Omega$$
We have
$$R_{TH} = (0.1)(1+\beta)R_E = (0.1)(101)(0.625) \quad \text{or} \quad R_{TH} = 6.31\ k\Omega$$
Also
$$V_{TH} = \frac{1}{R_1}\cdot R_{TH}\cdot V_{CC} = \frac{1}{R_1}(6.31)(7.5)$$
We have
$$I_{BQ} = \frac{I_{CQ}}{\beta} = \frac{0.6}{100} = 0.006\ mA$$
and
$$V_{CC} = (1+\beta)I_{BQ}R_E + V_{EB}(on) + I_{BQ}R_{TH} + V_{TH}$$
$$7.5 = (101)(0.006)(0.625) + 0.7 + (0.006)(6.31) + \frac{1}{R_1}(6.31)(7.5)$$
which yields
$$R_1 = 7.41\ k\Omega$$
Since $R_{TH} = R_1 \| R_2 = 6.31\ \text{k}\Omega$, then $R_2 = 42.5\ \text{k}\Omega$

TYU6.6

We have
$$A_v = \frac{-\beta R_C}{r_\pi + (1+\beta)R_E} = -(0.95)\left(\frac{R_C}{R_E}\right)$$
or
$$A_v = -(0.95)\left(\frac{2}{0.4}\right) = -4.75$$
Assume, from Example 6.5 that, $r_\pi = 1.2\ \text{k}\Omega$

Then

$$\frac{-\beta(2)}{1.2+(1+\beta)(0.4)} = -4.75$$

or

$$\beta = 76$$

TYU6.7

Dc analysis: by symmetry, $V_{TH} = 0$

$$R_{TH} = R_1 \| R_2 = 20 \| 20 = 10\ \text{k}\Omega$$

We can write

$$I_{BQ} = \frac{0-0.7-(-5)}{10+(126)(5)} = 0.00672\ mA$$

$$I_{CQ} = \beta I_{BQ} = (125)(0.00672) = 0.84\ mA$$

Small-signal transistor parameters:

$$r_\pi = \frac{\beta V_T}{I_{CQ}} = \frac{(125)(0.026)}{0.84} = 3.87\ k\Omega$$

$$g_m = \frac{I_{CQ}}{V_T} = \frac{0.84}{0.026} = 32.3\ mA/V$$

$$r_o = \frac{V_A}{I_{CQ}} = \frac{200}{0.84} = 238\ k\Omega$$

(a) We can write

$$V_o = -g_m V_\pi \left(r_o \| R_C \| R_L\right) \text{ and } V_\pi = V_s$$

so

$$A_\upsilon = \frac{V_o}{V_s} = -g_m\left(r_o \| R_C \| R_L\right) = -(32.3)(238\|2.3\|5)$$

or $A_\upsilon = -50.5$

(b)

$$R_o = r_o \| R_C = 238 \| 2.3 = 2.28\ \text{k}\Omega$$

TYU6.8

We find

$$I_{CQ} = 0.418\ mA,$$

$$V_{CEQ} = 5-(0.418)(5.6)-\left(\frac{121}{120}\right)(0.418)(0.6)$$

or $V_{CEQ} = 2.41\ \text{V}$

So

$$\Delta v_{CE} = (2.41-0.5)\times 2\text{, or } \Delta v_{CE} = 3.82\ V$$

TYU6.9

For $I_{CQ} \cong I_{EQ}$,

$$V_{CEQ} = 10 - I_{CQ}(4+4) = 10 - I_{CQ}(8)$$

$$\Delta I_C = I_{CQ} - 0.1$$

$$\Delta V_{CE} = V_{CEQ} - 0.7$$

$$\Delta V_{CE} = \Delta I_C(4) = (I_{CQ} - 0.1)(4) = V_{CEQ} - 0.7$$

So

$$V_{CEQ} = (I_{CQ} - 0.1)(4) + 0.7$$

Then

$$(I_{CQ} - 0.1)(4) + 0.7 = 10 - I_{CQ}(8) \Rightarrow I_{CQ} = 0.8083 \text{ mA}$$

$$V_{CEQ} = 10 - (0.8083)(8) \Rightarrow V_{CEQ} = 3.533 \text{ V}$$

Then peak-to-peak values are

$$\Delta V_{CE} = (3.533 - 0.7)(2) = 5.67 \text{ V}$$

$$\Delta I_C = (0.8083 - 0.1)(2) = 1.42 \text{ mA}$$

TYU6.10

We can write

$$I_{BQ} = \frac{0 - 0.7 - (-10)}{100 + (131)(10)} \Rightarrow 6.60\ \mu A$$

$$I_{CQ} = (130)(6.60\ \mu A) = 0.857\ mA$$

Assume nominal small-signal parameters of:

$$h_{ie} = 4\ k\Omega,\ h_{fe} = 134$$

$$h_{re} = 0,\ h_{oe} = 12\ \mu S \Rightarrow \frac{1}{h_{oe}} = 83.3\ k\Omega$$

We find

$$R_{ib} = h_{ie} + (1 + h_{fe})\left(R_E \| R_L \| \frac{1}{h_{oe}}\right)$$

$$= 4 + (135)(10 \| 10 \| 83.3) = 641\ k\Omega$$

To find the voltage gain:

$$V_s' = \frac{R_B \| R_{ib}}{R_B \| R_{ib} + R_S} \cdot V_s = \frac{100 \| 641}{100 \| 641 + 10} \cdot V_s = (0.896) V_s$$

Also

$$\frac{V_o}{V_s'} = \frac{(1 + h_{fe})R'}{h_{ie} + (1 + h_{fe})R'}$$

where

$$R' = R_E \| R_L \| \frac{1}{h_{oe}} = 10 \| 10 \| 83.3 = 4.72\ \text{k}\Omega$$

Then

$$A_v = \frac{V_o}{V_s} = \frac{(0.896)(135)(4.72)}{4 + (135)(4.72)} = 0.891$$

To find the current gain

$$A_i = \frac{I_o}{I_i} = \left(\frac{R_E \left\| \frac{1}{h_{oe}} \right.}{R_E \left\| \frac{1}{h_{oe}} \right. + R_L} \right)(1+h_{fe})\left(\frac{R_B}{R_B + R_{ib}} \right)$$

$$= \left(\frac{10\|83.3}{10\|83.3+10} \right)(135)\left(\frac{100}{100+641} \right)$$

or

$$A_i = 8.59$$

To find the output resistance:

$$R_o = R_E \left\| \frac{1}{h_{oe}} \right\| \frac{h_{ie} + R_S \| R_B}{1+h_{fe}}$$

$$= 10 \| 83.3 \left\| \frac{4+10\|100}{135} \right. \Rightarrow R_o = 96.0\,\Omega$$

TYU6.11

$$R_{TH} = R_1 \| R_2 = 50\|50 = 25\text{ k}\Omega$$

$$V_{TH} = \left(\frac{R_2}{R_1 + R_2} \right) \cdot V_{CC} = \left(\frac{1}{2} \right)(5) = 2.5\text{ V}$$

Now

$$I_{BQ} = \frac{V_{CC} - V_{EB}(on) - V_{TH}}{R_{TH} + (1+\beta) R_E}$$

$$= \frac{5-0.7-2.5}{25+(101)(2)} = 0.00793\ mA$$

and

$$I_{CQ} = (100)(0.00793) = 0.793\ mA$$

Small-signal transistor parameters:

$$g_m = \frac{I_{CQ}}{V_T} = \frac{0.793}{0.026} = 30.5\ mA/V$$

$$r_\pi = \frac{\beta V_T}{I_{CQ}} = \frac{(100)(0.026)}{0.793} = 3.28\ k\Omega$$

$$r_o = \frac{V_A}{I_{CQ}} = \frac{125}{0.793} = 158\ k\Omega$$

(a) Define

$$R' = R_E \| R_L \| r_o = 2\|0.5\|158 \cong 0.40\ k\Omega$$

$$A_v = \frac{(1+\beta) R'}{r_\pi + (1+\beta) R'} = \frac{(101)(0.4)}{3.28+(101)(0.4)}$$

or $A_\upsilon = 0.925$

(b)

$$R_{ib} = r_\pi + (1+\beta) R' = 3.28 + (101)(0.4)$$

$$R_{ib} = 43.7\ k\Omega$$

$$R_o = R_E \| r_o \| \frac{r_\pi}{1+\beta} = 2\|158\|\frac{3.28}{101}$$

or

$$R_o = 32.0\ \Omega$$

TYU6.12

(a) $I_{BQ}R_B + V_{BE}(on) + (1+\beta)I_{BQ}R_E + V^- = 0$

$$I_{BQ} = \frac{3.3-0.7}{100+(121)(15)} = 0.001358 \text{ mA}$$

$$I_{EQ} = 0.1643 \text{ mA}; \quad I_{CQ} = 0.1629 \text{ mA}$$

$$V_{CEQ} = 6.6-(0.1643)(15) = 4.14 \text{ V}$$

(b) $A_\upsilon = \dfrac{(1+\beta)(R_E\|R_L)}{r_\pi + (1+\beta)(R_E\|R_L)} \cdot \left(\dfrac{R_i}{R_i+R_S}\right)$

We find

$$g_m = \frac{0.1629}{0.026} = 6.265 \text{ mA/V}$$

$$r_\pi = \frac{(120)(0.026)}{0.1629} = 19.15\ \text{k}\Omega$$

Now

$$R_{ib} = r_\pi + (1+\beta)(R_E\|R_L) = 19.15+(121)(15\|2) = 232.7\ \text{k}\Omega$$

$$R_i = R_{ib}\|R_B = 232.7\|100 = 69.94\ \text{k}\Omega$$

Then

$$A_\upsilon = \frac{(121)(15\|2)}{19.15+(121)(15\|2)} \cdot \left(\frac{69.94}{69.94+2}\right) = 0.892$$

Also

$$A_i = (1+\beta)\left(\frac{R_B}{R_B+R_{ib}}\right)\left(\frac{R_E}{R_E+R_L}\right) = (121)\left(\frac{100}{100+232.7}\right)\left(\frac{15}{15+2}\right)$$

$$A_i = 32.1$$

(c) We found

$$R_{ib} = 232.7\ \text{k}\Omega$$

Now

$$R_o = \left(\frac{r_\pi + R_B\|R_S}{1+\beta}\right)\| R_E = \left(\frac{19.15+100\|2}{121}\right)\|15 = 0.1745\|15$$

$$R_o = 172\ \Omega$$

TYU6.13

(a) dc analysis:

$$I_{EQ} = \frac{V_{EE}-V_{EB}(on)}{R_E} = \frac{10-0.7}{10} = 0.93\ mA$$

$$I_{CQ} = \left(\frac{\beta}{1+\beta}\right)I_{EQ} = \left(\frac{100}{101}\right)(0.93) = 0.921\ mA$$

$$V_{ECQ} = V_{EE} - I_{EQ}R_E - I_{CQ}R_C - (-V_{CC})$$
$$= 10 - (0.93)(10) - (0.921)(5) - (-10)$$

or

$$V_{ECQ} = 6.1\ V$$

(b) Small-signal transistor parameters:

$$r_\pi = \frac{\beta V_T}{I_{CQ}} = \frac{(100)(0.026)}{0.921} = 2.82\ k\Omega$$

$$g_m = \frac{I_{CQ}}{V_T} = \frac{0.921}{0.026} = 35.42\ mA/V$$

Small-signal current gain:

$I_o = g_m V_\pi$, and $V_\pi = V_s$

Also

$$I_i = \frac{V_s}{R_E \| r_\pi} + g_m V_\pi = V_s\left(\frac{1}{R_E \| r_\pi} + g_m\right)$$

Then

$$A_i = \frac{I_o}{I_i} = \frac{g_m V_\pi}{V_\pi\left(\frac{1}{R_E \| r_\pi} + g_m\right)} = \frac{g_m (R_E \| r_\pi)}{1 + g_m (R_E \| r_\pi)}$$
$$= \frac{(35.42)(10 \| 2.82)}{1 + (35.42)(10 \| 2.82)}$$

or

$$A_I = 0.987$$

(c) Small-signal voltage gain:

$$V_o = g_m V_\pi R_C = g_m V_s R_C$$

$$A_v = \frac{V_o}{V_s} = g_m R_C = (35.42)(5)$$

or

$$A_v = 177$$

TYU6.14

(a) $I_{BQ}R_B + V_{BE}(on) + (1+\beta)I_{BQ}R_E = V_{EE}$

$$I_{BQ} = \frac{3.3 - 0.7}{100 + (121)(12)} = 0.001675\ \text{mA}$$

$$I_{CQ} = 0.201\ \text{mA}$$

$$g_m = \frac{0.201}{0.026} = 7.73\ \text{mA/V};\quad r_\pi = \frac{(120)(0.026)}{0.201} = 15.52\ \text{k}\Omega;\quad r_o = \infty$$

(b) $$A_i = \left(\frac{R_E}{R_E + \frac{r_\pi}{1+\beta}}\right)\left(\frac{\beta}{1+\beta}\right)\left(\frac{R_C}{R_C + R_L}\right) = \left(\frac{12}{12 + \frac{15.52}{121}}\right)\left(\frac{120}{121}\right)\left(\frac{12}{12+6}\right)$$

$$A_i = 0.654$$

Now

$$A_\upsilon = g_m\left(\frac{R_C\|R_L}{R_S}\right)\left[\frac{r_\pi}{1+\beta}\|R_E\|R_S\right] = (7.73)\left(\frac{12\|6}{0.5}\right)\left[\frac{15.52}{121}\|12\|0.5\right]$$

$$A_\upsilon = (7.73)(8)(0.1012) = 6.26$$

(c) $R_i = R_E\left\|\frac{r_\pi}{1+\beta} = 12\right\|\frac{15.52}{121} \Rightarrow R_i = 127\ \Omega$

$$R_o = R_C = 12\ \text{k}\Omega$$

TYU6.15

dc analysis

$$5 = I_{BQ}R_B + V_{BE}(on) + I_{EQ}R_E$$

$$I_{BQ} = \frac{5-0.7}{R_B+(101)R_E} = \frac{4.3}{R_B+(101)R_E}$$

$$I_{CQ} = \frac{(100)(4.3)}{R_B+(101)R_E}$$

Also

$$5 = I_{CQ}R_C + V_{CEQ} + I_{EQ}R_E - 5$$

or

$$V_{CEQ} = 10 - I_{CQ}\left[R_C + \left(\frac{101}{100}\right)R_E\right]$$

ac analysis :

$$V_o = -g_mV_\pi(R_C\|R_L)$$

and

$$V_s = -V_\pi - \frac{V_\pi}{r_\pi}\cdot R_B = -V_\pi\left(1+\frac{R_B}{r_\pi}\right)$$

or

$$V_\pi = -\left(\frac{r_\pi}{r_\pi+R_B}\right)\cdot V_s$$

Then

$$A_v = \frac{V_o}{V_s} = \frac{\beta}{r_\pi+R_B}(R_C\|R_L)$$

where

$$\beta = g_mr_\pi$$

For

$I_{CQ} = 1\ mA,$

$$r_\pi = \frac{\beta V_T}{I_{CQ}} = \frac{(100)(0.026)}{1} = 2.6\ k\Omega$$

Then

$$A_v = 20 = \frac{(100)(2\|2)}{2.6+R_B}$$

which yields

$$R_B = 2.4\ k\Omega$$

Then from

$$I_{CQ} = 1 = \frac{(100)(4.3)}{2.4 + (101)R_E}$$

we find

$$R_E = 4.23\ \text{k}\Omega$$

TYU6.16

(a) dc analysis

For $I_{EQ2} = 1\ mA,$

$$I_{CQ2} = \left(\frac{100}{101}\right)(1) = 0.990\ mA$$

$$I_{EQ1} = \frac{I_{EQ2}}{1+\beta} = \frac{1}{101} = 0.0099\ mA$$

$$I_{BQ1} = \frac{I_{EQ1}}{1+\beta} = \frac{0.0099}{101} = 0.000098\ mA$$

$$I_{CQ1} = (100)(0.000098) = 0.0098\ mA$$

$$V_{B1} = -I_{BQ1}R_B = -(0.000098)(10)$$

$$V_{B1} = -0.00098 \cong 0$$

$$V_{E1} = -0.7\ V$$

$$V_{E2} = -1.4\ V$$

$$I_1 = I_{CQ1} + I_{CQ2} = 0.0098 + 0.990 \cong 1\ mA$$

$$V_O = 5 - (1)(4) = 1\ V$$

$$V_{CEQ2} = 1 - (-1.4) = 2.4\ V$$

$$V_{CEQ1} = 1 - (-0.7) = 1.7\ V$$

(b) small-signal transistor parameters:

$$r_{\pi 1} = \frac{\beta V_T}{I_{CQ1}} = \frac{(100)(0.026)}{0.0098} = 265\ \text{k}\Omega$$

$$g_{m1} = \frac{I_{CQ1}}{V_T} = \frac{0.0098}{0.026} = 0.377\ \text{mA/V}$$

$$r_{\pi 2} = \frac{\beta V_T}{I_{CQ2}} = \frac{(100)(0.026)}{0.990} = 2.63\ \text{k}\Omega$$

$$g_{m2} = \frac{I_{CQ2}}{V_T} = \frac{0.990}{0.026} = 38.1\ \text{mA/V}$$

$$r_{o1} = r_{o2} = \infty$$

(c) small-signal voltage gain

$$V_o = -(g_{m1}V_{\pi 1} + g_{m2}V_{\pi 2})R_C$$

$$V_s = V_{\pi 1} + V_{\pi 2}$$

$$V_{\pi 2} = \left(\frac{V_{\pi 1}}{r_{\pi 1}} + g_{m1}V_{\pi 1}\right)\cdot r_{\pi 2} = \left(\frac{1+\beta}{r_{\pi 1}}\right)\cdot V_{\pi 1} r_{\pi 2}$$

$$V_o = -\left[g_{m1}V_{\pi 1} + g_{m2}\left(\frac{1+\beta}{r_{\pi 1}}\right)\cdot r_{\pi 2}V_{\pi 1}\right]\cdot R_C$$

$$V_s = V_{\pi 1} + \left(\frac{1+\beta}{r_{\pi 1}}\right)\cdot r_{\pi 2} V_{\pi 1}$$

$$= V_{\pi 1}\left[1+(1+\beta)\left(\frac{r_{\pi 2}}{r_{\pi 1}}\right)\right]$$

$$V_{\pi 1} = \frac{V_s}{1+(1+\beta)\left(\frac{r_{\pi 2}}{r_{\pi 1}}\right)}$$

Now

$$A_v = \frac{V_o}{V_s} = -\frac{\left[g_{m1} + g_{m2}(1+\beta)\left(\frac{r_{\pi 2}}{r_{\pi 1}}\right)\right]\cdot R_C}{1+(1+\beta)\left(\frac{r_{\pi 2}}{r_{\pi 1}}\right)}$$

$$A_v = -\frac{\left[0.377+(38.1)(101)\left(\frac{2.63}{265}\right)\right](4)}{1+(101)\left(\frac{2.63}{265}\right)}$$

or

$$A_v = -77.0$$

(d)

$$R_i = r_{\pi 1} + (1+\beta) r_{\pi 2} = 265 + (101)(2.63)$$

or

$$R_i = 531\ k\Omega$$

TYU6.17

(a) $$R_1 + R_2 + R_3 = \frac{9}{0.1} = 90\ \text{k}\Omega$$

$$R_E = \frac{0.7}{1} = 0.7\ \text{k}\Omega$$

$$V_{B1} = 0.7 + 0.7 = 1.4\ \text{V} \Rightarrow \left(\frac{R_3}{90}\right)(9) = 1.4 \Rightarrow R_3 = 14\ \text{k}\Omega$$

$$V_{B2} = 0.7 + 2.5 + 0.7 = 3.9\ \text{V} \Rightarrow \left(\frac{R_2 + R_3}{90}\right)(9) = 3.9 \Rightarrow R_2 = 25\ \text{k}\Omega$$

Then $R_1 = 51\ \text{k}\Omega$

$$V_{C2} = 0.7 + 2.5 + 2.5 = 5.7\ \text{V}$$

So

$$R_C = \frac{9-5.7}{1} = 3.3\ \text{k}\Omega$$

(b) $$g_m = \frac{1}{0.026} = 38.46\ \text{mA/V}; \quad r_\pi = \frac{(100)(0.026)}{1} = 2.6\ \text{k}\Omega$$

(c) $$A_\upsilon = -g_{m1} g_{m2}\left(\frac{r_{\pi 2}}{1+\beta_2}\right)(R_C \| R_L) = -(38.46)^2\left(\frac{2.6}{101}\right)(3.3 \| 10) = -94.5$$

TYU6.18

(a) dc analysis

$$R_{TH} = R_1 \| R_2 = 125 \| 30 = 24.2\ k\Omega$$

$$V_{TH} = \left(\frac{R_2}{R_1 + R_2}\right) \cdot V_{CC} = \left(\frac{30}{125+30}\right)(12)$$

or

$$V_{TH} = 2.32\ V$$

Now

$$V_{TH} = I_{BQ} R_{TH} + V_{BE}(on) + (1+\beta) I_{BQ} R_E$$

$$I_{BQ} = \frac{2.32 - 0.7}{24.2 + (81)(0.5)} = 0.0250\ mA$$

$$I_{CQ} = (80)(0.025) = 2.00\ mA$$

$$V_{CEQ} = V_{CC} - I_{CQ}\left[R_C + \left(\frac{1+\beta}{\beta}\right) R_E\right]$$

$$= 12 - (2)\left[2 + \left(\frac{81}{80}\right)(0.5)\right]$$

or

$$V_{CEQ} = 6.99\ V$$

Power dissipated in R_C:

$$P_{RC} = I_{CQ}^2 R_C = (2.0)^2 (2) = 8.0\ mW$$

Power dissipated in R_L:

$$I_{LQ} = 0 \Rightarrow P_{RL} = 0$$

Power dissipated in transistor:

$$P_Q = I_{BQ} V_{BEQ} + I_{CQ} V_{CEQ}$$
$$= (0.025)(0.7) + (2.0)(6.99) = 14.0\ mW$$

(b) With

$$v_s = 18 \cos \omega t\,(mV)$$

$$r_\pi = \frac{\beta V_T}{I_{CQ}} = \frac{(80)(0.026)}{2.0} = 1.04\ k\Omega$$

We can write

$$v_{ce} = \frac{\beta}{r_\pi}(R_C \| R_L) V_P \cos \omega t$$

Power dissipated in R_L:

$$\bar{p}_{RL} = \frac{|v_{ce}(rms)|^2}{R_L} = \frac{1}{2} \cdot \frac{1}{R_L} \cdot \left[\frac{\beta}{r_\pi}(R_C \| R_L) V_P\right]^2$$

$$= \frac{1}{2} \cdot \frac{1}{2 \times 10^3} \cdot \left[\frac{80}{1.04}(2 \| 2)(0.018)\right]^2$$

or

$$\bar{p}_{RL} = 0.479\ mW$$

Power dissipated in R_C:

Since $R_C = R_L = 2\ k\Omega$, we find

$$\bar{p}_{RC} = 8.0 + 0.479 = 8.48\ mW$$

$$\overline{P}_Q \cong I_{CQ} V_{CEQ} - \left(\frac{\beta}{r_\pi}\right)^2 \left(\frac{V_P}{\sqrt{2}}\right)^2 \left(R_C \| R_L\right)$$

$$= \left(2\times10^{-3}\right)(6.99) - \left(\frac{80}{1.04\times10^3}\right)^2 \left(\frac{0.018}{\sqrt{2}}\right)^2 \left(2\times10^3 \| 2\times10^3\right)$$

or

$$\overline{p}_Q = 13.0\ mW$$

TYU6.19

(a) dc analysis

$$R_{TH} = R_1 \| R_2 = 53.8 \| 10 = 8.43\ k\Omega$$

$$V_{TH} = \left(\frac{R_2}{R_1 + R_2}\right) \cdot V_{CC} = \left(\frac{10}{53.8+10}\right)(5)$$

or

$$V_{TH} = 0.7837\ V$$

Now

$$I_{BQ} = \frac{0.7837 - 0.7}{8.43} = 0.00993\ mA$$

$$I_{CQ} = (100)(0.00993) = 0.993\ mA$$

$$V_{CEQ} = V_{CC} - I_{CQ} R_C$$

$$2.5 = 5 - (0.993) R_C$$

which yields

$$R_C = 2.52\ k\Omega$$

(b)

Power dissipated in R_C:

$$P_{RC} = I_{CQ}^2 R_C = (0.993)^2 (2.52)$$

or

$$P_{RC} = 2.48\ mW$$

Power dissipated in transistor:

$$P_Q \cong I_{CQ} V_{CEQ} = (0.993)(2.5)$$

or

$$P_Q = 2.48\ mW$$

(c) ac analysis

Maximum ac collector current:

$$i_c = (0.993)\cos\omega t\ (mA)$$

Power dissipated in R_C:

$$\overline{p}_{RC} = \frac{1}{2}(0.993)^2 R_C = \frac{1}{2}(0.993)^2 (2.52)$$

or

$$\overline{p}_{RC} = 1.24\ mW$$

Now

$$\text{Fraction} = \frac{\overline{p}_{RC}}{P_{RC} + P_Q} = \frac{1.24}{2.48 + 2.48} = 0.25$$

Chapter 7

Exercise Solutions

EX7.1

(a) (i) $f_L = \dfrac{1}{2\pi\tau_S} \Rightarrow \tau_S = \dfrac{1}{2\pi f_L} = \dfrac{1}{2\pi(50)} \Rightarrow 3.183 \text{ ms}$

$$\tau_S = (R_S + R_P)C_S$$

$$3.183\times10^{-3} = (2+8)\times10^3(C_S) \Rightarrow C_S = 0.318\,\mu\text{F}$$

(ii) $|T| = \left(\dfrac{R_P}{R_P+R_S}\right)\left[\dfrac{f/f_L}{\sqrt{1+\left(f/f_L\right)^2}}\right] = \left(\dfrac{8}{8+2}\right)\left[\dfrac{f/f_L}{\sqrt{1+\left(f/f_L\right)^2}}\right]$

For $f = 20$, $\dfrac{f}{f_L} = \dfrac{20}{50} = 0.4$; $|T| = (0.8)\left[\dfrac{0.4}{\sqrt{1+(0.4)^2}}\right] = 0.297$

For $f = 50$, $\dfrac{f}{f_L} = \dfrac{50}{50} = 1$; $|T| = (0.8)\dfrac{(1)}{\sqrt{2}} = 0.566$

For $f = 100$, $\dfrac{f}{f_L} = \dfrac{100}{50} = 2$; $|T| = (0.8)\dfrac{(2)}{\sqrt{1+(2)^2}} = 0.716$

(b)

(i) $\tau_P = (R_S \| R_P)C_P = (4.7\|25)\times10^3\times(120\times10^{-12}) = 4.747\times10^{-7}\ s$

$$f_H = \frac{1}{2\pi\tau_P} = \frac{1}{2\pi(4.747\times10^{-7})} \Rightarrow 335 \text{ kHz}$$

(ii) $|T| = \left(\dfrac{R_P}{R_P+R_S}\right)\cdot\dfrac{1}{\sqrt{1+\left(f/f_H\right)^2}} = \dfrac{(0.84175)}{\sqrt{1+\left(f/f_H\right)^2}}$

For $f = 0.2 f_H$; $|T| = \dfrac{(0.84175)}{\sqrt{1+(0.2)^2}} = 0.825$

For $f = f_H$; $|T| = \dfrac{(0.84175)}{\sqrt{2}} = 0.595$

For $f = 8 f_H$; $|T| = \dfrac{(0.84175)}{\sqrt{1+(8)^2}} = 0.104$

EX7.2

(a) $A_\upsilon(mid) = \dfrac{R_P}{R_P + R_S}$

$$-2 = 20\log_{10}\left(\frac{R_P}{R_P + R_S}\right) \Rightarrow \frac{R_P}{R_P + R_S} = 0.7943$$

$$\frac{7.5}{7.5 + R_S} = 0.7943 \Rightarrow R_S = 1.942 \text{ k}\Omega$$

$$f_L = \frac{1}{2\pi\tau_S} \Rightarrow \tau_S = \frac{1}{2\pi f_L} = \frac{1}{2\pi(200)} = 0.7958 \times 10^{-3} \text{ s}$$

$$\tau_S = (R_S + R_P)C_S$$

$$0.7958 \times 10^{-3} = (1.942 + 7.5) \times 10^3 (C_S) \Rightarrow C_S = 0.0843\,\mu\text{F}$$

$$\tau_P = (R_S \| R_P)C_P = (1.942 \| 7.5) \times 10^3 \times (80 \times 10^{-12}) = 1.234 \times 10^{-7} \text{ s}$$

$$f_H = \frac{1}{2\pi\tau_P} = \frac{1}{2\pi(1.234 \times 10^{-7})} \Rightarrow 1.29 \text{ MHz}$$

(b) $\tau_S = 0.796$ ms

$\tau_P = 0.123\,\mu$s

EX7.3

(a) $R_{TH} = R_1 \| R_2 = 110 \| 42 = 30.39 \text{ k}\Omega$

$$V_{TH} = \left(\frac{R_2}{R_1 + R_2}\right) \cdot V_{CC} = \left(\frac{42}{110 + 42}\right)(3) = 0.8289 \text{ V}$$

$$I_{BQ} = \frac{V_{TH} - V_{BE}(on)}{R_{TH} + (1+\beta)R_E} = \frac{0.8289 - 0.7}{30.39 + (151)(0.5)} = 0.001217 \text{ mA}$$

$$I_{CQ} = \beta I_{BQ} = 0.1826 \text{ mA}$$

$$\tau_S = (R_1 \| R_2 \| R_{ib})C_C$$

where $R_{ib} = r_\pi + (1+\beta)R_E$

Now

$$r_\pi = \frac{(150)(0.026)}{0.1826} = 21.36 \text{ k}\Omega$$

Then $R_{ib} = 21.36 + (151)(0.5) = 96.86 \text{ k}\Omega$

$$\tau_S = (110 \| 42 \| 96.86) \times 10^3 \times (0.47 \times 10^{-6}) \Rightarrow 10.87 \text{ ms}$$

(b) $f_L = \dfrac{1}{2\pi\tau_S} = \dfrac{1}{2\pi(10.87 \times 10^{-3})} = 14.6 \text{ Hz}$

$$A_\upsilon = \frac{-\beta R_C}{r_\pi + (1+\beta)R_E} = \frac{-(150)(7)}{21.36 + (151)(0.5)} = -10.84$$

EX7.4

(a) $I_{DQ} = K_n(V_{GSQ} - V_{TN})^2$

$$250 = 100(V_{GSQ} - 0.4)^2 \Rightarrow V_{GSQ} = 1.981 \text{ V}$$

$$R_S = \frac{-V_{GSQ} - (-3)}{I_{DQ}} = \frac{3 - 1.981}{0.25} = 4.08 \text{ k}\Omega$$

$$V_D = -V_{GSQ} + V_{DSQ} = -1.981 + 1.7 = -0.281 \text{ V}$$

$$R_D = \frac{3 - V_D}{I_{DQ}} = \frac{3 - (-0.281)}{0.25} = 13.1 \text{ k}\Omega$$

(b) $\tau_S = (R_D + R_L)C_C = (13.1 + 20) \times 10^3 \times (0.7 \times 10^{-6}) \Rightarrow \tau_S = 23.17 \text{ ms}$

$$f_L = \frac{1}{2\pi\tau_S} = \frac{1}{2\pi(23.17 \times 10^{-3})} = 6.87 \text{ Hz}$$

EX7.5

$$\tau_S = (R_L + R_o)C_{C2}$$

$$f = \frac{1}{2\pi\tau_S} \Rightarrow C_{C2} = \frac{1}{2\pi(R_L + R_o)}$$

$$R_o = R_E \| r_o \left\| \left\{ \frac{r_\pi + (R_S \| R_B)}{1 + \beta} \right\} \right.$$

From Example 7-5, $R_0 = 35.5\ \Omega$

$$C_{C2} = \frac{1}{2\pi(10)\left[10 \times 10^3 + 35.5\right]}$$

$$\underline{C_{C2} = 1.59\ \mu\text{F}}$$

EX7.6

(a)

$$R_{TH} = 5 \text{ K}$$

$$V_{TH} = -3.7527$$

$$I_{BQ} = \frac{-3.7527 - 0.7 - (-5)}{5 + (101)(0.5)} = \frac{0.54726}{55.5}$$

$$= 0.00986$$

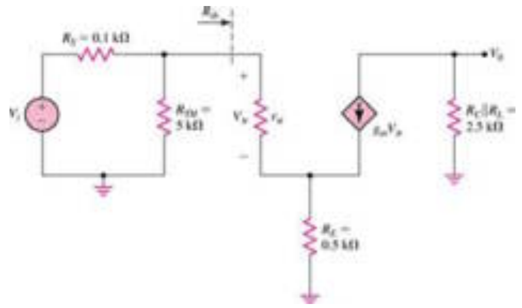
$$I_{CQ} = 0.986 \text{ mA}$$

$$g_m = 37.925 \quad r_\pi = 2.637 \text{ K}$$

$$0.986 = \frac{5 - V_o}{5} - \frac{V_o}{5} = 1 - V_o(0.4)$$

$$V_o = 0.035$$

(b)



$$V_o = -g_m V_\pi \left(R_C \| R_L \right)$$

$$R_{ib} = r_\pi + (1+\beta) R_E = 2.64 + (101)(0.5) = 53.14 \text{ k}\Omega$$

$$V_\pi = \frac{V_b}{1 + \left(\dfrac{1+\beta}{r_\pi} \right) R_E} = \frac{V_b}{1 + \left(\dfrac{101}{2.637} \right)(0.5)} = \frac{V_b}{14.885}$$

$$V_b = \frac{R_{TH} \| R_{ib}}{R_{TH} \| R_{ib} + R_S} \cdot V_i = \frac{5 \| 53.14}{5 \| 53.14 + 0.1} \cdot V_i = (0.9786) V_i$$

$$A_\upsilon = \frac{-(37.925)(2.5)}{14.885} (0.9786) \Rightarrow A_\upsilon = -6.23$$

(c)

EX7.7

a.

$$I_{BQ} = \frac{0 - 0.7 - (-10)}{0.5 + (101)(4)} = 0.0230 \text{ mA}$$

$$I_{CQ} = 2.30 \text{ mA}$$

$$r_\pi = \frac{\beta V_T}{I_{CQ}} = \frac{(100)(0.026)}{2.30} = 1.13 \text{ k}\Omega$$

$$g_m = \frac{I_{CQ}}{V_T} = \frac{2.30}{0.026} = 88.46 \text{ mA/V}$$

$$\tau_B = \frac{R_E (R_S + r_\pi) C_E}{R_S + r_\pi + (1+\beta) R_E}$$

$$= \frac{(4 \times 10^3)(0.5 + 1.13) C_E}{0.5 + 1.13 + (101)(4)}$$

$$\tau_B = \frac{1}{2\pi f_B} = \frac{1}{2\pi(200)} \Rightarrow \tau_B = 0.7958 \text{ ms}$$

$$\tau_B = 16.07 C_E \Rightarrow C_E = \frac{0.796 \times 10^{-3}}{16.07} \Rightarrow C_E = 49.5 \, \mu\text{F}$$

b.

$$\tau_A = R_E C_E = (4 \times 10^3)(49.5 \times 10^{-6}) \Rightarrow \tau_A = 0.198 \text{ s}$$

$$f_A = \frac{1}{2\pi \tau_A} = \frac{1}{2\pi(0.198)} \Rightarrow f_A = 0.804 \text{ Hz}$$

EX7.8

(a) $$f_\beta = \frac{1}{2\pi r_\pi (C_\pi + C_\mu)}$$

$$r_\pi = \frac{(120)(0.026)}{0.2} = 15.6 \text{ k}\Omega$$

$$C_\pi + C_\mu = \frac{1}{2\pi r_\pi f_\beta} = \frac{1}{2\pi (15.6\times 10^3)(90\times 10^6)} \Rightarrow 0.113 \text{ pF}$$

$$C_\pi = 0.113 - 0.02 = 0.093 \text{ pF}$$

(b) $$|h_{fe}| = \frac{\beta_o}{\sqrt{1+\left(\frac{f}{f_\beta}\right)^2}}$$

(i) For $f = 50$ MHz, $$|h_{fe}| = \frac{120}{\sqrt{1+\left(\frac{50}{90}\right)^2}} = 105$$

(ii) For $f = 125$ MHz, $$|h_{fe}| = \frac{120}{\sqrt{1+\left(\frac{125}{90}\right)^2}} = 70.1$$

(iii) For $f = 500$ MHz, $$|h_{fe}| = \frac{120}{\sqrt{1+\left(\frac{500}{90}\right)^2}} = 21.3$$

EX7.9

$$r_\pi = \frac{(150)(0.026)}{0.15} = 26 \text{ k}\Omega$$

$$f_\beta = \frac{1}{2\pi r_\pi (C_\pi + C_\mu)} = \frac{1}{2\pi (26\times 10^3)(0.8+0.012)\times 10^{-12}}$$

or

$$f_\beta = 7.54 \text{ MHz}$$

$$f_T = \beta_o f_\beta = (150)(7.54) \Rightarrow f_T = 1.13 \text{ GHz}$$

EX7.10

(a) $$R_{TH} = R_1 \| R_2 = 200\|220 = 104.8 \text{ k}\Omega$$

$$V_{TH} = \left(\frac{R_2}{R_1+R_2}\right)\cdot V_{CC} = \left(\frac{220}{200+220}\right)(5) = 2.619 \text{ V}$$

$$I_{BQ} = \frac{V_{TH} - V_{BE}(on)}{R_{TH} + (1+\beta)R_E} = \frac{2.619 - 0.7}{104.8 + (101)(1)} = 0.009325 \text{ mA}$$

$$I_{CQ} = \beta I_{BQ} = 0.9325 \text{ mA}$$

Now

$$r_\pi = \frac{(100)(0.026)}{0.9325} = 2.788 \text{ k}\Omega \quad ; \quad g_m = \frac{0.9325}{0.026} = 35.87 \text{ mA/V}$$

$$I_b = \left(\frac{r_s \| R_1 \| R_2}{r_s \| R_1 \| R_2 + r_\pi}\right) \cdot I_s = \left(\frac{100 \| 104.8}{100 \| 104.8 + 2.788}\right) \cdot I_s = 0.9483 I_s$$

$$I_o = -\beta I_b \left(\frac{R_C}{R_C + R_L}\right) = -(100)(0.9483) I_s \left(\frac{2.2}{2.2 + 4.7}\right)$$

or

$$A_i = \frac{I_o}{I_s} = -30.24$$

(b) (i) For $C_\mu = 0 \Rightarrow C_M = 0$

(ii) For $C_\mu = 0.08 \text{ pF} \Rightarrow C_M = C_\mu \left[1 + g_m (R_C \| R_L)\right]$

$$C_M = (0.08)\left[1 + (35.87)(2.2 \| 4.7)\right] = 4.38 \text{ pF}$$

(c) $R_{eq} = r_s \| R_{TH} \| r_\pi = 100 \| 104.8 \| 2.788 = 2.644 \text{ k}\Omega$

(i) $$f_{3dB} = \frac{1}{2\pi R_{eq} C_\pi} = \frac{1}{2\pi (2.644 \times 10^3)(10^{-12})} \Rightarrow 60.2 \text{ MHz}$$

(ii) $$f_{3dB} = \frac{1}{2\pi (2.644 \times 10^3)(1 + 4.38) \times 10^{-12}} \Rightarrow 11.2 \text{ MHz}$$

EX7.11

$$g_m = 2\pi f_T (C_{gs} + C_{gd}) = 2\pi (3 \times 10^9)(60 + 8) \times 10^{-15} \Rightarrow 1.282 \text{ mA/V}$$

$$g_m = 2\sqrt{K_n I_{DQ}} \Rightarrow I_{DQ} = \frac{1}{K_n}\left(\frac{g_m}{2}\right)^2 = \frac{1}{1.2}\left(\frac{1.282}{2}\right)^2$$

or

$$I_{DQ} = 0.342 \text{ mA}$$

EX7.12

(a) $$V_G = \left(\frac{166}{166 + 234}\right)(10) = 4.15 \text{ V}$$

$$V_G = V_{GS} + K_n R_S (V_{GS} - V_{TN})^2$$

$$4.15 = V_{GS} + (0.8)(0.5)(V_{GS}^2 - 4V_{GS} + 4)$$

or

$$0.4V_{GS}^2 - 0.6V_{GS} - 2.55 = 0$$

which yields

$$V_{GS} = 3.384 \text{ V}$$

$$I_D = (0.8)(3.384 - 2)^2 = 1.532 \text{ mA}$$

Now

$$g_m = 2\sqrt{K_n I_D} = 2\sqrt{(0.8)(1.532)} = 2.214 \text{ mA/V}$$

$$R_{TH} = R_1 \| R_2 = 166 \| 234 = 97.11 \text{ k}\Omega$$

So

$$A_\upsilon = -g_m (R_D \| R_L)\left(\frac{R_{TH}}{R_{TH} + R_i}\right) = -(2.214)(4 \| 20)\left(\frac{97.11}{97.11 + 10}\right)$$

or

$$A_\upsilon = -6.69$$

(b) $C_M = C_{gd}\left[1 + g_m\left(R_D \| R_L\right)\right] = 20\left[1 + (2.214)(4\|20)\right] = 167.6 \text{ fF}$

(c) $f_{3-dB} = \dfrac{g_m}{2\pi\left(C_{gs} + C_M\right)} = \dfrac{2.214\times 10^{-3}}{2\pi(100 + 167.6)\times 10^{-15}}$

or

$$f_{3-dB} = 1.32 \text{ GHz}$$

EX7.13

dc analysis

$V_{TH} = 0, \quad R_{TH} = 10 \text{ k}\Omega$

$$I_{BQ} = \frac{0 - 0.7 - (-5)}{10 + (126)(5)} = 0.00672 \text{ mA}$$

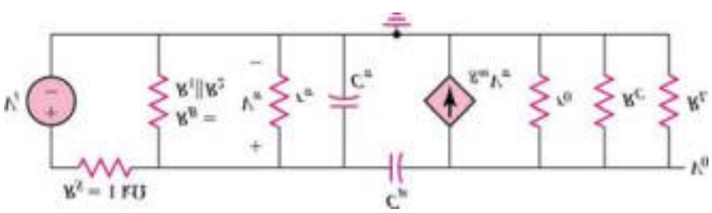
$$I_{CQ} = 0.840 \text{ mA}$$

$$r_\pi = \frac{\beta V_T}{I_{CQ}} = \frac{(125)(0.026)}{0.840} = 3.87 \text{ k}\Omega$$

$$g_m = \frac{I_{CQ}}{V_T} = \frac{0.840}{0.026} = 32.3 \text{ mA/V}$$

$$r_0 = \frac{V_A}{I_{CQ}} = \frac{200}{0.84} = 238 \text{ k}\Omega$$

High-frequency equivalent circuit



a.

Miller Capacitance

$$C_M = C_\mu\left(1 + g_m R_L'\right)$$

$$R_L' = r_o \| R_C \| R_L = 238 \| 2.3 \| 5 = 1.565 \text{ k}\Omega$$

$$C_M = (3)\left[1 + (32.3)(1.565)\right] \Rightarrow C_M = 155 \text{ pF}$$

b.

$$R_{eq} = R_S \| R_B \| r_\pi = R_S \| R_1 \| R_2 \| r_\pi$$

$$= 1 \| 20 \| 20 \| 3.87 = 0.736 \text{ k}\Omega$$

$$\tau_p = R_{eq}\left(C_\pi + C_M\right) = \left(0.736\times 10^3\right)(24 + 155)\times 10^{-12}$$

$$= 1.314\times 10^{-7} \text{ s}$$

$$f_H = \frac{1}{2\pi\left(1.314\times 10^{-7}\right)} \Rightarrow f_H = 1.21 \text{ MHz}$$

c.

$$(A_\upsilon)_M = -g_m R_L' \left[\frac{R_B \| r_\pi}{R_B \| r_\pi + R_S} \right] = -(32.3)(1.565)\left[\frac{10\|3.87}{10\|3.87 + 1} \right]$$

or

$$(A_\upsilon)_M = -37.2$$

EX7.14

The dc analysis

$$I_{BQ} = \frac{10 - 0.7}{100 + (101)(10)} = 0.00838 \text{ mA}$$

$$I_{CQ} = 0.838 \text{ mA}$$

$$r_\pi = \frac{\beta V_T}{I_{CQ}} = \frac{(100)(0.026)}{0.838} = 3.10 \text{ k}\Omega$$

$$g_m = \frac{I_{CQ}}{V_T} = 32.22 \text{ mA/V}$$

For the input

$$\tau_{p\pi} = \left[\left(\frac{r_\pi}{1+\beta} \right) \| R_E \| R_S \right] C_\pi = \left[\left(\frac{3.10}{101} \right) \| 10 \| 1 \right] \times 10^3 \times 24 \times 10^{-12}$$

$$= 7.13 \times 10^{-10} \text{ s}$$

$$f_{H\pi} = \frac{1}{2\pi \tau_{p\pi}} = \frac{1}{2\pi(7.13 \times 10^{-10})} \Rightarrow f_{H\pi} = 223 \text{ MHz}$$

For the output

$$\tau_{p\mu} = (R_C \| R_L) C_\mu = (10\|1) \times 10^3 \times 3 \times 10^{-12}$$

$$= 2.73 \times 10^{-9} \text{ s}$$

$$f_{H\mu} = \frac{1}{2\pi \tau_{p\mu}} = \frac{1}{2\pi(2.73 \times 10^{-9})} \Rightarrow f_{H\mu} = 58.4 \text{ MHz}$$

$$(A_\upsilon)_M = g_m (R_C \| R_L) \left[\frac{R_E \left\| \left(\frac{r_\pi}{1+\beta} \right) \right.}{R_E \left\| \left(\frac{r_\pi}{1+\beta} \right) \right. + R_S} \right]$$

$$= (32.22)(10\|1) \left[\frac{10 \left\| \left(\frac{3.1}{101} \right) \right.}{10 \left\| \left(\frac{3.1}{101} \right) \right. + 1} \right] \Rightarrow (A_\upsilon)_M = 0.870$$

EX7.15

$$V_{B1} = \left(\frac{R_3}{R_1 + R_2 + R_3}\right)(12) = \left(\frac{7.92}{58.8 + 33.3 + 7.92}\right)(12) = 0.9502 \text{ V}$$

Neglecting base currents

$$I_C = \frac{0.9502 - 0.7}{0.5} = 0.50 \text{ mA}$$

$$r_\pi = \frac{\beta V_T}{I_C} = \frac{(100)(0.026)}{0.5} = 5.2 \text{ K}$$

$$g_m = \frac{I_C}{V_T} = \frac{0.5}{0.026} = 19.23 \text{ mA/V}$$

From Eq (7.119(a)),

$$\tau_{p\pi} = \left(R_S \| R_{B1} \| r_\pi\right)\left(C_{\pi 1} + C_{M1}\right)$$

$$R_{B1} = R_2 \| R_3 = 33.3 \| 7.92 = 6.398 \text{ k}\Omega$$

$$C_{M1} = 2C_{\mu 1} = 6 \text{ pF}$$

Then

$$\tau_{p\pi} = \left(1 \| 6.398 \| 5.2\right) \times 10^3 \times (24 + 6) \times 10^{-12} \Rightarrow \tau_{p\pi} = 22.24 \text{ ns}$$

$$f_{H\pi} = \frac{1}{2\pi \tau_{p\pi}} = \frac{1}{2\pi\left(22.24 \times 10^{-9}\right)} \Rightarrow f_{H\pi} = 7.15 \text{ MHz}$$

From Eq (7.120(a)),

$$\tau_{p\mu} = \left(R_C \| R_L\right) C_{\mu 2} = (7.5 \| 2) \times 10^3 \times 3 \times 10^{-12} \Rightarrow \tau_{p\mu} = 4.737 \text{ ns}$$

$$f_{H\mu} = \frac{1}{2\pi \tau_{p\mu}} = \frac{1}{2\pi\left(4.737 \times 10^{-9}\right)} \Rightarrow f_{H\mu} = 33.6 \text{ MHz}$$

From Eq. (7.125),

$$\left|A_\upsilon\right|_M = g_{m2}\left(R_C \| R_L\right)\left[\frac{R_{B1} \| r_{\pi 1}}{R_{B1} \| r_{\pi 1} + R_S}\right] = (19.23)(7.5 \| 2)\left[\frac{6.40 \| 5.2}{6.40 \| 5.2 + 1}\right]$$

$$\left|A_\upsilon\right|_M = 22.5$$

Test Your Understanding Solutions

TYU7.1

a.

$$V_0 = -(g_m V_\pi) R_L$$

$$V_\pi = \frac{r_\pi}{r_\pi + \dfrac{1}{sC_C} + R_S} \times V_i$$

$$T(s) = \frac{V_0(s)}{V_i(s)} = \frac{-g_m r_\pi R_L}{r_\pi + R_S + (1/sC_C)}$$

$$= \frac{-g_m r_\pi R_L (sC_C)}{1 + s(r_\pi + R_S)C_C}$$

$$g_m r_\pi = \beta$$

$$\underline{T(s) = \frac{-\beta R_L}{r_\pi + R_S} \times \left(\frac{s(r_\pi + R_S)C_C}{1 + s(r_\pi + R_S)C_C} \right)}$$

Then $\tau = (r_\pi + R_S)C_C$

b.

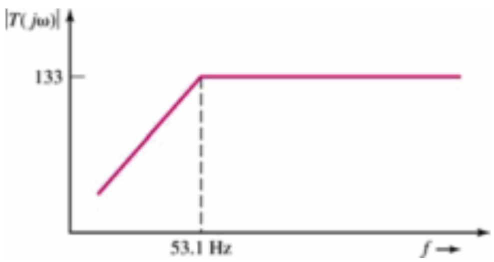
$$\underline{f_{3-dB} = \frac{1}{2\pi(r_\pi + R_S)C_C}}$$

$$f_{3-dB} = \frac{1}{2\pi\left[2\times10^3 + 1\times10^3\right]\left[10^{-6}\right]} \Rightarrow \underline{f_{3dB} = 53.1 \text{ Hz}}$$

$$|T(j\omega)|_{\max} = \frac{r_\pi g_m R_L}{r_\pi + R_S} = \frac{(2)(50)(4)}{2+1}$$

$$\underline{|T(j\omega)|_{\max} = 133}$$

c.



TYU7.2

(a) $\tau = R_L C_L = (10\times10^3)(2\times10^{-12}) \Rightarrow 0.02\,\mu\text{s}$

(b) $f_{3-dB} = \dfrac{1}{2\pi\tau} = \dfrac{1}{2\pi(0.02\times10^{-6})} \Rightarrow 7.96\ \text{MHz}$

$$|A_\upsilon|_{\max} = \frac{r_\pi}{r_\pi + R_S}\cdot(g_m R_L) = \left(\frac{2.4}{2.4+0.1}\right)(50)(10) = 480$$

TYU7.3

(a) $\tau_S = (R_S + r_\pi)C_C = (0.1 + 2.4)\times 10^3 \times (5\times 10^{-6}) \Rightarrow 12.5 \text{ ms}$

$\tau_P = R_L C_L = (10\times 10^3)(4\times 10^{-12}) \Rightarrow 0.04\,\mu\text{ s}$

(b) $A_\upsilon = -\left(\dfrac{r_\pi}{r_\pi + R_S}\right)(g_m R_L) = -\left(\dfrac{2.4}{2.4+0.1}\right)(50)(10) = -480$

(c) $f_L = \dfrac{1}{2\pi\tau_S} = \dfrac{1}{2\pi(12.5\times 10^{-3})} = 12.7 \text{ Hz}$

$f_H = \dfrac{1}{2\pi\tau_P} = \dfrac{1}{2\pi(0.04\times 10^{-6})} \Rightarrow 3.98 \text{ MHz}$

TYU7.4 Computer Analysis

TYU7.5 Computer Analysis

TYU7.6

$$r_\pi = \frac{(120)(0.026)}{0.12} = 26 \text{ k}\Omega$$

$$f_\beta = \frac{1}{2\pi r_\pi (C_\pi + C_\mu)} \Rightarrow (C_\pi + C_\mu) = \frac{1}{2\pi r_\pi f_\beta}$$

or

$$C_\pi + C_\mu = \frac{1}{2\pi(26\times 10^3)(15\times 10^6)} \Rightarrow 0.408 \text{ pF}$$

Then

$$C_\pi = 0.408 - 0.08 = 0.328 \text{ pF}$$

TYU7.7

$$|h_{fe}| = \frac{\beta_o}{\sqrt{1+\left(\dfrac{f}{f_\beta}\right)^2}} \quad ; \quad \phi = -\tan^{-1}\left(\frac{f}{f_\beta}\right)$$

$$f_\beta = 167 \text{ MHz} \;; \quad \beta_o = 120$$

Then

(a) For $f = 150$ MHz; $|h_{fe}| = \dfrac{120}{\sqrt{1+\left(\dfrac{150}{167}\right)^2}} = 89.3$

$$\phi = -\tan^{-1}\left(\frac{150}{167}\right) = -41.9^\circ$$

For $f = 500$ MHz; $|h_{fe}| = \dfrac{120}{\sqrt{1+\left(\dfrac{500}{167}\right)^2}} = 38.0$

$$\phi = -\tan^{-1}\left(\frac{500}{167}\right) = -71.5°$$

For $f = 4$ GHz; $\quad |h_{fe}| = \dfrac{120}{\sqrt{1+\left(\dfrac{4000}{167}\right)^2}} = 5.0$

$$\phi = -\tan^{-1}\left(\frac{4000}{167}\right) = -87.6°$$

TYU7.8

(a) $f_\beta = \dfrac{f_T}{\beta_o} = \dfrac{10^9}{150} \Rightarrow f_\beta = 6.67 \text{ MHz}$

$$f_\beta = \frac{1}{2\pi r_\pi (C_\pi + C_\mu)} \Rightarrow (C_\pi + C_\mu) = \frac{1}{2\pi r_\pi f_\beta}$$

or

$$(C_\pi + C_\mu) = \frac{1}{2\pi(12\times 10^3)(6.667\times 10^6)} \Rightarrow 1.989 \text{ pF}$$

Then

$$C_\pi = 1.989 - 0.15 = 1.84 \text{ pF}$$

(b) $r_\pi = \dfrac{\beta V_T}{I_{CQ}} \Rightarrow I_{CQ} = \dfrac{\beta V_T}{r_\pi} = \dfrac{(150)(0.026)}{12} = 0.325 \text{ mA}$

TYU7.9

(a)

$$g_m = 2K_n(V_{GS} - V_{TN}) = 2(0.4)(3-1) \Rightarrow g_m = 1.6 \text{ mA/V}$$

$$g_m' = 80\% \text{ of } g_m = 1.28 \text{ mA/V}$$

$$g_m' = \frac{g_m}{1 + g_m r_S}$$

$$1 + g_m r_S = \frac{g_m}{g_m'}$$

$$r_S = \frac{1}{g_m}\left(\frac{g_m}{g_m'} - 1\right) = \frac{1}{1.6}\left(\frac{1.6}{1.28} - 1\right)$$

$$r_S = 0.156 \text{ k}\Omega \Rightarrow \underline{r_S = 156 \text{ ohms}}$$

(b)

$$g_m = 2K_n(V_{GS} - V_{TN}) = 2(0.4)(5-1) \Rightarrow g_m = 3.2 \text{ mA/V}$$

$$g_m' = \frac{g_m}{1 + g_m r_S} = \frac{3.2}{1 + (3.2)(0.156)} = 2.134$$

$$\frac{\Delta g_m}{g_m} = \frac{3.2 - 2.134}{3.2} \Rightarrow \text{A 33.3\% reduction}$$

TYU7.10

$$g_m = 2\sqrt{\left(\frac{0.1}{2}\right)(15)(0.1)} = 0.5477 \text{ mA/V}$$

$$f_T = \frac{g_m}{2\pi\left(C_{gs} + C_{gsp} + C_{gdp}\right)} \Rightarrow \left(C_{gs} + C_{gsp} + C_{gdp}\right) = \frac{g_m}{2\pi f_T}$$

$$= \frac{\left(0.5477\times10^{-3}\right)}{2\pi\left(1.2\times10^{9}\right)} \Rightarrow 72.64 \text{ fF}$$

Then

$$C_{gs} = 72.64 - 3 - 3 = 66.6 \text{ fF}$$

TYU7.11

$$f_T = \frac{g_m}{2\pi\left(C_{gs} + C_{gsp} + C_{gdp}\right)} \Rightarrow \left(C_{gs} + C_{gsp} + C_{gdp}\right) = \frac{g_m}{2\pi f_T}$$

$$= \frac{1.2\times10^{-3}}{2\pi\left(2.5\times10^{9}\right)} \Rightarrow 76.39 \text{ fF}$$

$$C_{gsp} + C_{gdp} = 76.39 - 60 = 16.39$$

or

$$C_{gsp} = C_{gdp} = 8.2 \text{ fF}$$

TYU7.12

dc analysis

$$V_G = \left(\frac{50}{50+150}\right)(10) - 5 = -2.5$$

$$V_S = V_G - V_{GS}. \quad I_D = \frac{V_S - (-5)}{R_S}$$

$$K_n\left(V_{GS} - V_{TN}\right)^2 = \frac{V_G - V_{GS} + 5}{R_S}$$

$$(1)(2)\left[V_{GS}^2 - 1.6V_{GS} + 0.64\right] = -2.5 - V_{GS} + 5$$

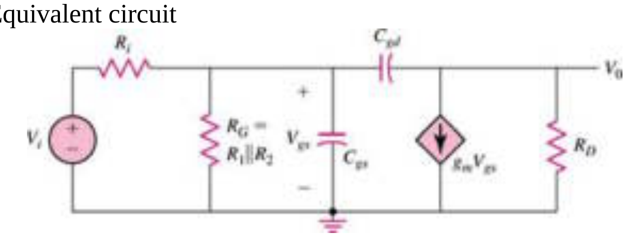
$$2V_{GS}^2 - 2.2V_{GS} - 1.22 = 0$$

$$V_{GS} = \frac{2.2 \pm \sqrt{(2.2)^2 + 4(2)(1.22)}}{2(2)} \Rightarrow V_{GS} = 1.505 \text{ V}$$

$$g_m = 2K_n\left(V_{GS} - V_{TN}\right) = 2(1)(1.505 - 0.8)$$

$$= 1.41 \text{ mA/V}$$

Equivalent circuit



(a) $C_M = C_{gd}(1 + g_m R_D) = (0.2)[1 + (1.42)(5)] \Rightarrow \underline{C_M = 1.61\text{ pF}}$

(b)

$$\tau_P = (R_i \| R_G)(C_{gs} + C_M)$$
$$= (20\|50\|150) \times 10^3 \times (2 + 1.61) \times 10^{-12} = 4.71 \times 10^{-8}\text{ s}$$

$$f_H = \frac{1}{2\pi\tau_P} = \frac{1}{2\pi(4.71\times10^{-8})} \Rightarrow f_H = 3.38\text{ MHz}$$

$$(A_v)_M = -g_m R_D \left(\frac{R_G}{R_G + R_S}\right)$$

c.

$$(A_v)_M = -(1.41)(5)\left(\frac{37.5}{37.5 + 20}\right) \Rightarrow \underline{(A_v)_M = -4.60}$$

TYU7.13 Computer Analysis

Chapter 8

Exercise Solutions

EX8.1

(a) $P_T = I_C V_{CE}$; At $V_{CEQ} = \frac{1}{2} V_{CC} = 12\ \text{V}$

$$25 = I_{CQ}(12) \Rightarrow I_{C,\max} = 2I_{CQ} = 2\left(\frac{25}{12}\right) = 4.17\ \text{A}$$

$$R_L = \frac{24}{4.167} = 5.76\,\Omega$$

$$P_{Q,\max} = 25\ \text{W}$$

(b) $25 = I_{CQ}\left(\frac{1}{2}\cdot V_{CC}\right) = I_{CQ}(6) \Rightarrow I_{CQ} = 4.17\ \text{A}, \ \Rightarrow I_{C,\max} = 5\ \text{A}$

$$R_L = \frac{12}{5} = 2.4\,\Omega$$

At $I_{CQ} = 2.5\ \text{A},\ V_{CEQ} = 6\ \text{V}$

$$P_{Q,\max} = (2.5)(6) = 15\ \text{W}$$

EX8.2

$$P_Q = (2)(8) = 16\ \text{W}$$

(a) $T_{dev} = 25 + (16)(3+1+4) = 153°\,\text{C}$

(b) $T_{case} = 25 + (16)(1+4) = 105°\,\text{C}$

(c) $T_{snk} = 25 + (16)(4) = 89°\,\text{C}$

EX8.3

$$\theta_{\text{dev-case}} = \frac{T_{J,\max} - T_{\text{amb}}}{P_{\text{D,rated}}} = \frac{200-25}{50} = 3.5°\text{C/W}$$

$$P_{D,\max} = \frac{T_{J,\max} - T_{\text{amb}}}{\theta_{\text{dev-case}} + \theta_{\text{case-snk}} + \theta_{\text{snk-amb}}}$$

$$= \frac{200-25}{3.5+0.5+2} \Rightarrow \underline{P_{D,\max} = 29.2\ \text{W}}$$

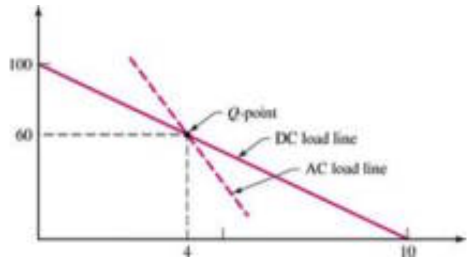
$$T_{\text{case}} = T_{\text{amb}} + P_{D,\max}\left(\theta_{\text{case-snk}} + \theta_{\text{snk-amb}}\right)$$

$$= 25 + (29.2)(0.5+2) \Rightarrow \underline{T_{\text{case}} = 98°\text{C}}$$

EX8.4

a. $I_{DQ} = \frac{10-4}{0.1} \Rightarrow \underline{I_{DQ} = 60 \text{ mA}}$

b.



$$v_{ds} = -\left(\frac{9}{10}\right)(60)(0.050) = -2.7 \text{ V} \Rightarrow v_{DS}(\min) = 4 - 2.7 = 1.3 \text{ V}$$

So maximum swing is determined by drain-to-source voltage.

$$V_{PP} = 2 \times (2.5) = 5.0 \text{ V}$$

c.

$$\overline{P_L} = \frac{1}{2} \cdot \frac{V_P^2}{R_L} = \frac{1}{2} \cdot \frac{(2.5)^2}{0.1} \Rightarrow \underline{\overline{P_L} = 31.25 \text{ mW}}$$

$$\overline{P_S} = V_{DD} \cdot I_{DQ} = (10)(60) = 600 \text{ mW}$$

$$\eta = \frac{\overline{P_L}}{\overline{P_S}} = \frac{31.25}{600} \Rightarrow \underline{\eta = 5.2\%}$$

EX8.5 Computer Analysis

EX8.6 No Exercise Problem

EX8.7

(a) For $\upsilon_O = 8$ V, $i_L = \frac{8}{25} = 0.32$ A

$$I_{DQ} = (0.2)(0.32) \Rightarrow 64 \text{ mA}$$

$$I_{DQ} = K(V_{GS} - V_{TN})^2$$

$$64 = 250(V_{GS} - 1.2)^2 \Rightarrow V_{GS} = \frac{V_{BB}}{2} = 1.706 \text{ V}$$

Then $V_{BB} = 3.412$ V

(b) $\upsilon_O = \upsilon_I + \frac{V_{BB}}{2} - \upsilon_{GSn} \Rightarrow \upsilon_I = \upsilon_O - \frac{V_{BB}}{2} + \upsilon_{GSn}$

$$\frac{d\upsilon_I}{d\upsilon_O} = 1 + \frac{d\upsilon_{GSn}}{d\upsilon_O}$$

We have

$$\frac{d\upsilon_{GSn}}{d\upsilon_O} = \frac{d\upsilon_{GSn}}{di_{dn}} \cdot \frac{di_{dn}}{d\upsilon_O}$$

$$\upsilon_{GSn} = \sqrt{\frac{i_{dn}}{K}} + V_{TN} \Rightarrow \frac{d\upsilon_{GSn}}{di_{dn}} = \frac{1}{2} \cdot \frac{1}{\sqrt{K}} \cdot \frac{1}{\sqrt{i_{dn}}}$$

(i) For $\upsilon_O \approx 0$ (very small), then

$$i_{dn} = i_L + i_{dp} \Rightarrow -\Delta i_{dp} \cong \Delta i_{dn}$$

so $\Delta i_{dn} \cong \frac{1}{2}\Delta i_L$

then $\dfrac{\Delta i_{dn}}{\Delta \upsilon_O} = \dfrac{1}{2}\cdot\dfrac{\Delta i_L}{\Delta \upsilon_O} = \dfrac{1}{2}\cdot\dfrac{1}{R_L} = \dfrac{1}{50} = 0.02$

For $\upsilon_O \approx 0$, $i_{dn} = 0.064$ A

$$\frac{d\upsilon_{GSn}}{di_{dn}} = \frac{1}{2}\cdot\frac{1}{\sqrt{0.25}}\cdot\frac{1}{\sqrt{0.064}} = 3.953$$

Then

$$\frac{d\upsilon_I}{d\upsilon_O} = 1 + (3.953)(0.02) = 1.079$$

Or

$$\frac{d\upsilon_O}{d\upsilon_I} = 0.927$$

(ii) For $\upsilon_O \cong 8$ V, $i_{dn} = i_L$

$$\frac{di_{dn}}{d\upsilon_O} = \frac{di_L}{d\upsilon_O} = \frac{1}{R_L} = 0.04$$

then

$$\frac{d\upsilon_{GSn}}{di_{dn}} = \frac{1}{2}\cdot\frac{1}{\sqrt{0.25}}\cdot\frac{1}{\sqrt{0.32}} = 1.768$$

$$\frac{d\upsilon_I}{d\upsilon_O} = 1 + (1.768)(0.04) = 1.0707$$

Or

$$\frac{d\upsilon_O}{d\upsilon_I} = 0.934$$

EX8.8

a.

$R_b = r_\pi + (1+\beta)R'_E$ and $R'_E = a^2 R_L = (10)^2(8) = 800\ \Omega$

$R_i = 1.5\ \text{k}\Omega = R_{TH} \| R_b$

$$I_Q = \frac{V_{CC}}{a^2 R_L} = \frac{18}{(10)^2(8)} = 22.5\ \text{mA}$$

$$r_\pi = \frac{(100)(0.026)}{22.5} = 0.116\ \text{k}\Omega$$

$R_b = 0.116 + (101)(0.8) = 80.9\ \text{k}\Omega$

$$1.5 = R_{TH}\|80.9 = \frac{R_{TH}(80.9)}{R_{TH}+(80.9)} \Rightarrow (80.9-1.5)R_{TH} = (1.5)(80.9) \Rightarrow R_{TH} = 1.53\ \text{k}\Omega$$

$$V_{TH} = \left(\frac{R_2}{R_1+R_2}\right)V_{CC} = \frac{1}{R_1}\cdot R_{TH}\cdot V_{CC}$$

$$I_{BQ} = \frac{I_Q}{\beta} = \frac{22.5}{100} = 0.225 \text{ mA}$$

$$I_{BQ} = \frac{V_{TH} - 0.7}{R_{TH}} \Rightarrow \frac{1}{R_1}(1.53)(18) = (0.225)(1.53) + 0.7 \Rightarrow \underline{R_1 = 26.4 \text{ k}\Omega}$$

$$\frac{26.4R_2}{26.4 + R_2} = 1.53$$

$$(26.4 - 1.53)R_2 = (1.53)(26.4) \Rightarrow \underline{R_2 = 1.62 \text{ k}\Omega}$$

b.

$$v_E = 0.9V_{CC} = (0.9)(18) = 16.2 \text{ V}$$

$$i_E = 0.9I_{CQ} = (0.9)(22.5) = 20.25 \text{ mA}$$

$$v_0 = \frac{v_E}{a} = \frac{16.2}{10} \Rightarrow \underline{V_P = 1.62 \text{ V}}$$

$$i_0 = ai_E = (10)(20.25) \Rightarrow \underline{I_P = 203 \text{ mA}}$$

$$\overline{P_L} = \frac{1}{2}(1.62)(0.203) \Rightarrow \underline{\overline{P_L} = 0.164 \text{ W}}$$

EX8.9

(a) For $I_Q = 1$ mA, $\upsilon_{BE} = (0.026)\ln\left(\frac{10^{-3}}{2\times 10^{-14}}\right) = 0.6405$ V

Then $V_{BB} = 1.281$ V

For D_1, D_2; $I_{Bias} = (1.2\times 10^{-14})\exp\left(\frac{0.6405}{0.026}\right) = 0.60$ mA

(b) $\upsilon_O = 1.2$ V, $i_L = \frac{1.2}{1} = 1.2$ mA

1st approximation:

$i_{Cn} = 1.6$ mA, $i_{Bn} = 0.016$ mA

$$\upsilon_{BEn} = (0.026)\ln\left(\frac{1.6\times 10^{-3}}{2\times 10^{-14}}\right) = 0.65274 \text{ V}$$

$$I_D = 0.60 - 0.016 = 0.584 \text{ mA}$$

$$V_{BB} = 2(0.026)\ln\left(\frac{0.584\times 10^{-3}}{1.2\times 10^{-14}}\right) = 1.27963 \text{ V}$$

then $\upsilon_{EBp} = 1.27963 - 0.65274 = 0.62689$ V

$$i_{Cp} = (2\times 10^{-14})\exp\left(\frac{0.62689}{0.026}\right) = 0.59206 \text{ mA}$$

2nd approximation:

$i_{En} = 1.2 + 0.59206 = 1.792$ mA; $i_{Cn} = 1.7743$ mA

After 4 iterations:

$i_{Cn} = 1.73$ mA; $i_{Cp} = 0.547$ mA

$\upsilon_{BEn} = 0.6547$ V; $\upsilon_{EBp} = 0.6248$ V

$I_D = 0.5827$ mA

(c) $\upsilon_O = 3$ V; $i_L = \frac{3}{1} = 3$ mA

1st approximation;

$i_{Cn} = 3.3$ mA, $i_{Bn} = 0.033$ mA

$$\upsilon_{BEn} = (0.026)\ln\left(\frac{3.3\times10^{-3}}{2\times10^{-14}}\right) = 0.67156 \text{ V}$$

$$I_D = 0.6 - 0.033 = 0.567 \text{ mA}$$

$$V_{BB} = 2(0.026)\ln\left(\frac{0.567\times10^{-3}}{1.2\times10^{-14}}\right) = 1.2781 \text{ V}$$

$$\upsilon_{EBp} = 1.2781 - 0.67156 = 0.6065 \text{ V}$$

$$i_{Cp} = \left(2\times10^{-14}\right)\exp\left(\frac{0.6065}{0.026}\right) = 0.2706 \text{ mA}$$

Then $i_{En} = 3 + 0.2706 = 3.2706$ mA; $i_{Cn} = 3.2382$ mA

After 4 iterations:

$$i_{Cn} = 3.24 \text{ mA};\ i_{Cp} = 0.276 \text{ mA}$$

$$\upsilon_{BEn} = 0.671 \text{ V},\ \upsilon_{EBp} = 0.607 \text{ V}$$

$$I_D = 0.5676 \text{ mA}$$

EX8.10 No Exercise EX8.10

EX8.11

a.

$$v_I = 0 = v_0,\ v_{B3} = 0.7 \text{ V}$$

$$I_{R1} = \frac{12-0.7}{R_1} = \frac{11.3}{0.25} \Rightarrow I_{R1} = 45.2 \text{ mA}$$

If transistors are matched, then

$$i_{E1} = i_{E3}$$

$$i_{R1} = i_{E1} + i_{B3} = i_{E1} + \frac{i_{E3}}{1+\beta}$$

$$i_{R1} = i_{E1}\left(1 + \frac{1}{1+\beta}\right) = i_{E1}\left(1 + \frac{1}{41}\right)$$

$$i_{E1} = \frac{45.2}{1.024} \Rightarrow \underline{i_{E1} = i_{E2} = 44.1 \text{ mA}}$$

$$i_{B1} = i_{B2} = \frac{i_{E1}}{1+\beta} = \frac{44.1}{41} \Rightarrow \underline{i_{B1} = i_{B2} = 1.08 \text{ mA}}$$

b.

For $v_I = 5 \text{ V} \Rightarrow v_0 = 5 \text{ V}$

$$i_0 = \frac{5}{8} \Rightarrow \underline{i_0 = 0.625 \text{ A}}$$

$$i_{E3} \cong 0.625 \text{ A},\ i_{B3} = \frac{0.625}{41} \Rightarrow i_{B3} = 15.2 \text{ mA}$$

$$v_{B3} = 5.7 \text{ V} \Rightarrow i_{R1} = \frac{12-5.7}{0.25} = 25.2 \text{ mA}$$

$$i_{E1} = 25.2 - 15.2 \Rightarrow \underline{i_{E1} = 10.0 \text{ mA}} \Rightarrow \underline{i_{B1} = \frac{10}{41} = 0.244 \text{ mA}}$$

$$v_{B4} = 5 - 0.7 = 4.3 \text{ V}$$

$$I_{R2} = \frac{4.3-(-12)}{0.25} = \underline{65.2 \text{ mA} \cong i_{E2}}$$

$$\underline{i_{B2} = \frac{65.2}{41} = 1.59 \text{ mA}}$$

$$i_I = i_{B2} - i_{B1} = 1.59 - 0.244 \Rightarrow \underline{i_I = 1.35 \text{ mA}}$$

$$A_I = \frac{i_0}{i_I} = \frac{625}{1.35} \Rightarrow \underline{A_I = 463}$$

c.

From Equation (8.55)

$$A_I = \frac{(1+\beta)R}{2R_L} = \frac{(41)(250)}{2(8)} = \underline{641}$$

Test Your Understanding Solutions

TYU8.1

For $V_{DS} = 0,\ I_D(\max) = \frac{24}{20} = \underline{1.2 \text{ A} = \text{I}_\text{D}(\max)}$

For $I_D = 0 \Rightarrow \underline{V_{DS}(\max) = 24 \text{ V}}$

Maximum power when

$$V_{DS} = \frac{V_{DS}(\max)}{2} = 12 \text{ V and}$$

$$I_D = \frac{I_D(\max)}{2} = 0.6 \text{ A} \Rightarrow \underline{P_D(\max) = (12)(0.6) = 7.2 \text{ Watts}}$$

TYU8.2

(a) $R_E = \frac{V_{CC}-(-V_{CC})}{I_{C,\max}} = \frac{12-(-12)}{0.25} = 96\,\Omega$

(b) For $I_{CQ} = 0.125$ A, $V_{CEQ} = 12$ V

$P_{Q,\max} = (0.125)(12) = 1.5$ W

TYU8.3

(a) $\Delta T = P \cdot \theta = (6)(1.8) = 10.8°\text{ C}$

(b) $P = \frac{\Delta T}{\theta} = \frac{100}{2.5} = 40$ W

TYU8.4

(a) $V_{CEQ} = 6 = V_{CC} - I_{CQ}R_L = 12 - I_{CQ}(1) \Rightarrow I_{CQ} = 6 \text{ mA}$

$P_Q = I_{CQ}V_{CEQ} = (6)(6) = 36 \text{ mW}$

(b) (i) $\overline{P_L} = \dfrac{1}{2} \cdot \dfrac{V_P^2}{R_L} = \dfrac{1}{2}\dfrac{(4.5)^2}{1} = 10.1 \text{ mW}$

(ii) $\eta = \dfrac{10.1}{I_{CQ}V_{CC}} \times 100\% = \dfrac{10.1}{(6)(12)} \times 100\% = 14.1\%$

(iii) $\overline{P_Q} = 36 - 10.1 = 25.9 \text{ mW}$

TYU8.5

a. $\overline{P_L} = \dfrac{1}{2} \cdot \dfrac{V_P^2}{R_L} \Rightarrow V_P = \sqrt{2R_L\overline{P_L}} = \sqrt{2(8)(25)} \Rightarrow V_P = 20 \text{ V} \Rightarrow V_{CC} = \dfrac{20}{0.8} \Rightarrow \underline{V_{CC} = 25 \text{ V}}$

b. $I_P = \dfrac{V_P}{R_L} = \dfrac{20}{8} \Rightarrow \underline{I_P = 2.5 \text{ A}}$

$\overline{P_Q} = \dfrac{V_{CC}V_P}{\pi R_L} - \dfrac{V_P^2}{4R_L}$

c. $\overline{P_Q} = \dfrac{(25)(20)}{\pi(8)} - \dfrac{(20)^2}{4(8)} = 19.9 - 12.5 \Rightarrow \underline{\overline{P_Q} = 7.4 \text{ W}}$

d. $\eta = \dfrac{\pi V_P}{4V_{CC}} = \dfrac{\pi}{4} \cdot \dfrac{20}{25} \Rightarrow \underline{\eta = 62.8\%}$

TYU8.6

a. $\overline{P_L} = \dfrac{1}{2} \cdot \dfrac{V_P^2}{R_L} = \dfrac{(4)^2}{2(0.1)} \Rightarrow \underline{\overline{P_L} = 80 \text{ mW}}$

b. $I_P = \dfrac{V_P}{R_L} = \dfrac{4}{0.1} \Rightarrow \underline{I_P = 40 \text{ mA}}$

$\overline{P_Q} = \dfrac{V_{CC}V_P}{\pi R_L} - \dfrac{V_P^2}{4R_L}$

c. $\overline{P_Q} = \dfrac{(5)(4)}{\pi(0.1)} - \dfrac{(4)^2}{4(0.1)} = 63.7 - 40 \Rightarrow \underline{\overline{P_Q} = 23.7 \text{ mW}}$

d. $\eta = \dfrac{\pi V_P}{4V_{CC}} = \dfrac{\pi}{4} \cdot \dfrac{4}{5} \Rightarrow \underline{\eta = 62.8\%}$

TYU8.7

a.

$$I_{CQ} \cong \frac{1}{2}\cdot\left(\frac{2V_{CC}}{R_L}\right) = \frac{V_{CC}}{R_L} = \frac{12}{1.5} = 8 \text{ mA}$$

$$R_{TH} = R_1 \| R_2$$

$$V_{TH} = \left(\frac{R_2}{R_1+R_2}\right)V_{CC} = \frac{1}{R_1}\cdot R_{TH}\cdot V_{CC}$$

$$I_{BQ} = \frac{I_{CQ}}{\beta} = \frac{8}{75} = 0.107 \text{ mA} = \frac{V_{TH}-V_{BE}}{R_{TH}+(1+\beta)R_E}$$

$$\text{Let } R_{TH} = (1+\beta)R_E = (76)(0.1) = 7.6 \text{ k}\Omega$$

$$0.107 = \frac{\frac{1}{R_1}\cdot(7.6)(12)-0.7}{7.6+7.6}$$

$$\frac{1}{R_1}\cdot(91.2) = 2.33 \Rightarrow \underline{R_1 = 39.1 \text{ k}\Omega}$$

$$\frac{39.1R_2}{39.1+R_2} = 7.6 \Rightarrow (39.1-7.6)R_2 = (7.6)(39.1) \Rightarrow \underline{R_2 = 9.43 \text{ k}\Omega}$$

b.

$$\overline{P_L} = \frac{1}{2}\cdot(0.9I_{CQ})^2 R_L = \frac{1}{2}[(0.9)(8)]^2(1.5) \Rightarrow \underline{\overline{P_L} = 38.9 \text{ mW}}$$

$$\overline{P_S} = V_{CC}I_{CQ} = (12)(8) = 96 \text{ mW}$$

$$\overline{P_Q} = \overline{P_S} - \overline{P_L} = 96 - 38.9 \Rightarrow \underline{\overline{P_Q} = 57.1 \text{ mW}}$$

$$\eta = \frac{\overline{P_L}}{\overline{P_S}} = \frac{38.9}{96} \Rightarrow \underline{\eta = 40.5\%}$$

TYU8.8

(a) $$\upsilon_{BEn} = (0.026)\ln\left(\frac{10^{-3}}{5\times10^{-16}}\right) = 0.73643 \text{ V}$$

$$\upsilon_{EBp} = (0.026)\ln\left(\frac{10^{-3}}{8\times10^{-16}}\right) = 0.72421 \text{ V}$$

$$V_{BB} = \upsilon_{BEn} + \upsilon_{EBp} = 1.4606 \text{ V}$$

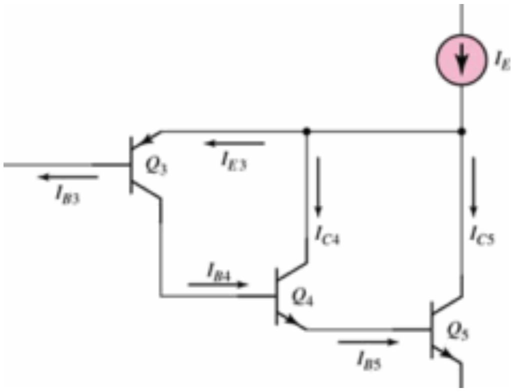
(b) See above

(c) $$\upsilon_I = \upsilon_{BEn} - \frac{V_{BB}}{2} = 0.73643 - \frac{1.4606}{2}$$

or

$$\upsilon_I = 6.1 \text{ mV}$$

TYU8.9



$$
\begin{aligned}
I_E &= I_{E3} + I_{C4} + I_{C5} \\
&= I_{E3} + I_{C4} + \beta_5 I_{B5} \\
&= I_{E3} + \beta_4 I_{B4} + \beta_5 (1+\beta_4) I_{B4} \\
I_E &= (1+\beta_3) I_{B3} + \beta_4 \beta_3 I_{B3} + \beta_5 (1+\beta_4) \beta_3 I_{B3}
\end{aligned}
$$

If β_4 and β_5 are large, then $I_E \cong \beta_3 \beta_4 \beta_5 I_{B3}$

So that composite current gain is $\underline{\beta \cong \beta_3 \beta_4 \beta_5}$

Chapter 9

Exercise Solutions

EX9.1

(a) $i_1 = \dfrac{\upsilon_I}{R_1} = \dfrac{25\times10^{-3}}{R_1} = 10\times10^{-6} \Rightarrow R_1 = 2.5\ \text{k}\Omega$

$A_\upsilon = -\dfrac{R_2}{R_1} \Rightarrow -25 = \dfrac{-R_2}{2.5} \Rightarrow R_2 = 62.5\ \text{k}\Omega$

(b) $|\upsilon_O| = |A_\upsilon|\cdot\upsilon_I = (25)(25\times10^{-3}) = 0.625\ \text{V}$

$-0.625 \le \upsilon_O \le 0.625\ \text{V}$

EX9.2

$$A_\upsilon = -\frac{R_2}{R_1}\left(1+\frac{R_3}{R_4}+\frac{R_3}{R_2}\right)$$

$A_\upsilon = -75$, Let $R_1 = 20\ \text{k}\Omega$

$$A_\upsilon = -75 = -\frac{R_2}{R_1}\left(1+\frac{R_3}{R_4}\right)-\frac{R_3}{R_1}$$

Let $\dfrac{R_2}{R_1} = \dfrac{R_3}{R_1} = 8$

Then $R_2 = R_3 = 160\ \text{k}\Omega$

$$75 = 8\left(1+\frac{R_3}{R_4}\right)+8$$

or $\dfrac{R_3}{R_4} = 7.375$

So $R_4 = \dfrac{160}{7.375} = 21.7\ \text{k}\Omega$

EX9.3

(a) $$A_\upsilon = -\frac{R_2}{R_1}\cdot\frac{1}{\left[1+\dfrac{1}{A_{od}}\left(1+\dfrac{R_2}{R_1}\right)\right]}$$

$R_1 = 25\ \text{k}\Omega$, $A_\upsilon = -15.0$, $A_{od} = 10^4$

Then

$$-15.0 = -\frac{R_2}{R_1}\cdot\frac{1}{\left[1+\dfrac{1}{10^4}\left(1+\dfrac{R_2}{R_1}\right)\right]}$$

which yields $\dfrac{R_2}{R_1} = 15.024 \Rightarrow R_2 = 375.6\ \text{k}\Omega$

(b) (i) $A_{od} = 10^5$

Then $A_\upsilon = -(15.024)\cdot\dfrac{1}{\left[1+\dfrac{1}{10^5}(16.024)\right]} = -15.0216$

(ii) $A_{od} = 10^3$

$$A_\upsilon = -(15.024)\cdot\frac{1}{\left[1+\dfrac{1}{10^3}(16.024)\right]} = -14.787$$

EX9.4

(a) $\upsilon_O = -3(\upsilon_{I1} + 2\upsilon_{I2} + 0.3\upsilon_{I3} + 4\upsilon_{I4})$

$\upsilon_O = -3\upsilon_{I1} - 6\upsilon_{I2} - 0.9\upsilon_{I3} - 12\upsilon_{I4}$

Then $\dfrac{R_F}{R_1} = 3$, $\dfrac{R_F}{R_2} = 6$, $\dfrac{R_F}{R_3} = 0.9$, $\dfrac{R_F}{R_4} = 12$

R_3 will be the maximum resistance.

Let $R_3 = 400\,\text{k}\Omega \Rightarrow R_F = 360\ \text{k}\Omega$, $R_1 = 120\ \text{k}\Omega$, $R_2 = 60\ \text{k}\Omega$, $R_4 = 30\ \text{k}\Omega$

(b) (i) $\upsilon_O = -3(0.1) - 6(-0.2) - 0.9(-1) - 12(0.05) = +1.2\ \text{V}$

(ii) $\upsilon_O = -3(-0.2) - 6(0.3) - 0.9(1.5) - 12(-0.1) = -1.35\ \text{V}$

EX9.5

We may note that $\dfrac{R_3}{R_2} = \dfrac{3}{1.5} = 2$ and $\dfrac{R_F}{R_1} = \dfrac{20}{10} = 2$ so that $\dfrac{R_3}{R_2} = \dfrac{R_F}{R_1}$

Then

$$i_L = \frac{-v_I}{R_2} = \frac{-(-3)}{1.5\ \text{k}\Omega} \Rightarrow \underline{i_L = 2\ \text{mA}}$$

$$v_L = i_L Z_L = (2\times10^{-3})(200) = 0.4\ \text{V}$$

$$i_4 = \frac{v_L}{R_2} = \frac{0.4}{1.5\ \text{k}\Omega} = 0.267\ \text{mA}$$

$$i_3 = i_4 + i_L = 0.267 + 2 = 2.267\ \text{mA}$$

$$v_0 = i_3 R_3 + v_L = (2.267\times10^{-3})(3\times10^3) - 0.4 \Rightarrow v_0 = 7.2\ \text{V}$$

EX9.6

(a) $A_d = \dfrac{R_2}{R_1} = 50$

For $\upsilon_{I2} = 50\ \text{mV}$ and $\upsilon_{I1} = -50\ \text{mV}$

$\upsilon_O = 50(0.05 - (-0.05)) = 5\ \text{V}$

$|i_{R2}| \cong \dfrac{5-0.05}{R_2} = 50\,\mu\text{A}$

Set $R_2 = R_4 = 100\ \text{k}\Omega$

$R_1 = R_3 = 2\ \text{k}\Omega$

(b) $i_{R3} = \dfrac{0.05}{R_3 + R_4} = \dfrac{0.05}{100+2} \Rightarrow 0.49\,\mu\text{A}$

EX9.7

We have the general relation that

$$v_0 = \left(1+\frac{R_2}{R_1}\right)\left(\frac{[R_4/R_3]}{1+[R_4/R_3]}\right)v_{I2} - \frac{R_2}{R_1}v_{I1}$$

$R_1 = R_3 = 10\ \text{k}\Omega,\ R_2 = 20\ \text{k}\Omega,\ R_4 = 21\ \text{k}\Omega$

$$v_0 = \left(1+\frac{20}{10}\right)\left(\frac{[21/10]}{1+[21/10]}\right)v_{I2} - \left(\frac{20}{10}\right)v_{I1}$$

$v_0 = 2.0323 v_{I2} - 2.0 v_I$

a. $v_{I1} = 1,\ v_{I2} = -1$

$v_0 = -2.0323 - 2.0 \Rightarrow \underline{v_0 = -4.032\ \text{V}}$

b. $v_{I1} = v_{I2} = 1\ \text{V}$

$v_0 = 2.0323 - 2.0 \Rightarrow \underline{v_0 = 0.0323\ \text{V}}$

c. $v_{cm} = v_{I1} = v_{I2}$ so common-mode gain

$$\underline{A_{cm} = \frac{v_0}{v_{cm}} = 0.0323}$$

d.

$$CMRR_{dB} = 20\log_{10}\left(\frac{A_d}{A_{cm}}\right)$$

$$A_d = \frac{2.0323}{2} - (2.0)\left(-\frac{1}{2}\right) = 2.016$$

$$CMRR_{dB} = 20\log_{10}\left(\frac{2.016}{0.0323}\right) = 35.9\ \text{dB}$$

EX9.8

(a) $A_d = \dfrac{R_4}{R_3}\left(1+\dfrac{2R_2}{R_1}\right)$

$$A_d(\text{max}) = \frac{90}{30}\left(1+\frac{2(50)}{2}\right) = 153$$

$$A_d(\text{min}) = \frac{90}{30}\left(1+\frac{2(50)}{2+100}\right) = 5.94$$

$$5.94 \le A_d \le 153$$

(b) $i_1 = \dfrac{\upsilon_{I1}-\upsilon_{I2}}{R_1} = \dfrac{0.025-(-0.025)}{2} \Rightarrow i_1 = 25\,\mu\text{A}$

EX9.9

(a) $R_1C_2 = (10^4)(0.1\times10^{-6}) \Rightarrow 1\ \text{ms}$

(i) $0 < t < 1$

$$\upsilon_O = 0 - \frac{1}{1}\cdot t'\Big|_0^1 = -1\ \text{V}$$

(ii) $1 < t < 2$

$$\upsilon_O = -1 - \frac{(-1)}{1}\cdot t'\Big|_1^2 = -1 + 1(2-1) = 0$$

(iii) $2 < t < 3$

$$\upsilon_O = 0 - \frac{1}{1} \cdot t' \Big|_2^3 = -1 \text{ V}$$

(iv) $3 < t < 4$

$$\upsilon_O = -1 - \frac{(-1)}{1} \cdot t' \Big|_3^4 = 0$$

(b) $R_1 C_2 = (10^4)(10^{-6}) \Rightarrow 10 \text{ ms}$

(i) $0 < t < 1$

$$\upsilon_O = 0 - \frac{(1)}{10} \cdot t' \Big|_0^1 = -0.1 \text{ V}$$

(ii) $1 < t < 2$

$$\upsilon_O = -0.1 - \frac{(-1)}{10} \cdot t' \Big|_1^2 = 0$$

(iii) $2 < t < 3$

$$\upsilon_O = 0 - \frac{(1)}{10} \cdot t' \Big|_2^3 = -0.1 \text{ V}$$

(iv) $3 < t < 4$

$$\upsilon_O = -0.1 - \frac{(-1)}{10} \cdot t' \Big|_3^4 = 0$$

EX9.10

(a) $R_N = R_1 \| R_2 = 40 \| 20 = 13.33 \text{ k}\Omega$

$$R_P = R_A \| R_B \| R_C = 50 \| 50 \| 100 = 20 \text{ k}\Omega$$

$$\upsilon_O = -\frac{R_F}{R_1}\upsilon_{I1} - \frac{R_F}{R_2}\upsilon_{I2} + \left(1 + \frac{R_F}{R_N}\right)\left[\frac{R_P}{R_A}\upsilon_{I3} + \frac{R_P}{R_B}\upsilon_{I4}\right]$$

$$\upsilon_O = -\frac{80}{40}\upsilon_{I1} - \frac{80}{20}\upsilon_{I2} + \left(1 + \frac{80}{13.33}\right)\left[\frac{20}{50}\upsilon_{I3} + \frac{20}{50}\upsilon_{I4}\right]$$

$$\upsilon_O = -2\upsilon_{I1} - 4\upsilon_{I2} + 2.8\upsilon_{I3} + 2.8\upsilon_{I4}$$

(b) (i) $\upsilon_O = -2(0.1) - 4(0.15) + 2.8(0.2) + 2.8(0.3) = 0.6 \text{ V}$

(ii) $\upsilon_O = -2(-0.2) - 4(0.25) + 2.8(-0.1) + 2.8(0.2) = -0.32 \text{ V}$

EX9.11 Computer Analysis

Test Your Understanding Solutions

TYU9.1

(a) $A_\upsilon = -\dfrac{R_2}{R_1} \Rightarrow -12 = -\dfrac{240}{R_1} \Rightarrow R_1 = 20 \text{ k}\Omega$

(b) (i) $i_1 = \dfrac{\upsilon_I}{R_1} = \dfrac{-0.15}{20} \Rightarrow i_1 = -7.5\,\mu\text{ A}$

(ii) $i_1 = \dfrac{0.25}{20} \Rightarrow i_1 = 12.5\,\mu\text{ A}$

TYU9.2

(a)

$$A_v = \frac{-R_2}{R_1 + R_S}$$

$$A_v(\min) = \frac{-100}{19+1.3} = -4.926$$

$$A_v(\max) = \frac{-100}{19+0.7} = -5.076$$

so $\underline{4.926 \le |A_v| \le 5.076}$

(b)

$$i_1(\max) = \frac{0.1}{19+0.7} = 5.076\ \mu A$$

$$i_1(\min) = \frac{0.1}{19+1.3} = 4.926\ \mu A$$

so $\underline{4.926 \le i_1 \le 5.076\ \mu A}$

(c) Maximum current specification is violated.

TYU9.3

$$A_\upsilon = -\frac{R_2}{R_1} \cdot \frac{1}{\left[1 + \dfrac{1}{A_{od}}\left(1 + \dfrac{R_2}{R_1}\right)\right]} = -\frac{200}{20} \cdot \frac{1}{\left[1 + \dfrac{1}{10^4}\left(1 + \dfrac{200}{20}\right)\right]}$$

or

$$A_\upsilon = -9.989$$

(a) $\upsilon_O = (-9.989)(50) \Rightarrow \upsilon_O = -0.49945\text{ V}$

$$\upsilon_1 = -\frac{\upsilon_O}{A_{od}} = -\frac{(-0.49945)}{10^4} \Rightarrow \upsilon_1 = 49.945\,\mu\text{ V}$$

(b) $\upsilon_I = \dfrac{\upsilon_O}{A_\upsilon} = \dfrac{+5}{-9.989} = -0.50055\text{ V}$

$$\upsilon_1 = -\frac{\upsilon_O}{A_{od}} = -\frac{+5}{10^4} \Rightarrow \upsilon_1 = -0.5\text{ mV}$$

(c) $\upsilon_O = -A_{od}\upsilon_1 = -(10^4)(0.2) \Rightarrow \upsilon_O = -2\text{ V}$

$$\upsilon_I = \frac{\upsilon_O}{A_\upsilon} = \frac{-2}{-9.989} = 0.20022\text{ V}$$

TYU9.4

$$\upsilon_O = -\frac{R_F}{R_1}\upsilon_{I1} - \frac{R_F}{R_2}\upsilon_{I2} - \frac{R_F}{R_3}\upsilon_{I3}$$

$$= -\frac{200}{20}\upsilon_{I1} - \frac{200}{40}\upsilon_{I2} - \frac{200}{50}\upsilon_{I3}$$

$$= -10\upsilon_{I1} - 5\upsilon_{I2} - 4\upsilon_{I3}$$

(a) $\upsilon_O = -10(-0.25) - 5(0.30) - 4(-0.50) \Rightarrow \upsilon_O = 3 \text{ mV}$

(b) $\upsilon_O = -10(10) - 5(-40) - 4(25) = 0$

TYU9.5

$$|v_O| = \frac{v_{I1} + v_{I2} + v_{I3}}{3} = \frac{R_F}{R}(v_{I1} + v_{I2} + v_{I3})$$

$$\frac{R_F}{R} = \frac{1}{3} \Rightarrow R_1 = R_2 = R_3 \equiv R = 1\ M\Omega$$

Then $R_F = \frac{1}{3}\ M\Omega = 333\ k\Omega$

TYU9.6

(a) $A_\upsilon = 10 = \left(1 + \frac{R_2}{R_1}\right) \Rightarrow \frac{R_2}{R_1} = 9$

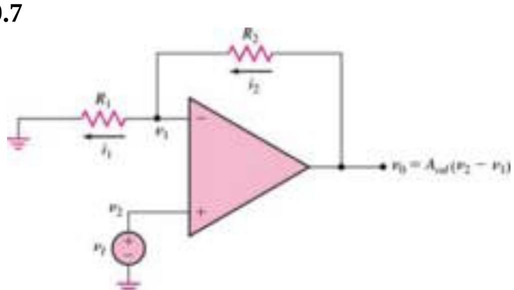
Set $R_2 = 180 \text{ k}\Omega$, $R_1 = 20 \text{ k}\Omega$

(b) $A_\upsilon = 5 = \left(1 + \frac{R_2}{R_1}\right) \Rightarrow \frac{R_2}{R_1} = 4$

For $\upsilon_O = 5\text{ V}$, $\upsilon_1 = 1 \text{ V}$

$|i_{R2}| = 100\,\mu\text{A} = \frac{5-1}{R_2} \Rightarrow R_2 = 40 \text{ k}\Omega$, then $R_1 = 10 \text{ k}\Omega$

TYU9.7



$$v_0 = A_{od}(v_2 - v_1) = A_{od}(v_I - v_1)$$

$$\frac{v_0}{A_{od}} - v_I = -v_1 \text{ or } v_1 = v_I - \frac{v_0}{A_{od}}$$

$$i_1 = \frac{v_1}{R_1} = i_2 \text{ and } i_2 = \frac{v_0 - v_1}{R_2}$$

Then $v_1\left(\frac{1}{R_1}\right)=\frac{v_0-v_1}{R_2}$

$v_1\left(\frac{1}{R_1}+\frac{1}{R_2}\right)=\frac{v_0}{R_2}$

$v_0\left(1+\frac{R_2}{R_1}\right)v_1=\left(1+\frac{R_2}{R_1}\right)\left(v_I-\frac{v_0}{A_{od}}\right)$

So $A_v=\frac{v_0}{v_I}=\frac{\left(1+\frac{R_2}{R_1}\right)}{1+\frac{1}{A_{od}}\left(1+\frac{R_2}{R_1}\right)}$

TYU9.8

For $v_{I2}=0,\ v_2=\left(\frac{R_b}{R_b+R_a}\right)v_{I1}$ and

$$v_0\left(v_{I1}\right)=\left(1+\frac{R_2}{R_1}\right)\left(\frac{R_b}{R_b+R_a}\right)v_{I1}$$
$$=\left(1+\frac{70}{5}\right)\left(\frac{50}{50+25}\right)v_{I1}$$
$$=10v_{I1}$$

For $v_{I1}=0,\ v_2=\left(\frac{R_a}{R_b+R_a}\right)v_{I2}$

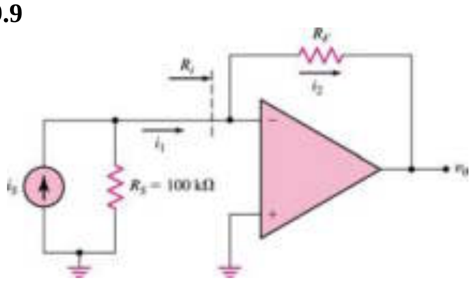
$$v_0\left(v_{I2}\right)=\left(1+\frac{R_2}{R_1}\right)\left(\frac{R_a}{R_b+R_a}\right)v_{I2}$$
$$=\left(1+\frac{70}{5}\right)\left(\frac{25}{25+50}\right)v_{I2}$$
$$=5v_{I2}$$

Then

$v_0=v_0\left(v_{I1}\right)+v_0\left(v_{I2}\right)$

$\underline{v_0=10v_{I1}+5v_{I2}}$

TYU9.9



$R_S >> R_i$ so $i_1=i_2=i_S=100\ \mu\text{A}$

$v_0=-i_SR_F$

We want $-10=-\left(100\times10^{-6}\right)R_F\Rightarrow\underline{R_F=100\ \text{k}\Omega}$

TYU9.10

We want $i_L = 1 \text{ mA}$ when $v_I = -5 \text{ V}$

$$i_L = \frac{-V_I}{R_2} \Rightarrow R_2 = \frac{-v_I}{i_2} = \frac{-(-5)}{10^{-3}} \Rightarrow \underline{R_2 = 5 \text{ k}\Omega}$$

$$v_L = i_L Z_L = \left(10^{-3}\right)(500) \Rightarrow v_L = 0.5 \text{ V}$$

$$i_4 = \frac{v_L}{R_2} = \frac{0.5}{5 \text{ k}\Omega} \Rightarrow i_4 = 0.1 \text{ mA}$$

$$i_3 = i_4 + i_L = 0.1 + 1 = 1.1 \text{ mA}$$

If op-amp is biased at $\pm 10 \text{ V}$, output must be limited to $\approx 8 \text{ V}$.

So $v_0 = i_3 R_3 + v_L$

$$8 = \left(1.1 \times 10^{-3}\right) R_3 + 0.5 \Rightarrow R_3 = 6.82 \text{ k}\Omega$$

Let $\underline{R_3 = 7.0 \text{ k}\Omega}$

Then we want $\dfrac{R_3}{R_2} = \dfrac{R_F}{R_1} = \dfrac{7}{5} = 1.4$

Can choose $\underline{R_1 = 10 \text{ k}\Omega}$ and $\underline{R_F = 14 \text{ k}\Omega}$

TYU9.11

(a) $\upsilon_{O1} = \upsilon_{I1} + i_1 R'_2 = \upsilon_{I1} + \left(\dfrac{\upsilon_{I1} - \upsilon_{I2}}{R_1}\right) R'_2$

$$\upsilon_{O1} = \left(1 + \frac{R'_2}{R_1}\right)\upsilon_{I1} - \frac{R'_2}{R_1}\upsilon_{I2}$$

$$\upsilon_{O2} = \left(1 + \frac{R_2}{R_1}\right)\upsilon_{I2} - \frac{R_2}{R_1}\upsilon_{I1}$$

Now

$$\upsilon_O = \frac{R_4}{R_3}\left(\upsilon_{O2} - \upsilon_{O1}\right)$$

We can write $\upsilon_{I1} = \upsilon_{cm} - \dfrac{\upsilon_d}{2}$ and $\upsilon_{I2} = \upsilon_{cm} + \dfrac{\upsilon_d}{2}$

Then

$$\upsilon_{O1} = \left(1 + \frac{R'_2}{R_1}\right)\left(\upsilon_{cm} - \frac{\upsilon_d}{2}\right) - \frac{R'_2}{R_1}\left(\upsilon_{cm} + \frac{\upsilon_d}{2}\right) = \upsilon_{cm} - \left(1 + \frac{2R'_2}{R_1}\right)\left(\frac{\upsilon_d}{2}\right)$$

$$\upsilon_{O2} = \left(1 + \frac{R_2}{R_1}\right)\left(\upsilon_{cm} + \frac{\upsilon_d}{2}\right) - \frac{R_2}{R_1}\left(\upsilon_{cm} - \frac{\upsilon_d}{2}\right) = \upsilon_{cm} + \left(1 + \frac{2R_2}{R_1}\right)\left(\frac{\upsilon_d}{2}\right)$$

Then

$$\upsilon_O = \frac{R_4}{R_3}\left[\left(1 + \frac{2R_2}{R_1}\right)\left(\frac{\upsilon_d}{2}\right) + \upsilon_{cm} + \left(1 + \frac{2R'_2}{R_1}\right)\left(\frac{\upsilon_d}{2}\right) - \upsilon_{cm}\right]$$

or

$$\upsilon_O = \frac{R_4}{R_3}\left[1 + \frac{R_2 + R'_2}{R_1}\right] \cdot \upsilon_d$$

So

$$A_{cm} = 0$$

(b) For $A_d(\max)$, let $R_1 = 2\ \text{k}\Omega$, $R'_2 = 50\ \text{k}\Omega\ +5\% = 52.5\ \text{k}\Omega$

Then $A_d(\max) = \frac{90}{30}\left[1 + \frac{50+52.5}{2}\right] = 156.75$

For $A_d(\min)$, let $R_1 = 102\ \text{k}\Omega$, $R'_2 = 50\ \text{k}\Omega\ -5\% = 47.5\ \text{k}\Omega$

Then $A_d(\min) = \frac{90}{30}\left[1 + \frac{50+47.5}{102}\right] = 5.87$

(c) $\text{CMRR} = \infty$

TYU9.12

$$i_1 = \frac{\upsilon_{I1} - \upsilon_{I2}}{R_1} \Rightarrow R_1(\mathit{fixed}) = \frac{[2-(-2)]\times 10^{-3}}{2\times 10^{-6}} \Rightarrow 2\ \text{k}\Omega$$

$$A_d(\max) = (2.5)\left(1 + \frac{2R_2}{2}\right) = 500 \Rightarrow R_2 = 199\ \text{k}\Omega$$

$$A_d(\min) = (2.5)\left(1 + \frac{2(199)}{2 + R_1(\text{var})}\right) = 5 \Rightarrow R_1(\text{var}) = 396\ \text{k}\Omega$$

TYU9.13

End of 1st pulse: $\upsilon_o = \frac{-1}{\tau}\times t\Big|_0^{10\,\mu s} = \frac{-10\times 10^{-6}}{\tau}$

After 10 pulses: $\upsilon_o = -5 = \frac{-(10)(10\times 10^{-6})}{\tau}$

So $\tau = \frac{100\times 10^{-6}}{5} \Rightarrow \tau = 20\ \mu\text{s}$

$\tau = 20\times 10^{-6} = R_1 C_2$

For example, $\underline{C_2 = 0.01\times 10^{-6} = 0.01\ \mu\text{F}} \Rightarrow \underline{R_1 = 2\ \text{k}\Omega}$

TYU9.14

(a)

$$\upsilon_A = \left(\frac{R-\Delta R}{R-\Delta R+R+\Delta R}\right)\cdot V^+ = \left(\frac{R-\Delta R}{2R}\right)\cdot V^+$$

$$\upsilon_B = \left(\frac{R+\Delta R}{R+\Delta R+R-\Delta R}\right)\cdot V^+ = \left(\frac{R+\Delta R}{2R}\right)\cdot V^+$$

$$\upsilon_{O1} = \upsilon_A - \upsilon_B = \left[\left(\frac{R-\Delta R}{2R}\right) - \left(\frac{R+\Delta R}{2R}\right)\right]\cdot V^+$$

so

$$\upsilon_{O1} = \left(\frac{-\Delta R}{R}\right)\cdot V^+ = \left(\frac{-5}{20\times 10^3}\right)\Delta R = \left(-2.5\times 10^{-4}\right)\Delta R$$

We have $\upsilon_{O1} = \left(-2.5\times 10^{-4}\right)(-100) \Rightarrow \upsilon_{O1} = 25\ \text{mV}$

(b)

For the instrumentation amplifier

$$\upsilon_O = \frac{R_4}{R_3}\left(1+\frac{2R_2}{R_1}\right)(\upsilon_{O1})$$

$$3 = \frac{R_4}{R_3}\left(1+\frac{2R_2}{R_1}\right)(0.025)$$

or $120 = \frac{R_4}{R_3}\left(1+\frac{2R_2}{R_1}\right)$; For example, set $\frac{R_4}{R_3}=10$ and $\frac{R_2}{R_1}=5.5$

TYU9.15

(a)

$$\upsilon_A = \left(\frac{R}{R+R}\right)\cdot V^+ = \frac{1}{2}(3) = 1.5 \text{ V}$$

$$\upsilon_B = \left(\frac{R}{R+R(1+\delta)}\right)\cdot V^+ = \left(\frac{1}{2+\delta}\right)(3)$$

$$\upsilon_{O1} = \upsilon_A - \upsilon_B = 1.5 - \left(\frac{1}{2+\delta}\right)(3) = \frac{(2+\delta)(1.5)-3}{2+\delta} = \frac{1.5\delta}{2+\delta} \cong 0.75\delta \text{ V}$$

(b)

For an instrumentation amplifier

$$\upsilon_O = \frac{R_4}{R_3}\left(1+\frac{2R_2}{R_1}\right)(\upsilon_{O1})$$

For $\delta = 0.025$, want $\upsilon_O = 3$ V

$$3 = \frac{R_4}{R_3}\left(1+\frac{2R_2}{R_1}\right)(0.75)(0.025)$$

or

$$160 = \frac{R_4}{R_3}\left(1+\frac{2R_2}{R_1}\right)$$

For example, set $\frac{R_4}{R_3}=10$ and $\frac{R_2}{R_1}=7.5$

Chapter 10

Exercise Solutions

EX10.1

$$I_{REF} = \frac{V^+ - V_{BE}(on) - V^-}{R_1} = \frac{3 - 0.7 - (-3)}{47} = 0.1128 \text{ mA}$$

$$I_O = \frac{I_{REF}}{\left(1 + \frac{2}{\beta}\right)} = \frac{0.112766}{\left(1 + \frac{2}{120}\right)} = 0.1109 \text{ mA}$$

$$I_{B1} = I_{B2} = \frac{I_O}{\beta} \Rightarrow 0.9243\,\mu\text{ A}$$

EX10.2

$$I_{REF} = \frac{V^+ - V_{BE}(\text{on}) - V^-}{R_1} = \frac{5 - 0.7 - (-5)}{12}$$

$$I_{REF} = 0.775 \text{ mA}$$

$$I_0 = \frac{I_{REF}}{1 + \frac{2}{\beta}} = \frac{0.775}{1 + \frac{2}{75}} = 0.7549 \text{ mA}$$

$$\Delta I_0 = (0.02)(0.7549) = 0.0151 \text{ mA and } \Delta I_0 = \frac{1}{r_0}\Delta V_{CE2} \Rightarrow r_0 = \frac{\Delta V_{CE2}}{\Delta I_0}$$

$$r_0 = \frac{4}{0.0151} = 265 \text{ k}\Omega = \frac{V_A}{I_0} \Rightarrow V_A = (265)(0.7549) \Rightarrow \underline{V_A \cong 200 \text{ V}}$$

EX10.3

$$I_{REF} = \frac{3 - 0.6 - 0.7 - (-3)}{30} = 0.15667 \text{ mA}$$

$$I_O = \frac{I_{REF}}{1 + \frac{2}{\beta(1+\beta_3)}} = \frac{0.15667}{1 + \frac{2}{(120)(81)}} = 0.15663 \text{ mA}$$

$$I_{C1} = I_{C2} = I_O$$

$$I_{B1} = I_{B2} = \frac{I_O}{\beta} \Rightarrow 1.3053\,\mu\text{ A}$$

$$I_{E3} = I_{B1} + I_{B2} = 2.6106\ \mu\text{ A}$$

$$I_{B3} = \frac{I_{E3}}{1+\beta_3} = 0.03223\ \mu\text{ A}$$

EX10.4

$$R_1 = \frac{V^+ - V_{BE1} - V^-}{I_{REF}} = \frac{3 - 0.6 - (-3)}{0.10} = 54 \text{ k}\Omega$$

$$R_E = \frac{V_T}{I_O}\ln\left(\frac{I_{REF}}{I_O}\right) = \frac{0.026}{0.02}\ln\left(\frac{100}{20}\right) = 2.09 \text{ k}\Omega$$

$$V_{BE2} = V_{BE1} - I_O R_E = 0.6 - (0.02)(2.09) = 0.558 \text{ V}$$

EX10.5

(a) $$V_{BE1} = V_T \ln\left(\frac{I_{REF}}{I_{S1}}\right) = (0.026)\ln\left(\frac{120\times10^{-6}}{2\times10^{-16}}\right) = 0.7051 \text{ V}$$

(b) $$V_{BE2} = V_T \ln\left(\frac{I_O}{I_{S2}}\right) = (0.026)\ln\left(\frac{50\times10^{-6}}{2\times10^{-16}}\right) = 0.6824 \text{ V}$$

$$R_E = \frac{V_T}{I_O}\ln\left(\frac{I_{REF}}{I_O}\right) = \frac{0.026}{0.05}\ln\left(\frac{120}{50}\right) \Rightarrow 455\ \Omega$$

(c) $$I_O R_E = V_T \ln\left(\frac{I_{REF}}{I_O}\right)$$

$$I_O(0.7) = (0.026)\ln\left(\frac{0.120}{I_O}\right)$$

By trial and error, $I_O = 40.4\ \mu\text{A}$

Now,

$$V_{BE2} = V_{BE1} - I_O R_E = 0.7051 - (0.0404)(0.7) = 0.6768 \text{ V}$$

EX10.6

$$I_0 R_E = V_T \ln\left(\frac{I_{REF}}{I_0}\right)$$

$$R_E = \frac{0.026}{0.025}\ln\left(\frac{0.70}{0.025}\right) \Rightarrow R_E = 3.465 \text{ k}\Omega$$

$$g_{m2} = \frac{I_0}{V_T} = \frac{0.025}{0.026} \Rightarrow g_{m2} = 0.9615 \text{ mA/V}$$

$$r_{\pi 2} = \frac{\beta V_T}{I_0} = \frac{(150)(0.026)}{0.025} = 156 \text{ k}\Omega$$

$$r_{02} = \frac{V_A}{I_0} = \frac{100}{0.025} = 4000 \text{ k}\Omega$$

$$R_E' = R_E \,\|\, r_{\pi 2} = 3.47 \,\|\, 156 = 3.39 \text{ k}\Omega$$

$$R_0 = r_{02}\left(1 + g_{m2}R_E'\right) = 4000\left[1 + (0.962)(3.39)\right]$$

$$R_0 = 17.04 \text{ M}\Omega$$

$$dI_0 = \frac{1}{R_0}\cdot dV_{C2} = \frac{3}{17{,}040} \Rightarrow \underline{dI_0 = 0.176\ \mu\text{A}}$$

EX10.7

$$I_{REF} = I_R + I_{BR} + I_{B1} + \ldots + I_{BN}$$

$$I_R = I_{01} = I_{02} = \ldots = I_{0N} \text{ and } I_{BR} = I_{B1} = I_{B2} = \ldots = I_{BN} = \frac{I_{01}}{\beta}$$

$$I_{REF} = I_{01} + (N+1)\left(\frac{I_{01}}{\beta}\right) = I_{01}\left(1 + \frac{N+1}{\beta}\right)$$

$$\text{So } I_{01} = I_{02} = \ldots = I_{0N} = \frac{I_{REF}}{1 + \dfrac{N+1}{\beta}}$$

$$\frac{I_{01}}{I_{REF}} = 0.90 = \frac{1}{1 + \dfrac{N+1}{50}}$$

$$1 + \frac{N+1}{50} = \frac{1}{0.9}$$

$$N+1 = \left(\frac{1}{0.9} - 1\right)(50)$$

$$N = \left(\frac{1}{0.9} - 1\right)(50) - 1$$

$$N = 4.55 \Rightarrow \underline{N = 4}$$

EX10.8

$$V_{DS2}(sat) = 0.4 = V_{GS2} - 0.4 \Rightarrow V_{GS2} = 0.8 \text{ V}$$

$$I_O = \left(\frac{k_n'}{2}\right)\left(\frac{W}{L}\right)_2 (V_{GS2} - V_{TN})^2$$

$$0.1 = \left(\frac{0.1}{2}\right)\left(\frac{W}{L}\right)_2 (0.8 - 0.4)^2 \Rightarrow \left(\frac{W}{L}\right)_2 = 12.5$$

$$I_{REF} = 0.5 = \left(\frac{0.1}{2}\right)\left(\frac{W}{L}\right)_1 (0.8 - 0.4)^2 \Rightarrow \left(\frac{W}{L}\right)_1 = 62.5$$

$$V_{GS3} = (V^+ - V^-) - V_{GS1} = 1.8 - (-1.8) - 0.8 = 2.8 \text{ V}$$

$$I_{REF} = 0.5 = \left(\frac{0.1}{2}\right)\left(\frac{W}{L}\right)_3 (2.8 - 0.4)^2 \Rightarrow \left(\frac{W}{L}\right)_3 = 1.74$$

EX10.9

$$I_{REF} = K_n (V_{GS} - V_{TN})^2$$

$$0.020 = 0.080 (V_{GS} - 1)^2$$

a. $\underline{V_{GS} = 1.5 \text{ V}}$ all transistors

b.

$$V_{G4} = V_{GS3} + V_{GS1} + V^- = 1.5 + 1.5 - 5 = -2 \text{ V}$$

$$V_{S4} = V_{G4} - V_{GS4} = -2 - 1.5 = -3.5 \text{ V}$$

$$V_{D4}(\min) = V_{S4} + V_{DS4}(\text{sat}) \text{ and } V_{DS4}(sat) = V_{GS4} - V_{TN} = 1.5 - 1 = 0.5 \text{ V}$$

$$\text{So } V_{D4}(\min) = -3.5 + 0.5 \Rightarrow \underline{V_{D4}(\min) = -3.0 \text{ V}}$$

c.

$$R_0 = r_{04} + r_{02}\left(1 + g_m r_{04}\right)$$

$$r_{02} = r_{04} = \frac{1}{\lambda I_0} = \frac{1}{(0.02)(0.020)} = 2500 \text{ k}\Omega$$

$$g_m = 2K_n\left(V_{GS} - V_{TN}\right) = 2(0.080)(1.5-1) \Rightarrow g_m = 0.080 \; mA/V$$

$$R_0 = 2500 + 2500\left(1 + (0.080)(2500)\right) \Rightarrow \underline{R_0 = 505 \text{ M}\Omega}$$

EX10.10

For Q_2 : $v_{DS}(\min) = |V_P| = 2 \text{ V} \Rightarrow V_S(\min) = v_{DS}(\min) - 5 = 2 - 5 \Rightarrow \underline{V_S(\min) = -3 \text{ V}}$

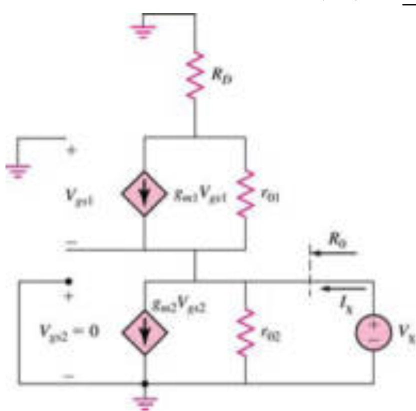
$$I_0 = I_{DSS2}\left(1 + \lambda v_{DS2}\right) = 0.5\left(1 + (0.15)(2)\right) \Rightarrow \underline{I_0 = 0.65 \text{ mA}}$$

$$I_0 = I_{DSS1}\left(1 - \frac{v_{GS1}}{V_{P1}}\right)^2$$

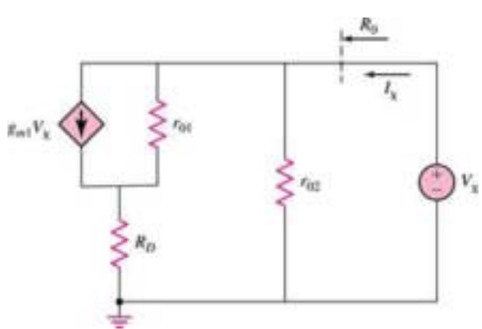
$$0.65 = 0.80\left(1 - \frac{v_{GS1}}{-2}\right)^2$$

$$\frac{v_{GS1}}{-2} = 0.0986 \Rightarrow v_{GS1} = -0.197 \text{ V}$$

$$v_{GS1} = V_I - V_S - 0.197 = V_I - (-3) \Rightarrow \underline{V_I(\min) = -3.2 \text{ V}}$$



$$V_{gs2} = 0, \; V_{gs1} = -V_X$$



$$I_X = \frac{V_X}{r_{02}} + \frac{V_X - V_1}{r_{01}} + g_{m1}V_X \qquad (1)$$

$$\frac{V_1}{R_D} + \frac{V_1 - V_X}{r_{01}} = g_{m1} V_X \qquad (2)$$

$$V_1 = \frac{V_X\left(\dfrac{1}{r_{01}} + g_{m1}\right)}{\dfrac{1}{R_D} + \dfrac{1}{r_{01}}}$$

$$\frac{I_X}{V_X} = \frac{1}{R_0} = \frac{1}{r_{02}} + \frac{1}{r_{01}} + g_{m1} - \frac{\dfrac{1}{r_{01}}\left(\dfrac{1}{r_{01}} + g_{m1}\right)}{\dfrac{1}{R_D} + \dfrac{1}{r_{01}}}$$

$$= \frac{1}{r_{02}} + \left(\frac{1}{r_{01}} + g_{m1}\right)\left[1 - \frac{\dfrac{1}{r_{01}}}{\dfrac{1}{R_D} + \dfrac{1}{r_{01}}}\right]$$

$$= \frac{1}{r_{02}} + \left(\frac{1}{r_{01}} + g_{m1}\right)\left(\frac{\dfrac{1}{R_D}}{\dfrac{1}{R_D} + \dfrac{1}{r_{01}}}\right)$$

For $\quad R_D << r_{o1} \Rightarrow \dfrac{1}{R_o} \cong \dfrac{1}{r_{o2}} + \left(\dfrac{1}{r_{o1}} + g_{m1}\right)$

For Q_1:

$$g_{m1} = \frac{2I_{DSS1}}{|V_P|}\left(1 - \frac{V_{GS1}}{V_P}\right) = \frac{2(0.8)}{2}\left(1 - \frac{-0.197}{-2}\right)$$

$$g_{m1} = 0.721 \text{ mA/V}$$

$$r_0 = \frac{1}{\lambda I_0} = \frac{1}{(0.15)(0.65)} = 10.3 \text{ k}\Omega$$

$$\frac{1}{R_0} = \frac{1}{10.3} + \frac{1}{10.3} + 0.721 = 0.915 \Rightarrow \underline{R_0 = 1.09 \text{ k}\Omega}$$

EX10.11

$$I_{REF} = I_S \exp\left(\frac{V_{EB2}}{V_T}\right)$$

a.
$$V_{EB2} = V_T \ln\left(\frac{I_{REF}}{I_S}\right) = (0.026)\ln\left(\frac{0.5\times10^{-3}}{10^{-12}}\right) \Rightarrow \underline{V_{EB2} = 0.521 \text{ V}}$$

b.
$$R_1 = \frac{5 - 0.521}{0.5} \Rightarrow \underline{R_1 = 8.96 \text{ k}\Omega}$$

(c) Combining Equations (10.79), (10.80), and (10.81), we find

$$I_{S0}\left[\exp\left(\frac{V_I}{V_T}\right)\right]\left(1+\frac{V_{CEo}}{V_{AN}}\right)=I_{REF}\times\frac{\left(1+\frac{V_{EC2}}{V_{AP}}\right)}{\left(1+\frac{V_{EB2}}{V_{AP}}\right)}$$

$$10^{-12}\left[\exp\left(\frac{V_I}{V_T}\right)\right]\left(1+\frac{2.5}{100}\right)=\left(0.5\times10^{-3}\right)\frac{\left(1+\frac{2.5}{100}\right)}{\left(1+\frac{0.521}{100}\right)}$$

$$1.025\times10^{-12}\exp\left(\frac{V_I}{V_T}\right)=5.098\times10^{-4}\exp\left(\frac{V_I}{V_T}\right)=4.974\times10^{8}\Rightarrow \underline{V_I=0.521\text{ V}}$$

d.
$$A_v=\frac{-\left(\frac{1}{V_T}\right)}{\frac{1}{V_{AN}}+\frac{1}{V_{AP}}}=\frac{-\frac{1}{0.026}}{\frac{1}{100}+\frac{1}{100}}=\frac{-38.46}{0.01+0.01}\Rightarrow \underline{A_v=-1923}$$

EX10.12

(a) $A_\upsilon=-g_{mo}\left(r_{on}\|r_{op}\right)$

$$r_{on}=\frac{V_{AN}}{I_{Co}}=\frac{100}{0.25}=400\text{ k}\Omega$$

$$r_{op}=\frac{V_{AP}}{I_{Co}}=\frac{60}{0.25}=240\text{ k}\Omega$$

$$g_{mo}=\frac{0.25}{0.026}=9.615\text{ mA/V}$$

$$A_\upsilon=-(9.615)(400\|240)=-1442$$

(b) $A_\upsilon=-(0.6)(1442)=-865=-g_{mo}\left(r_{on}\|r_{op}\|R_L\right)$

$$-865=-(9.615)(150\|R_L)\Rightarrow R_L=225\text{ k}\Omega$$

EX10.13

(a) $I_{REF}=I_O=K_n\left(V_{IQ}-V_{TN}\right)^2$

$$0.20=0.10\left(V_{IQ}-0.5\right)^2\Rightarrow V_{IQ}=1.914\text{ V}$$

(b) $A_\upsilon=-g_{mo}\left(r_{on}\|r_{op}\right)$

$$g_{mo}=2\sqrt{K_nI_Q}=2\sqrt{(0.1)(0.2)}=0.2828\text{ mA/V}$$

$$r_{on}=r_{op}=\frac{1}{\lambda I_Q}=\frac{1}{(0.015)(0.2)}=333\text{ k}\Omega$$

$$A_\upsilon=-(0.2828)(333\|333)=-47.1$$

(c) $A_\upsilon=-(0.5)(47.1)=-23.55=-g_{mo}\left(r_{on}\|r_{op}\|R_L\right)$

$$23.55=(0.2828)(333\|333\|R_L)\Rightarrow R_L=166.5\text{ k}\Omega$$

Test Your Understanding Solutions

TYU10.1

$$I_{REF} = \left(1+\frac{2}{\beta}\right)I_O = \left(1+\frac{2}{120}\right)(0.20) = 0.2033 \text{ mA}$$

$$R_1 = \frac{2.5-0.7-(-2.5)}{0.2033} = 21.15 \text{ k}\Omega$$

TYU10.2

Neglecting base currents

$$V_{BE1} = (0.026)\ln\left(\frac{150\times10^{-6}}{8\times10^{-15}}\right) = 0.6150 \text{ V}$$

$$I_O = \left(5\times10^{-15}\right)\exp\left(\frac{0.6150}{0.026}\right) \Rightarrow 93.75\,\mu\text{A}$$

TYU10.3

$$I_0 = I_{REF}\cdot\frac{1}{\left(1+\dfrac{2}{\beta(1+\beta)}\right)} = \frac{0.50}{\left(1+\dfrac{2}{50(51)}\right)} \Rightarrow \underline{I_0 = 0.4996 \text{ mA}}$$

$$I_{B3} = \frac{I_0}{\beta} \Rightarrow \underline{I_{B3} = 9.99\ \mu\text{A}}$$

$$I_{E3} = \left(\frac{1+\beta}{\beta}\right)I_{C3} = \underline{I_{E3} = 0.5096 \text{ mA}}$$

$$I_{C2} = \frac{I_{E3}}{\left(1+\dfrac{2}{\beta}\right)} = \frac{0.5096}{\left(1+\dfrac{2}{50}\right)} \Rightarrow \underline{I_{C2} = 0.490 \text{ mA} = I_{C1}}$$

$$I_{B1} = I_{B2} = \frac{I_{C2}}{\beta} \Rightarrow \underline{I_{B1} = I_{B2} = 9.80\ \mu\text{A}}$$

TYU10.4

For circuit - Figure 10.2(b)

(a) $I_O \cong I_{REF} = 1 \text{ mA}$

(b) $R_o = \dfrac{V_A}{I_O} = \dfrac{50}{1} = 50 \text{ k}\Omega$

(c) $dI_O = \dfrac{\Delta V_{C2}}{R_o} = \dfrac{3}{50} = 0.06 \text{ mA}$

$$\frac{dI_O}{I_O} = \frac{0.06}{1} \Rightarrow 6\%$$

From circuit - Figure 10.9

(a) $I_O R_E = V_T \ln\left(\dfrac{I_{REF}}{I_O}\right)$

$I_O(2) = (0.026)\ln\left(\dfrac{1}{I_O}\right)$

By trial and error, $I_O = 41.4\,\mu\text{A}$

(b) $r_{o2} = \dfrac{50}{0.0414} \Rightarrow 1.208\ \text{M}\Omega$

$g_{m2} = \dfrac{0.0414}{0.026} = 1.5923\ \text{mA/V}$; $r_{\pi 2} = \dfrac{(200)(0.026)}{0.0414} = 125.6\ \text{k}\Omega$

$R_E \| r_{\pi 2} = 2\|125.6 = 1.969\ \text{k}\Omega$

$R_o = (1.208)[1 + (1.5923)(1.969)] \Rightarrow 5\ \text{M}\Omega$

(c) $dI_O = \dfrac{3}{5} = 0.6\,\mu\text{A}$

$\dfrac{dI_O}{I_O} = \dfrac{0.6}{41.4} \Rightarrow 1.45\%$

TYU10.5

(a) $I_{REF} = \left(\dfrac{k_{n1}'}{2}\right)\left(\dfrac{W}{L}\right)_1 (V_{GS1} - V_{TN1})^2 = \left(\dfrac{k_{n3}'}{2}\right)\left(\dfrac{W}{L}\right)_3 (V_{GS3} - V_{TN3})^2$

$V_{GS3} = V^+ - V_{GS1} = 2.5 - V_{GS1}$

Then

$\left(\dfrac{100}{2}\right)(12.5)(V_{GS1} - 0.38)^2 = \left(\dfrac{95}{2}\right)(1.18)(2.5 - V_{GS1} - 0.42)^2$

We find $25(V_{GS1} - 0.38) = (7.4867)(2.08 - V_{GS1})$

Or $V_{GS1} = V_{GS2} = 0.7718\ \text{V}$

$I_{REF} = \left(\dfrac{100}{2}\right)(12.5)(0.7718 - 0.38)^2 = 95.93\,\mu\text{A}$

$I_O = \left(\dfrac{k_{n2}'}{2}\right)\left(\dfrac{W}{L}\right)_2 (V_{GS2} - V_{TN2})^2 = \left(\dfrac{105}{2}\right)(7.5)(0.7718 - 0.40)^2$

or

$I_O = 54.43\,\mu\text{A}$

(b) $\dfrac{\Delta I_{REF}}{I_{REF}} = \dfrac{95.93 - 100}{100} \times 100\% = -4.07\%$

$\dfrac{\Delta I_O}{I_O} = \dfrac{54.43 - 60}{60} \times 100\% = -9.28\%$

TYU10.6

(a) $I_{REF} = \left(\dfrac{k_n'}{2}\right)\left(\dfrac{W}{L}\right)_1 (V_{GS1} - V_{TN})^2 = \left(\dfrac{k_n'}{2}\right)\left(\dfrac{W}{L}\right)_3 (V_{GS3} - V_{TN})^2$

$V_{GS3} = (V^+ - V^-) - V_{GS1} = 6 - V_{GS1}$

then

$$\sqrt{12}(V_{GS1}-0.5)=\sqrt{3}(6-V_{GS1}-0.5)\Rightarrow V_{GS1}=2.167\ \text{V}$$

$$I_{REF}=\left(\frac{80}{2}\right)(12)(2.167-0.5)^2\Rightarrow 1.33\ \text{mA}$$

(b) $$I_O=\left(\frac{k_n'}{2}\right)\left(\frac{W}{L}\right)_2(V_{GS2}-V_{TN})^2[1+\lambda V_{DS}]$$

$$=\left(\frac{0.08}{2}\right)(6)(2.167-0.5)^2[1+(0.02)(2)]=0.6936\ \text{mA}$$

(c) $$I_O=\left(\frac{0.08}{2}\right)(6)(2.167-0.5)^2[1+(0.02)(4)]=0.7203\ \text{mA}$$

TYU10.7

$$I_{REF}=K_{n1}(V_{GS1}-V_{TN})^2=K_{n3}(V_{GS3}-V_{TN})^2$$

We have $V_{GS3}=(V^+-V^-)-V_{GS1}=6-V_{GS1}$

Then

$$\sqrt{0.35}(V_{GS1}-0.7)=\sqrt{0.10}(6-V_{GS1}-0.7)$$

which yields

$$V_{GS1}=2.302\ \text{V}$$

then

$$I_{REF}=0.35(2.302-0.7)^2=0.8986\ \text{mA}$$

$$I_O=3(0.30)(2.302-0.7)^2=2.31\ \text{mA}$$

TYU10.8

All transistors are identical

$$\Rightarrow \underline{I_0=I_{REF}=250\ \mu\text{A}}$$

$$I_{REF}=K_n(V_{GS}-V_{TN})^2$$

$$0.25=0.20(V_{GS}-1)^2\Rightarrow \underline{V_{GS}=2.12\ \text{V}}$$

TYU10.9

a. $$V_{EB2}=(0.026)\ln\left(\frac{0.1\times10^{-3}}{5\times10^{-14}}\right)\Rightarrow \underline{V_{EB2}=0.557\ \text{V}}$$

b. $$R_1=\frac{5-0.557}{0.1}\Rightarrow \underline{R_1=44.4\ \text{k}\Omega}$$

c.

$$I_{S0}\left[\exp\left(\frac{V_I}{V_T}\right)\right]\left(1+\frac{V_{CE0}}{V_{AN}}\right)=I_{REF}\times\left(\frac{1+\dfrac{V_{EC2}}{V_{AP}}}{1+\dfrac{V_{EB2}}{V_{AP}}}\right)$$

$$5\times10^{-14}\left[\exp\left(\frac{V_I}{V_T}\right)\right]\left(1+\frac{2.5}{100}\right)=\left(0.1\times10^{-3}\right)\left(\frac{1+\dfrac{2.5}{100}}{1+\dfrac{0.557}{100}}\right)$$

$$\left(5.125\times10^{-14}\right)\exp\left(\frac{V_I}{V_T}\right)=1.019\times10^{-4}$$

$$\exp\left(\frac{V_I}{V_T}\right)=1.988\times10^{9}\Rightarrow \underline{V_I=0.557\text{ V}}$$

d.

$$A_v=\frac{-\dfrac{1}{0.026}}{\dfrac{1}{100}+\dfrac{1}{100}}\Rightarrow \underline{A_v=-1923}$$

TYU10.10

(a) $I_{REF}=K_p\left(V_{SG}+V_{TP}\right)^2$

$$0.15=0.12\left(V_{SG}-0.7\right)^2\Rightarrow V_{SG}=1.818\text{ V}$$

(b) $$V_O=\frac{\left[1+\lambda_p\left(V^+-V_{SG}\right)\right]}{\lambda_n+\lambda_p}-\frac{K_n\left(V_I-V_{TN}\right)^2}{I_{REF}\left(\lambda_n+\lambda_p\right)}$$

Set $V_O=2.5$ V

$$2.5=\frac{\left[1+(0.02)(5-1.818)\right]}{0.04}-\frac{0.12\left(V_I-0.7\right)^2}{0.15(0.04)}\Rightarrow V_I=1.798\text{ V}$$

(c) $$A_\upsilon=\frac{-2K_n\left(V_I-V_{TN}\right)}{I_{REF}\left(\lambda_n+\lambda_p\right)}=\frac{-2(0.12)(1.798-0.7)}{(0.15)(0.04)}=-43.9$$

TYU10.11

(a) $I_{REF}=80=50\left(V_{SG}-0.7\right)^2\Rightarrow V_{SG}=1.965\text{ V}$

(b) $$V_O=\frac{\left[1+\lambda_p\left(V^+-V_{SG}\right)\right]}{\lambda_n+\lambda}-\frac{K_n\left(V_I-V_{TN}\right)^2}{I_{REF}\left(\lambda_n+\lambda_p\right)}$$

$$2.5=\frac{\left[1+(0.02)(5-1.965)\right]}{0.04}-\frac{(0.05)\left(V_I-0.7\right)^2}{(0.08)(0.04)}\Rightarrow V_I=1.940\text{ V}$$

(c) $$A_\upsilon=\frac{-2K_n\left(V_I-V_{TN}\right)}{I_{REF}\left(\lambda_n+\lambda_P\right)}=\frac{-2(0.05)(1.940-0.7)}{(0.08)(0.04)}=-38.74$$

TYU10.12

a.

$$g_m = \frac{I_{C0}}{V_T} = \frac{0.5}{0.026} \Rightarrow \underline{g_m = 19.2 \text{ mA/V}}$$

$$r_0 = \frac{V_{AN}}{I_{CQ}} = \frac{120}{0.5} \Rightarrow \underline{r_0 = 240 \text{ k}\Omega}$$

$$r_{02} = \frac{V_{AP}}{I_{CQ}} = \frac{80}{0.5} \Rightarrow \underline{r_{02} = 160 \text{ k}\Omega}$$

b.

$$A_v = -g_m\left(r_0 \| r_{02} \| R_L\right) = -(19.2)\left[240 \| 160 \| 50\right] \Rightarrow \underline{A_v = -631}$$

TYU10.13

$$I_C = 1\text{mA}, \quad g_m = \frac{1}{0.026} = 38.46 \text{ mA/V}$$

$$r_{\pi 1} = r_{\pi 2} = \frac{(100)(0.026)}{1} = 2.6 \text{ K}$$

$$r_{O1} = r_{O2} = \frac{80}{1} = 80 \text{ K}$$

$$r_O = \frac{120}{1} = 120 \text{ K}$$

$$R_{O1} = 2.6 \left\| \frac{1}{38.46} \right\| 80 = 0.0257 \text{ K}$$

For $R_1 = 9.3$ K

$$R' = R_1 \left\| \left(R_{O1} + R_E\right) = 9.3 \right\| (0.0257 + 1) = 0.924 \text{ K}$$

$$R_E'' = 1 \| [2.6 + 0.924] = 0.779 \text{ K}$$

$$R_{O2} = 80\left[1 + (38.46)(0.779)\right] = 2476.7 \text{ K}$$

$$A_v = -g_m\left(r_O \| R_{O2}\right) = -(38.46)(120 \| 2476.7) = -(38.46)(114.5)$$

$$A_v = -4404$$

For $R_L = 100$ K

$$A_v = -38.46\left[114.5 \| 100\right] = -2053$$

For $R_L = 10$ K

$$A_v = -38.46\left[114.5 \| 10\right] = -354$$

TYU10.14

M_1 and M_2 identical $\Rightarrow I_o = I_{REF}$

a.

$$I_O = K_n\left(V_I - V_{YN}\right)^2$$

$$0.25 = 0.2\left(V_I - 1\right)^2$$

$$V_I = 2.12 \text{ V}$$

$$g_m = 2K_n\left(V_I - V_{TN}\right) = 2\left(0.2\right)\left(2.12 - 1\right) \Rightarrow \underline{g_m = 0.447 \text{ mA/V}}$$

$$r_{0n} = \frac{1}{\lambda_n I_0} = \frac{1}{\left(0.01\right)\left(0.25\right)} \Rightarrow \underline{r_{0n} = 400 \text{ k}\Omega}$$

$$r_{0p} = \frac{1}{\lambda_p I_0} = \frac{1}{\left(0.02\right)\left(0.25\right)} \Rightarrow \underline{r_{0p} = 200 \text{ k}\Omega}$$

$$A_v = -g_m\left(r_0 \parallel r_{02} \parallel R_L\right)$$

b.

$$A_v = -\left(0.447\right)\left[400 \parallel 200 \parallel 100\right] \Rightarrow \underline{A_v = -25.5}$$

Chapter 11

Exercise Solutions

EX11.1

(a) $\upsilon_E = 0 - 0.7 = -0.7\ \text{V}$

$\upsilon_{C1} = \upsilon_{C2} = 5 - (0.15)(20) = 2\ \text{V}$

$\upsilon_{CE1} = \upsilon_{CE2} = 2 - (-0.7) = 2.7\ \text{V}$

(b) $\upsilon_E = -1 - 0.7 = -1.7\ \text{V}$

$\upsilon_{C1} = \upsilon_{C2} = 2\ \text{V}$

$\upsilon_{CE1} = \upsilon_{CE2} = 3.7\ \text{V}$

(c) $\upsilon_E = +1 - 0.7 = +0.3\ \text{V}$

$\upsilon_{C1} = \upsilon_{C2} = 2\ \text{V}$

$\upsilon_{CE1} = \upsilon_{CE2} = 2 - 0.3 = 1.7\ \text{V}$

EX11.2

(a) $$\frac{i_{C1}}{I_Q} = 0.25 = \frac{1}{1 + \exp\left(\dfrac{-\upsilon_d}{V_T}\right)}$$

We find, $\exp\left(\dfrac{-\upsilon_d}{V_T}\right) = 3 \Rightarrow -\upsilon_d = (0.026)\ln(3)$

Or $\upsilon_d = -28.56\ \text{mV}$

(b) $$\frac{i_{C2}}{I_Q} = \frac{1}{1 + \exp\left(\dfrac{+\upsilon_d}{V_T}\right)} = 0.9$$

We find, $\exp\left(\dfrac{\upsilon_d}{V_T}\right) = 0.1111 \Rightarrow \upsilon_d = (0.026)\ln(0.1111)$

Or $\upsilon_d = -57.13\ \text{mV}$

EX11.3

(a) $\text{CMRR}_{dB} = 75\ \text{dB} \Rightarrow \text{CMRR} = 5623.4$

$$5623.4 = \frac{1}{2}\left[1 + \frac{(101)(0.8)R_o}{(0.026)(100)}\right] \Rightarrow R_o = 362\ \text{k}\Omega$$

(b) $\text{CMRR}_{dB} = 95\ \text{dB} \Rightarrow \text{CMRR} = 56{,}234$

$$56{,}234 = \frac{1}{2}\left[1 + \frac{(101)(0.8)R_o}{(0.026)(100)}\right] \Rightarrow R_o = 3.62\ \text{M}\Omega$$

EX11.4

(a) $\upsilon_{C1} = -g_m \cdot \dfrac{\upsilon_d}{2} \cdot R_{C1}$

$$\frac{\upsilon_{C1}}{\upsilon_d} = -150 = -\frac{g_m R_{C1}}{2}$$

We find $g_m = \dfrac{0.1}{0.026} = 3.846 \text{ mA/V}$

Then $R_{C1} = \dfrac{2(150)}{3.846} = 78.0 \text{ k}\Omega$

$$\upsilon_{C2} = +g_m \cdot \frac{\upsilon_d}{2} \cdot R_{C2}$$

$$\frac{\upsilon_{C2}}{\upsilon_d} = 100 = \frac{g_m R_{C2}}{2}$$

Then $R_{C2} = \dfrac{2(100)}{3.846} = 52.0 \text{ k}\Omega$

(b) For $V_{CB} = 0$, $\upsilon_{C1} = \upsilon_{C2} = 1.5 \text{ V}$ for $\upsilon_{cm} = 1.5 \text{ V}$

Then $1.5 = V^+ - I_{CQ}R_C = V^+ - (0.1)(78) \Rightarrow V^+ = +9.3 \text{ V}$

So $V^+ = -V^- = 9.3 \text{ V}$

EX11.5

(a) $\upsilon_o = A_d\upsilon_d + A_{cm}\upsilon_{cm}$

$$\upsilon_d = \upsilon_1 - \upsilon_2 = -20\,\mu\text{ V}$$

$$\upsilon_{cm} = \frac{\upsilon_1 + \upsilon_2}{2} = 0$$

Then $\upsilon_o = (150)(-20) \Rightarrow \upsilon_o = -3 \text{ mV}$

(b) $\upsilon_d = \upsilon_1 - \upsilon_2 = -20\,\mu\text{ V}$

$$\upsilon_{cm} = \frac{\upsilon_1 + \upsilon_2}{2} = 200\,\mu\text{ V}$$

Now $\text{CMRR}_{dB} = 50 \text{ dB} \Rightarrow \text{CMRR} = 316.2 = \left|\dfrac{A_d}{A_{cm}}\right| = \dfrac{150}{A_{cm}} \Rightarrow A_{cm} = 0.474$

Then $\upsilon_o = A_d\upsilon_d + A_{cm}\upsilon_{cm} = (150)(-20) + (0.474)(200)$

Or $\upsilon_o = -2.905 \text{ mV}$

EX11.6

$$R_{id} = 2\left[r_\pi + (1+\beta)R_E\right]$$

$$r_\pi = \frac{\beta V_T}{I_{CQ}} = \frac{(100)(0.026)}{0.25} = 10.4 \text{ K}$$

$$R_{id} = 2\left[10.4 + (101)(0.5)\right] = 122 \text{ K}$$

EX11.7

$$A_d = \frac{g_m R_C}{2(1+g_m R_E)}$$

$$10 = \frac{(9.62)(10)}{2\left[1+(9.62)R_E\right]}$$

$$1+(9.62)R_E = 4.81 \Rightarrow R_E = 0.396 \text{ K}$$

$$R_{id} = 2\left[r_\pi + (1+\beta)R_E\right] = 2\left[10.4+(101)(0.396)\right]$$

$$R_{id} = 100.8 \text{ K}$$

EX11.8

$$I_1 = \frac{10-V_{GS4}}{R_1} = K_{n3}\left(V_{GS4}-V_{TN}\right)^2$$

$$10-V_{GS4} = (0.1)(80)\left(V_{GS4}-0.8\right)^2$$

$$10-V_{GS4} = 8\left(V_{GS4}^2 - 1.6V_{GS4} + 0.64\right)$$

$$8V_{GS4}^2 - 11.8V_{GS4} - 4.88 = 0$$

$$V_{GS4} = \frac{11.8 \pm \sqrt{(11.8)^2 + 4(8)(4.88)}}{2(8)} = 1.81 \text{ V}$$

$$I_1 = I_Q = \frac{10-1.81}{80} = 0.102 \text{ mA}$$

$$I_{D1} = I_{D2} = \frac{0.102}{2} = 0.0512 \text{ mA}$$

$$= K_{n1}\left(V_{GS1}-V_{TN}\right)^2$$

$$0.0512 = 0.050\left(V_{GS1}-0.8\right)^2 \Rightarrow V_{GS1} = 1.81 \text{ V}$$

$$v_{01} = v_{02} = 5-(0.0512)(40) = 2.95 \text{ V}$$

$$\begin{aligned}
Max\ v_{cm} : V_{DS1}(sat) &= V_{GS1} - V_{TN} \\
&= 1.81 - 0.8 = 1.01 \text{ V}
\end{aligned}$$

$$\begin{aligned}
v_{cm}(\text{max}) &= v_{01} - V_{DS1}(\text{sat}) + V_{GS1} \\
&= 2.95 - 1.01 + 1.81 \\
v_{cm}(\text{max}) &= 3.75 \text{ V}
\end{aligned}$$

$$\begin{aligned}
Min\ v_{cm} : V_{DS4}(sat) &= V_{GS4} - V_{TN} \\
&= 1.81 - 0.8 = 1.01 \text{ V} \\
v_{cm}(\text{min}) &= V_{GS1} + V_{DS4}(\text{sat}) - 5 \\
&= 1.81 + 1.01 - 5 \\
v_{cm}(\text{min}) &= -2.18 \text{ V}
\end{aligned}$$

$$-2.18 \le v_{cm} \le 3.75 \text{ V}$$

EX11.9

(a) $A_d = \sqrt{\left(\frac{k_n^1}{2}\right)\left(\frac{W}{L}\right)\left(\frac{I_Q}{2}\right)} \cdot R_D$

$15 = \sqrt{\left(\frac{0.1}{2}\right)\left(\frac{W}{L}\right)\left(\frac{0.2}{2}\right)} \cdot (15) \Rightarrow \left(\frac{W}{L}\right) = 200$

(b) $g_f(\max) = \sqrt{\left(\frac{k_n'}{2}\right)\left(\frac{W}{L}\right)\left(\frac{I_Q}{2}\right)} = \sqrt{\left(\frac{0.1}{2}\right)(200)\left(\frac{0.2}{2}\right)} = 1 \text{ mA/V}$

EX11.10

(a) $r_{o2} = \frac{V_{A2}}{I_{CQ}} = \frac{150}{0.2} = 750 \text{ k}\Omega$

$r_{o4} = \frac{V_{A4}}{I_{CQ}} = \frac{90}{0.2} = 450 \text{ k}\Omega$

$g_m = \frac{I_{CQ}}{V_T} = \frac{0.2}{0.026} = 7.692 \text{ mA/V}$

$A_d = g_m\left(r_{o2} \| r_{o4}\right) = (7.692)(750 \| 450) = 2163$

(b) $A_d = g_m\left(r_{o2} \| r_{o4} \| R_L\right) = (7.692)(750 \| 450 \| 250) = 1018$

(c) $R_{id} = 2r_\pi$, $r_\pi = \frac{(120)(0.026)}{0.2} = 15.6 \text{ k}\Omega$

$R_{id} = 31.2 \text{ k}\Omega$

(d) $R_o = r_{o2} \| r_{o4} = 750 \| 450 = 281 \text{ k}\Omega$

EX11.11

We have $\left(\frac{W}{L}\right)_4 = 10$, $\left(\frac{W}{L}\right)_5 = \left(\frac{W}{L}\right)_6 = 0.33$

$I_{REF} = \left(\frac{k_n'}{2}\right)\left(\frac{W}{L}\right)_4 \left(V_{GS4} - V_{TN}\right)^2 = \left(\frac{k_n'}{2}\right)\left(\frac{W}{L}\right)_5 \left(V_{GS5} - V_{TN}\right)^2$

$(10)\left(V_{GS4} - 0.5\right)^2 = (0.33)\left(V_{GS5} - 0.5\right)^2$

$V_{GS5} = \frac{6 - V_{GS4}}{2}$

Then $(5.505)\left(V_{GS4} - 0.5\right) = \left(V_{gs5} - 0.5\right) = \frac{6 - V_{GS4}}{2} - 0.5$

Which yields $V_{GS4} = 0.8747 \text{ V}$

Then $I_{REF} = I_Q = \left(\frac{80}{2}\right)(10)(0.8747 - 0.5)^2 = 56.16\,\mu\text{A}$

$$A_d = 2\sqrt{2\left(\frac{k_n'}{2}\right)\left(\frac{W}{L}\right)_n \left(\frac{1}{I_Q}\right)} \cdot \frac{1}{\lambda_n + \lambda_p} = 2\sqrt{2\left(\frac{80}{2}\right)(10)\left(\frac{1}{56.16}\right)} \cdot \frac{1}{0.02 + 0.02}$$

$A_d = 188.7$

EX11.12

$$A_d = g_m\left(r_{o2} \| R_o\right)$$

$$400 = g_m\left(500 \| 101000\right) \Rightarrow g_m = 0.8\,\text{mA/V}$$

$$g_m = 2\sqrt{K_n I_{DQ}}$$

$$0.8 = 2\sqrt{\left(\frac{0.08}{2}\right)\left(\frac{W}{L}\right)_1 (0.01)} \Rightarrow \left(\frac{W}{L}\right)_1 = \left(\frac{W}{L}\right)_2 = 40$$

EX11.13

$$I_{e6} = (1+\beta)I_{b6} = I_{b7}$$

$$I_{c7} = \beta I_{b7} = \beta(1+\beta)I_{b6}$$

$$\frac{I_{c7}}{I_{b6}} = \beta(1+\beta) = (100)(101) = 1.01\times10^4$$

EX11.14

$$I_{CQB} = 0.5\ \text{mA},\quad I_{BQB} = \frac{0.5}{180} = 0.00278\ \text{mA} = I_{EQA}$$

$$I_{CQA} = 0.002747\ \text{mA}$$

$$r_{\pi A} = \frac{(90)(0.026)}{0.002747} = 851.8\ \text{k}\Omega$$

$$R_{oA} = \frac{r_{\pi A} + 300}{91} = \frac{851.8 + 300}{91} = 12.66\ \text{k}\Omega$$

$$r_{\pi B} = \frac{(180)(0.026)}{0.5} = 9.36\ \text{k}\Omega$$

$$R_o = 10 \left\| \frac{r_{\pi B} + R_{oA}}{1+\beta_B} \right. = 10 \left\| \left(\frac{9.36 + 12.66}{181}\right) \right. = 10 \| 0.1217$$

or

$$R_o = 120\,\Omega$$

EX11.15

$$I_1 = \frac{10 - 0.7 - (-10)}{R_1} = 0.6 \Rightarrow \underline{R_1 = 32.2\ \text{K}}$$

$$I_Q R_2 = V_T \ln\left(\frac{I_1}{I_Q}\right)$$

$$(0.2)R_2 = (0.026)\ln\left(\frac{0.6}{0.2}\right) \Rightarrow \underline{R_2 = 143\ \Omega}$$

$$I_{R6} = I_1 \Rightarrow \underline{R_3 = 0}$$

$$10 = I_{C1}R_C + V_{CE1} - 0.7$$

$$10.7 = (0.1)R_C + 4 \Rightarrow \underline{R_C = 67\ \text{K}}$$

$$v_{o2} = -0.7 + 4 = 3.3\ \text{V}$$

$$v_{E4} = 3.3 - 1.4 = 1.9\ \text{V}$$

$$I_{R4} = \frac{v_{E4}}{R_4} \Rightarrow R_4 = \frac{1.9}{0.6} \Rightarrow \underline{R_4 = 3.17 \text{ K}}$$

$$v_{C3} = v_{O2} - 1.4 + v_{CE4}$$
$$= 3.3 - 1.4 + 3 = 4.9 \text{ V}$$

$$I_{R5} = I_{R4} = 0.6 = \frac{10 - 4.9}{R_5} \Rightarrow \underline{R_5 = 8.5 \text{ K}}$$

$$v_{E5} = 4.9 - 0.7 = 4.2 \text{ V} \Rightarrow R_6 = \frac{4.2 - 0.7}{0.6} = \underline{5.83 \text{ K}}$$

$$R_7 = \frac{0 - (-10)}{5} \Rightarrow \underline{R_7 = 2 \text{ K}}$$

EX11.16

$$R_{i2} = r_{\pi 3} + (1+\beta) r_{\pi 4}$$

$$r_{\pi 4} = \frac{(100)(0.026)}{0.6} = 4.333 \text{ K}$$

$$r_{\pi 3} \approx \frac{\beta^2 V_T}{I_{R4}} = \frac{(100)^2 (0.026)}{0.6} = 433.3 \text{ K}$$

$$R_{i2} = 433.3 + (101)(4.333) \Rightarrow \underline{R_{i2} = 871 \text{ K}}$$

$$R_{i3} = r_{\pi 5} + (1+\beta\left[R_6 + r_{\pi 6} + (1+\beta) R_7\right]$$

$$r_{\pi 5} = \frac{(100)(0.026)}{0.6} = 4.333 \text{ K}$$

$$r_{\pi 6} = \frac{(100)(0.026)}{5} = 0.52 \text{ K}$$

$$R_{i3} = 4.333 + (101)\left[5.83 + 0.52 + (101)(2)\right]$$

$$\underline{R_{i3} = 21.0 \text{ M}\Omega}$$

$$A_{d1} = \frac{g_m}{2}\left(R_C \| R_{i2}\right) g_m = \frac{0.1}{0.026} = 3.846 \text{ mA/V}$$

$$A_{d1} = \frac{3.846}{2}(67 \| 871) = 119.64$$

$$A_2 = \left(\frac{I_{R4}}{2V_T}\right)\left(R_5 \| R_{i3}\right) = \frac{0.6}{2(0.026)}(8.5 \| 21000) = 98.037$$

$$A = A_{d1} \cdot A_2 = (119.64)(98.037) = 11{,}729$$

EX11.17

$$f_z = \frac{1}{2\pi R_o C_o} = \frac{1}{2\pi\left(10 \times 10^6\right)\left(0.2 \times 10^{-12}\right)}$$

$$f_z = 79.6 \text{ kHz}$$

$$f_p = \frac{1}{2\pi R_{eq} C_o}$$

From Example 11.17, $R_{eq} = 51.98\ \Omega$

$$f_p = \frac{1}{2\pi(51.98)\left(0.2 \times 10^{-12}\right)}$$

$$f_p = 15.3 \text{ GHz}$$

Test Your Understanding Solutions

TYU11.1

(a) $\upsilon_d = \upsilon_1 - \upsilon_2 = 2.10 - 2.12 = -0.02 \text{ V}$

$$\upsilon_{cm} = \frac{\upsilon_1 + \upsilon_2}{2} = \frac{2.10 + 2.12}{2} = 2.110 \text{ V}$$

(b) $\upsilon_d = \upsilon_1 - \upsilon_2 = 0.25 - 0.002\sin\omega t - [0.5 + 0.002\sin\omega t]$

$= -0.25 - 0.004\sin\omega t \text{ (V)}$

$$\upsilon_{cm} = \frac{0.25 - 0.002\sin\omega t + 0.5 + 0.002\sin\omega t}{2} = 0.375 \text{ V}$$

TYU11.2

(a) Need $\upsilon_{C1} = \upsilon_{C2} = 3 = 5 - (0.2)R_C \Rightarrow R_C = 10 \text{ k}\Omega$

(b) $g_m = \dfrac{0.2}{0.026} = 7.692 \text{ mA/V}$

$A_d = g_m R_C = (7.692)(10) = 76.9$

TYU11.3

(a) $\upsilon_o = A_d\upsilon_d + A_{cm}\upsilon_{cm}$

$\upsilon_d = \upsilon_1 - \upsilon_2 = 0.995\sin\omega t - 1.005\sin\omega t = -0.01\sin\omega t \text{ (V)}$

$$\upsilon_{cm} = \frac{\upsilon_1 + \upsilon_2}{2} = \frac{0.995\sin\omega t + 1.005\sin\omega t}{2} = 1.0\sin\omega t \text{ (V)}$$

Then

$\upsilon_o = (80)(-0.01\sin\omega t) + (-0.20)(1.0\sin\omega t) = -1.0\sin\omega t \text{ (V)}$

(b) $\upsilon_d = \upsilon_1 - \upsilon_2 = -0.01\sin\omega t \text{ (V)}$

$\upsilon_{cm} = 2 \text{ V}$

Then

$\upsilon_o = (80)(-0.01\sin\omega t) + (-0.20)(2) = -0.4 - 0.8\sin\omega t \text{ (V)}$

TYU11.4

From Equation (11.41)

$$CMRR = \frac{g_m R_O}{\left(\dfrac{\Delta R_C}{R_C}\right)}$$

For $CMRR|_{dB} = 75 \text{ dB} \Rightarrow CMRR = 5623.4$

$$5623.4 = \frac{(3.86)(100)}{\Delta R_C}\cdot(10)$$

Then

Or $\Delta R_C = 0.686 \text{ K}$

TYU11.5

From Equation (11.49)

$$CMRR = \frac{1+2R_O g_m}{2\left(\frac{\Delta g_m}{g_m}\right)}$$

For $CMRR|_{dB} = 90 \text{ dB} \Rightarrow CMRR = 31622.8$

Then $$31622.8 = \left(\frac{1+2(100)(3.86)}{2\Delta g_m}\right)(3.86)$$

Or $\Delta g_m = 0.0472 \text{ mA/V}$ or $\dfrac{\Delta g_m}{g_m} = \dfrac{0.0472}{3.86} = 0.0122 \Rightarrow 1.22\%$

TYU11.6

(a) $I_{EQ} = 0.2 \text{ mA}, \quad I_{B1} = I_{B2} = \dfrac{0.2}{151} \Rightarrow 1.32\,\mu\text{A}$

(b) $R_{id} = 2r_\pi = \dfrac{2(150)(0.026)}{0.2} = 39 \text{ k}\Omega$

$$I_b = \frac{10\sin\omega t\,(mV)}{39\,k\Omega} \Rightarrow I_b = 0.256\sin\omega t \;\;(\mu\text{ A})$$

(c) $R_{icm} = \dfrac{1}{2}\left[r_\pi + (1+\beta)(2R_o)\right]; \quad r_\pi = \dfrac{39}{2} = 19.5 \text{ k}\Omega$

$$R_{icm} = \frac{1}{2}\left[19.5 + (151)(2)(100)\right] \Rightarrow 15.11 \text{ M}\Omega$$

$$i_{cm} = \frac{1}{2}\cdot\frac{\upsilon_{cm}}{R_{icm}} = \frac{1}{2}\cdot\frac{3\sin\omega t}{15.11} \Rightarrow 0.0993\sin\omega t\,(\mu\text{ A})$$

TYU11.7

(a) $A_d = \sqrt{\left(\dfrac{k_n'}{2}\right)\left(\dfrac{W}{L}\right)\left(\dfrac{I_Q}{2}\right)} \cdot R_D$

$$12 = \sqrt{\left(\frac{0.1}{2}\right)\left(\frac{W}{L}\right)\left(\frac{0.4}{2}\right)} \cdot (7.5) \Rightarrow \left(\frac{W}{L}\right) = 256$$

(b) $i_{D2} = \left(\dfrac{k_n'}{2}\right)\left(\dfrac{W}{L}\right)(\upsilon_{GS2} - V_{TN})^2$

$$0.2 = \left(\frac{0.1}{2}\right)(256)(\upsilon_{GS2} - 0.5)^2 \Rightarrow \upsilon_{GS2} = 0.625 \text{ V}$$

$$\upsilon_{DS2}(sat) = 0.625 - 0.5 = 0.125 \text{ V}$$

$$\upsilon_O = V^+ - i_{D2}R_D = 3 - (0.2)(7.5) = 1.5 \text{ V}$$

$$\upsilon_{CM}(\max) = \upsilon_O - \upsilon_{DS2}(sat) + \upsilon_{GS2} = 1.5 - 0.125 + 0.625$$

or

$$\upsilon_{CM}(\max) = 2 \text{ V}$$

TYU11.8

From Example 11-8, $I_Q = 0.587$ mA

$$A_d = \sqrt{\frac{K_{n2} I_Q}{2}} \cdot R_D = \sqrt{\frac{(0.1)(0.587)}{2}} \cdot (16) \Rightarrow \underline{A_d = 2.74}$$

$$\text{For } M_4,\ R_0 = \frac{1}{\lambda_4 I_Q} = \frac{1}{(0.02)(0.587)} \Rightarrow R_0 = 85.2 \text{ k}\Omega$$

$$g_m = 2K_n(V_{GS2} - V_{TN}) = 2(0.1)(2.71-1)$$
$$= 0.342 \text{ mA/V}$$

$$A_{cm} = \frac{-g_m R_D}{1 + 2g_m R_0} = \frac{-(0.342)(16)}{1 + 2(0.342)(85.2)} \Rightarrow \underline{A_{cm} = -0.0923}$$

$$CMRR_{dB} = 20\log_{10}\left(\frac{2.74}{0.0923}\right) \Rightarrow \underline{CMRR_{dB} = 29.4 \text{ dB}}$$

TYU11.9

(a) $$\text{CMRR} = \frac{1}{2}\left[1 + 2\sqrt{2\left(\frac{k_n'}{2}\right)\left(\frac{W}{L}\right)(I_Q)} \cdot R_o\right] = \frac{1}{2}\left[1 + 2\sqrt{2\left(\frac{0.1}{2}\right)(10)(0.1)} \cdot (1000)\right]$$

Or

$$\text{CMRR} = 316.73 \Rightarrow \text{CMRR}_{dB} = 50 \text{ dB}$$

(b) $$\text{CMRR}_{dB} = 80 \text{ dB} \Rightarrow \text{CMRR} = 10^4$$

Then

$$10^4 = \frac{1}{2}\left[1 + 2\sqrt{2\left(\frac{0.1}{2}\right)(10)(0.1)} \cdot R_o\right] \Rightarrow R_o = 31.6 \text{ M}\Omega$$

TYU11.10

$$R_o = r_{o4} + r_{o2}(1 + g_{m4} r_{o4})$$

Assume $I_{REF} = I_O = 100\ \mu A$ and $\lambda = 0.01\ V^{-1}$

$$r_{o2} = r_{o4} = \frac{1}{\lambda I_D} = \frac{1}{(0.01)(0.1)} \Rightarrow 1\ M\Omega$$

Let $K_n(\text{all devices}) = 0.1\ mA/V^2$

Then $g_{m4} = 2\sqrt{K_n I_D} = 2\sqrt{(0.1)(0.1)} = 0.2\ mA/V$

$$R_o = 1000 + 1000(1 + (0.2)(1000)) \Rightarrow 202\ M\Omega$$

Now

$$V_{GS1} = V_{GS2} = \sqrt{\frac{I_D}{K_n}} + V_{TN} = \sqrt{\frac{0.05}{0.1}} + 1 = 1.707\ V$$

$$V_{DS1}(sat) = V_{GS1} - V_{TN} = 1.707 - 1 = 0.707\ V$$

So $v_{o1}(\min) = +4 - V_{GS1} + V_{DS1}(sat) = 4 - 1.707 + 0.707$

$$v_{o1}(\min) = 3\ V = 10 - I_D R_D = 10 - (0.05) R_D \Rightarrow \underline{R_D = 140\ k\Omega}$$

For a one-sided output, the differential gain is:

$$A_d = \frac{1}{2} g_{m1} R_D \text{ where } g_{m1} = 2\sqrt{K_n I_D}$$

$$= 2\sqrt{(0.1)(0.05)} = 0.1414 \; mA/V$$

$$A_d = \frac{1}{2}(0.1414)(140) \Rightarrow \underline{A_d = 9.90}$$

The common-mode gain is:

$$A_{cm} = \frac{\sqrt{2K_n I_Q}\cdot R_D}{1+2\sqrt{2K_n I_Q}\cdot R_o} = \frac{\sqrt{2(0.1)(0.1)}\cdot(140)}{1+2\sqrt{2(0.1)(0.1)}\cdot(202000)} \Rightarrow \underline{A_{cm} = 0.0003465}$$

Then

$$CMRR_{dB} = 20\log_{10}\left|\frac{A_d}{A_{cm}}\right| \Rightarrow \underline{CMRR_{dB} = 89.1 \; dB}$$

TYU11.11

a.

$$I_{B5} = \frac{I_Q}{\beta(1+\beta)} = \frac{0.5}{(180)(181)} \Rightarrow 15.3 \text{ nA}$$

So $\underline{I_0 = 15.3 \text{ nA}}$

b. For a balanced condition

$$V_{EC4} = V_{EC3} = V_{EB3} + V_{EB5} \Rightarrow \underline{V_{EC4} = 1.4 \text{ V}}$$

$$V_{CE2} = V_{C2} - V_{E2} = (10-1.4) - (-0.7) \Rightarrow \underline{V_{CE2} = 9.3 \; V}$$

TYU11.12

$$r_{o2} = \frac{V_{AN}}{I_{CQ}} = \frac{120}{0.05} = 2400 \text{ k}\Omega$$

$$r_{o4} = \frac{V_{AP}}{I_{CQ}} = \frac{80}{0.05} = 1600 \text{ k}\Omega$$

$$g_m = \frac{I_{CQ}}{V_T} = \frac{0.05}{0.026} = 1.923 \text{ mA/V}$$

$$A_d = g_m (r_{o2} \| r_{o4}) = (1.923)(2400 \| 1600) = 1846$$

TYU11.13

$$P = (I_Q + I_{REF})(5-(-5))$$

$$10 = (0.1 + I_{REF})(10) \Rightarrow I_{REF} = 0.9 \; mA$$

$$R_1 = \frac{5-0.7-(-5)}{I_{REF}} = \frac{9.3}{0.9} \Rightarrow \underline{R_1 = 10.3 \; k\Omega}$$

$$I_Q R_E = V_T \ln\left(\frac{I_{REF}}{I_Q}\right)$$

$$R_E = \frac{0.026}{0.1}\ln\left(\frac{0.9}{0.1}\right) \Rightarrow \underline{R_E = 0.571 \; k\Omega}$$

$$r_{o2} = \frac{V_{A2}}{I_{C2}} = \frac{120}{0.05} \Rightarrow 2.4\ M\Omega$$
$$r_{o4} = \frac{V_{A4}}{I_{C4}} = \frac{80}{0.05} \Rightarrow 1.6\ M\Omega$$
$$g_m = \frac{0.05}{0.026} = 1.923\ mA/V$$
$$A_d = g_m \left(r_{o2} \| r_{o4} \| R_L\right) = (1.923)\left(2400 \| 1600 \| 90\right) \Rightarrow \underline{A_d = 158}$$

TYU11.14

(a) $R_o = r_{o2} \| r_{o4}$

$$r_{o2} = \frac{V_{AN}}{I_{CQ}} = \frac{120}{0.05} \Rightarrow 2.4\ \text{M}\Omega$$
$$r_{o4} = \frac{V_{AP}}{I_{CQ}} = \frac{80}{0.05} \Rightarrow 1.6\ \text{M}\Omega$$
$$R_o = 2.4 \| 1.6 = 0.96\ \text{M}\Omega$$

(b) $R_L = R_o = 0.96\ \text{M}\Omega$

TYU11.15

$$g_m = 2\sqrt{K_n I_{DQ}} = 2\sqrt{(0.18)(0.1)} = 0.2683\ \text{mA/V}$$
$$r_{o2} = \frac{1}{\lambda_n I_{DQ}} = \frac{1}{(0.015)(0.1)} = 666.7\ \text{k}\Omega$$
$$r_{o4} = \frac{1}{\lambda_p I_{DQ}} = \frac{1}{(0.025)(0.1)} = 400\ \text{k}\Omega$$
$$A_d = g_m\left(r_{o2} \| r_{o4}\right) = (0.2683)(666.7 \| 400) = 67.1$$

TYU11.16

$$I_{E2} = 75\,\mu\text{A},\quad I_{B2} = 0.497\,\mu\text{A},\quad I_{C2} = 74.50\,\mu\text{A}$$
$$I_{D1} = 25 + 0.497 = 25.497\,\mu\text{A}$$
$$g_{m1} = 2\sqrt{K_n I_{D1}} = 2\sqrt{(0.05)(0.025497)} \Rightarrow 71.4\ (\mu\text{A/V})$$
$$g_{m2} = \frac{I_{C2}}{V_T} = \frac{0.0745}{0.026} = 2.865\ \text{mA/V}$$
$$r_{\pi 2} = \frac{(150)(0.026)}{0.0745} = 52.3\ \text{k}\Omega$$

Then

$$g_m^C = \frac{g_{m1}\left(1 + g_{m2} r_{\pi 2}\right)}{1 + g_{m1} r_{\pi 2}} = \frac{(0.0714)[1 + (2.865)(52.3)]}{1 + (0.0714)(52.3)} = 2.275\ \text{mA/V}$$

TYU11.17

From Figure 11.41

$$r_{04} = \frac{80}{0.5} = 160 \text{ k}\Omega$$

$$R_0 \cong \beta r_{04} = (150)(160) \text{ k}\Omega \Rightarrow \underline{R_0 = 24 \text{ M}\Omega}$$

From Figure 11.42

$$r_{06} = \frac{1}{\lambda I_D} = \frac{1}{(0.0125)(0.5)} \Rightarrow \underline{r_{06} = 160 \text{ k}\Omega}$$

$$0.5 = 0.5(V_{GS} - 1)^2 \Rightarrow V_{GS} = 2 \text{ V}$$

$$g_{m6} = 2K_n(V_{GS} - V_{TN}) = 2(0.5)(2-1) = 1 \; mA/V$$

$$r_{04} = 160 \text{ k}\Omega$$

$$R_0 = (g_{m6})(r_{06})(\beta r_{04}) = (1)(160)(150)(160) \Rightarrow \underline{R_0 = 3.840 \text{ M}\Omega}$$

TYU11.18

From Equation (11.126)

$$R_i = \frac{2(1+\beta)\beta V_T}{I_Q} = \frac{2(121)(120)(0.026)}{0.5} \Rightarrow R_i = 1.51 \text{ M}\Omega$$

$$r_{\pi 11} = \frac{\beta V_T}{I_Q} = \frac{(120)(0.026)}{0.5} = 6.24 \text{ k}\Omega$$

$$R_E' = r_{\pi 11} \| R_3 = 6.24 \| 0.1 = 0.0984 \text{ k}\Omega$$

$$g_{m11} = \frac{I_Q}{V_T} = \frac{0.5}{0.026} = 19.23 \text{ mA/V}$$

$$r_{o11} = \frac{V_A}{I_Q} = \frac{120}{0.5} = 240 \text{ k}\Omega$$

Then $R_{C11} = r_{011}(1 + g_{m11}R_E')$

$$= 240[1 + (19.23)(0.0984)]$$

$$= 694 \text{ k}\Omega$$

$$r_{\pi 8} = \frac{\beta V_T}{I_{C8}} = \frac{(120)(0.026)}{2} = 1.56 \text{ k}\Omega$$

$$R_{b8} = r_{\pi 8} + (1+\beta)R_4 = 1.56 + (121)(5) = 607 \text{ k}\Omega$$

Then $R_{L7} = R_{C11} \| R_{b8} = 694 \| 607 = 324 \text{ k}\Omega$

Then $A_\upsilon = \left(\frac{I_Q}{2V_T}\right)R_{L7} = \left[\frac{0.5}{2(0.026)}\right](324) \Rightarrow A_\upsilon = 3115$

$$R_o = R_4 \left\| \left(\frac{r_{\pi 8} + Z}{1+\beta}\right)\right.$$

$$Z = R_{C11} \| R_{C7}$$

$$R_{C7} = \frac{V_A}{I_Q} = \frac{120}{0.5} = 240 \text{ k}\Omega$$

$$Z = 694 \| 240 = 178 \text{ k}\Omega$$

$$R_o = 5 \left\| \left(\frac{1.56 + 178}{121}\right)\right. = 5 \| 1.48 \Rightarrow R_o = 1.14 \text{ k}\Omega$$

TYU11.19

$$A_v = \left(\frac{I_Q}{2V_T}\right) R_{L7}$$

$$10^3 = \left(\frac{0.5}{2(0.026)}\right) R_{L7} \Rightarrow \underline{R_{L7} = 104\ \text{k}\Omega}$$

Chapter 12

Exercise Solutions

EX12.1

(a) (i) $A_f = \dfrac{A}{1+A\beta} \Rightarrow 50 = \dfrac{5\times10^4}{1+(5\times10^4)\beta} \Rightarrow \beta = 0.01998$

(ii) $\dfrac{A_f}{1/\beta} = \dfrac{50}{1/0.01998} = 0.999$

(b) (i) $20 = \dfrac{100}{1+(100)\beta} \Rightarrow \beta = 0.04$

(ii) $\dfrac{A_f}{1/\beta} = \dfrac{20}{1/0.04} = 0.80$

EX12.2

(a) $A_f = \dfrac{A}{1+A\beta} \Rightarrow 50 = \dfrac{5\times10^5}{1+(5\times10^5)\beta} \Rightarrow \beta = 0.019998$

$A = (5\times10^5)(0.85) = 4.25\times10^5$

Now

$$A_f = \frac{4.25\times10^5}{1+(4.25\times10^5)(0.019998)} = 49.99912$$

$$\text{Percent change} = \frac{49.99912-50}{50}\times100\% = -1.76\times10^{-3}\%$$

(b) $20 = \dfrac{100}{1+(100)\beta} \Rightarrow \beta = 0.04$

$A = (100)(0.85) = 85$

Now

$$A_f = \frac{85}{1+(85)(0.04)} = 19.318$$

$$\text{Percent change} = \frac{19.318-20}{20}\times100\% = -3.41\%$$

EX12.3

(a) (i) $80 = \dfrac{5\times10^4}{1+(5\times10^4)\beta} \Rightarrow \beta = 0.01248$

(ii) $\omega_{fH} = \omega_H(1+\beta A_o) = (2\pi)(5)[1+(0.01248)(5\times10^4)] = (2\pi)(3.125\times10^3)$ rad/s

(b) (i) $A_f(0) = \dfrac{5\times10^4}{1+(5\times10^4)\left(\dfrac{0.01248}{2}\right)} = 159.7$

Percent change $= 100\%$

(ii) $\omega_{fH} = (2\pi)(5)\left[1+\left(\dfrac{0.01248}{2}\right)(5\times10^4)\right] = (2\pi)(1.565\times10^3)$ rad/s

Percent change $\cong -50\%$

EX12.4

(a)

$$v_{OA} = A_1A_2v_i + A_2v_n$$
$$= (100)(10)v_i + (10)v_n$$
$$\frac{S_o}{N_o} = \frac{1000v_i}{10v_n} = 100\frac{S_i}{N_i}$$

(b)

$$v_{OC} = \frac{A_1A_2}{1+\beta A_1A_2}v_i + \frac{A_2}{1+\beta A_1A_2}v_n$$
$$= \frac{10^5}{1+(0.001)10^5}v_i + \frac{10}{1+(0.001)(10^5)}v_n$$
$$\frac{S_o}{N_o} = \frac{10^3v_i}{0.1v_n} = 10^4\frac{S_i}{N_i}$$

EX12.5

a. $V_\varepsilon = V_S - V_{fb} = 100 - 99 = 1$ m V

$$V_0 = A_vV_\varepsilon \Rightarrow A_v = \frac{5}{0.001} \Rightarrow \underline{A_v = 5000 \text{ V/V}}$$
$$V_{fb} = \beta V_0 \Rightarrow \beta = \frac{V_{fb}}{V_0} = \frac{0.099}{5} \Rightarrow \underline{\beta = 0.0198 \text{ V/V}}$$
$$A_{vf} = \frac{A_v}{1+\beta A_v} = \frac{5000}{1+(0.0198)(5000)} \Rightarrow \underline{A_{vf} = 50 \text{ V/V}}$$

$$R_{if} = R_i(1+\beta A_v) = (5)\left[1+(0.0198)(5000)\right] \Rightarrow \underline{R_{if} = 500\text{ k}\Omega}$$

b. $$R_{0f} = \frac{R_0}{1+\beta A_v} = \frac{4}{1+(0.0198)(5000)} \Rightarrow \underline{R_{0f} \Rightarrow 40\ \Omega}$$

EX12.6

a. $I_\varepsilon = I_S - I_{fb} = 100 - 99 = 1\ \mu$A

$$A_i = \frac{I_0}{I_\varepsilon} = \frac{5}{0.001} \Rightarrow \underline{A_i = 5000 \text{ A/A}}$$
$$\beta = \frac{I_{fb}}{I_0} = \frac{0.099}{5} \Rightarrow \underline{\beta = 0.0198 \text{ A/A}}$$
$$A_{if} = \frac{A_i}{1+A_i\beta} = \frac{5000}{1+(5000)(0.0198)} \Rightarrow \underline{A_{if} = 50 \text{ A/A}}$$
$$R_{if} = \frac{R_i}{1+\beta A_i} = \frac{5}{1+(0.0198)(5000)} \Rightarrow \underline{R_{if} \Rightarrow 50\ \Omega}$$

b. $$R_{0f} = (1+\beta A_i)R_0 = \left[1+(0.0198)(5000)\right](4) \Rightarrow \underline{R_{0f} = 400\text{ k}\Omega}$$

EX12.7

(a) $A_{\upsilon f} = \left(1+\frac{R_2}{R_1}\right) = \left(1+\frac{60}{15}\right) = 5$

$V_o = A_{\upsilon f} \cdot V_i = (5)(0.1) = 0.5 \text{ V}$

(b) (i) $A_{\upsilon f} = \dfrac{A_\upsilon}{1+\dfrac{A_\upsilon}{\left(1+R_2/R_1\right)}} = \dfrac{5\times10^4}{1+\dfrac{5\times10^4}{5}} = 4.9995$

$V_o = (4.9995)(0.1) = 0.49995 \text{ V}$

(ii) $V_\in = \dfrac{V_o}{A_\upsilon} = \dfrac{0.49995}{5\times10^4} \Rightarrow V_\in = 9.999\,\mu\text{V}$

(c) (i) $A_{\upsilon f} = \dfrac{5\times10^5}{1+\dfrac{5\times10^5}{5}} = 4.99995$

(ii) $V_\in = \dfrac{0.499995}{5\times10^5} \Rightarrow V_\in = 0.99999\,\mu\text{V}$

EX12.8

Use a non inverting op-amp.

$$1+\frac{R_2}{R_1} = 15 \Rightarrow \frac{R_2}{R_1} = 14$$

$R_2 = 140 \text{ K}$

Let $R_1 = 10 \text{ K}$

$$\beta = \frac{1}{1+\frac{R_2}{R_1}} = 0.066667$$

Input resistance.

$$R_{if} = 5(0.06667)\left(5\times10^3\right) \cong 1.67 \text{ M}\Omega$$

$$R_{of} = \frac{50}{(0.066667)\left(5\times10^3\right)} \equiv 0.15\Omega$$

EX12.9

$$i_o = \left(\frac{h_{FE}}{1+h_{FE}}\right)\cdot\frac{R_E}{\left(R_E+\frac{r_\pi}{1+h_{FE}}\right)}\cdot i_s$$

$$r_\pi = \frac{(80)(0.026)}{0.5} = 4.16 \text{ k}\Omega$$

Then

$$\frac{r_\pi}{1+h_{FE}} = \frac{4.16}{81} = 0.0514 \text{ k}\Omega$$

Then we want

$$\frac{i_o}{i_i} = 0.95 = \left(\frac{80}{81}\right)\left(\frac{R_E}{R_E+0.0514}\right)$$

or

$$\left(\frac{R_E}{R_E + 0.0514}\right) = 0.9619$$

which yields

$$\underline{R_E(\min) = 1.30\ k\Omega}$$

and

$$V^+ = I_E R_E + 0.7 = \left(\frac{81}{80}\right)(0.5)(1.3) + 0.7 \Rightarrow \underline{V^+(\min) = 1.36\ V}$$

EX12.10

Use the configuration shown in figure 12.20.

$$R_S = 500\,\Omega,\ R_L = 200\,\Omega$$

$$1 + \frac{R_F}{R_1} = 15$$

Let

$$R_1 = 2\text{ K}$$

For example, let $R_F = 28\text{ K}$

EX12.11

(a) (i) $V_G = \left(\dfrac{20}{20+30}\right)(10) - 5 = -1\text{ V}$

$$V_G = V_{GS} + I_{DQ}R_S - 5 = V_{GS} + K_n R_S (V_{GS} - V_{TN})^2 - 5$$

$$4 = V_{GS} + (2)(0.4)(V_{GS}^2 - 4V_{GS} + 4)$$

$$0.8V_{GS}^2 - 2.2V_{GS} - 0.8 = 0 \Rightarrow V_{GS} = 3.075\text{ V}$$

So

$$I_{DQ} = 2(3.075 - 2)^2 = 2.312\text{ mA}$$

(ii) $V_i = V_{gs} + g_m V_{gs} R_S \Rightarrow V_{gs} = \dfrac{V_i}{1 + g_m R_S}$

$$I_o = -\left(\frac{R_D}{R_D + R_L}\right) g_m \cdot \frac{V_i}{1 + g_m R_S}$$

$$A_{gf} = \frac{I_o}{V_i} = -\left(\frac{g_m}{1 + g_m R_S}\right)\left(\frac{R_D}{R_D + R_L}\right)$$

Now

$$g_m = 2\sqrt{K_n I_{DQ}} = 2\sqrt{(2)(2.312)} = 4.30\text{ mA/V}$$

$$A_{gf} = -\left[\frac{4.30}{1 + (4.30)(0.4)}\right]\left(\frac{2}{2+2}\right) = -0.7904\text{ mA/V}$$

(b) (i) $4 = V_{GS} + (1.8)(0.4)(V_{GS}^2 - 4V_{GS} + 4)$

$0.72V_{GS}^2 - 1.88V_{GS} - 1.12 = 0 \Rightarrow V_{GS} = 3.111 \text{ V}$

So

$I_{DQ} = (1.8)(3.111 - 2)^2 = 2.222 \text{ mA}$

(ii) $g_m = 2\sqrt{(1.8)(2.222)} = 4.0 \text{ mA/V}$

$$A_{gf} = -\left[\frac{4.0}{1 + (4.0)(0.4)}\right]\left(\frac{2}{2+2}\right) = -0.7692 \text{ mA/V}$$

$$\text{Percent change} = \frac{0.7692 - 0.7904}{0.7904} \times 100\% = -2.68\%$$

EX12.12

Use the circuit with the configuration shown in Figure 12.27.

The LED replaces R_L.

$$A_{gf} = 10\,\text{mS} = 10 \times 10^{-3} = \frac{1}{R_E} \Rightarrow \underline{R_E = 100\,\Omega}$$

EX12.13

(a) (i) $V_{GS} = \left(\dfrac{150}{150 + 350}\right)(5) = 1.50 \text{ V}$

$I_{DQ} = K_n(V_{GS} - V_{TN})^2 = (1.5)(1.5 - 0.8)^2 = 0.735 \text{ mA}$

$g_m = 2\sqrt{K_n I_{DQ}} = 2\sqrt{(1.5)(0.735)} = 2.1 \text{ mA/V}$

$$V_o = -g_m V_{gs} R_D \;;\quad V_{gs} = \left(\frac{R_1 \| R_2}{R_1 \| R_2 + R_S}\right) \cdot V_i = \left(\frac{105}{105 + +20}\right) \cdot V_i = 0.84 V_i$$

$A_\upsilon = -(0.84)(2.1)(2) = -3.528$

(ii) $$\frac{V_{gs} - V_o}{R_F} + \frac{V_{gs}}{R_1 \| R_2} + \frac{V_{gs} - V_i}{R_S} = 0$$

$$V_{gs}\left(\frac{1}{R_F} + \frac{1}{R_1 \| R_2} + \frac{1}{R_S}\right) = \frac{V_o}{R_F} + \frac{V_i}{R_S}$$

$$V_{gs}\left(\frac{1}{47} + \frac{1}{105} + \frac{1}{20}\right) = \frac{V_o}{47} + \frac{V_i}{20}$$

$$V_{gs} = V_o(0.26337) + V_i(0.61881)$$

Now

$$\frac{V_o}{R_D} + g_m V_{gs} + \frac{V_o - V_{gs}}{R_F} = 0$$

$$\frac{V_o}{2} + \frac{V_o}{47} + \left(g_m - \frac{1}{R_F}\right)[V_o(0.26337) + V_i(0.61881)] = 0$$

or

$$V_o(1.0687) + V_i(1.2863) = 0$$

which yields

$$A_\upsilon = \frac{V_o}{V_i} = -1.204$$

(b) $K_n = 1.275 \text{ mA/V}^2$

(i) $I_{DQ} = (1.275)(1.5-0.8)^2 = 0.62475 \text{ mA}$

$g_m = 2\sqrt{(1.275)(0.62475)} = 1.785 \text{ mA/V}$

$A_\upsilon = -(0.84)(1.785)(2) = -2.9988$

Percent change $= \dfrac{2.9988-3.528}{3.528} \times 100\% = -15\%$

(ii) $V_o(0.52128) + (1.7637)[V_o(0.26337) + V_i(0.61881)] = 0$

$V_o(0.98579) + V_i(1.091395) = 0$

$A_\upsilon = \dfrac{V_o}{V_i} = -1.107$

Percent change $= \dfrac{1.107-1.204}{1.204} \times 100\% = -8.06\%$

EX12.14

From EX12.13; $I_{DQ} = 0.735 \text{ mA}$, $g_m = 2.1 \text{ mA/V}$

(a) $I_x = \dfrac{V_x}{R_D} + \dfrac{V_x}{r_o} + g_m V_{gs} + \dfrac{V_x}{R_F + R_1 \| R_2 \| R_S}$

We find

$$V_{gs} = \left(\frac{R_1 \| R_2 \| R_S}{R_1 \| R_2 \| R_S + R_F}\right) \cdot V_x$$

$$\frac{I_x}{V_x} = \frac{1}{R_{of}} = \frac{1}{R_D} + \frac{1}{r_o} + \frac{1 + g_m (R_1 \| R_2 \| R_S)}{R_F + R_1 \| R_2 \| R_S}$$

Now

$$R_1 \| R_2 \| R_S = 150 \| 350 \| 20 = 16.8 \text{ k}\Omega$$

For $\lambda = 0 \Rightarrow r_o = \infty$

Then

$$\frac{1}{R_{of}} = \frac{1}{2} + \frac{1 + (2.1)(16.8)}{47 + 16.8} = 0.5 + 0.56865$$

or

$$R_{of} = 0.9358 \text{ k}\Omega$$

(b) For $\lambda = 0.04 \Rightarrow r_o = \dfrac{1}{(0.04)(0.735)} = 34.01 \text{ k}\Omega$

Then

$$\frac{1}{R_{of}} = 0.5 + 0.0294 + 0.56865$$

or

$$R_{of} = 0.9107 \text{ k}\Omega$$

EX12.15

$$V_{TH} = \left(\frac{5.5}{5.5+51}\right)(10) = 0.9735 \text{ V}$$

$$R_{TH} = 5.5 \,\|\, 51 = 4.965 \text{ k}\Omega$$

$$I_{BQ} = \frac{0.973-0.7}{4.96+(121)(1)} = 0.00217 \text{ mA}$$

$$I_{CQ} = 0.2605 \text{ mA}$$

$$r_\pi = 11.98 \text{ k}\Omega,\ g_m = 10.02 \text{ mA/V}$$

$$R_{eq} = R_S \,\|\, R_1 \,\|\, R_2 \,\|\, r_\pi = (10) \,\|\, 51 \,\|\, 5.5 \,\|\, 12 = 2.598 \text{ k}\Omega$$

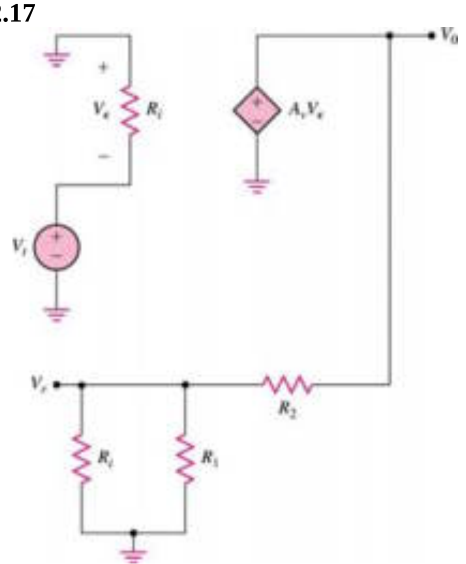
From Equation (12.99(b)):

$$T = (g_m R_C)\left(\frac{R_{eq}}{R_C + R_F + R_{eq}}\right)$$

$$= (10)(10)\left(\frac{2.598}{10+82+2.598}\right) \Rightarrow \underline{T = 2.75}$$

EX12.16 Computer Analysis

EX12.17



$$V_\varepsilon = -V_t,\ V_0 = A_v V_\varepsilon = -A_v V_t$$

$$V_r = \left(\frac{R_1 \,\|\, R_i}{R_1 \,\|\, R_i + R_2}\right)V_0 = -\left(\frac{R_1 \,\|\, R_i}{R_1 \,\|\, R_i + R_2}\right)(A_v V_t)$$

$$\underline{T = -\frac{V_r}{V_t} = A_v\left(\frac{R_1 \,\|\, R_i}{R_1 \,\|\, R_i + R_2}\right)}$$

or

$$\underline{T = \frac{A_v}{1 + \dfrac{R_2}{R_1 \| R_i}}}$$

EX12.18

$$\phi = -\tan^{-1}\left(\frac{f}{10^3}\right) - 2\tan^{-1}\left(\frac{f}{10^5}\right)$$

At $f_{180} \cong 10^5$ Hz, $\phi = -180°$

$$|T(f_{180})| = 1 = \frac{\beta(3000)}{\sqrt{1+\left(\frac{10^5}{10^3}\right)^2}\left[1+\left(\frac{10^5}{10^5}\right)^2\right]}$$

or

$$1 = \frac{\beta(3000)}{(100)(2)} \Rightarrow \beta = 0.0667$$

EX12.19

$$A_f(0) = \frac{3000}{1+\beta(3000)} = \frac{3000}{1+(0.008)(3000)} = 120$$

$$|T| = 1 = \frac{(0.008)(3000)}{\sqrt{1+\left(\frac{f}{10^3}\right)^2}\left[1+\left(\frac{f}{10^5}\right)^2\right]}$$

By trial and error,

$$f \cong 2.28\times10^4 \text{ Hz}$$

$$\phi = -\tan^{-1}\left(\frac{f}{10^3}\right) - 2\tan^{-1}\left(\frac{f}{10^5}\right)$$

$$= -\tan^{-1}\left(\frac{2.28\times10^4}{10^3}\right) - 2\tan^{-1}\left(\frac{2.28\times10^4}{10^5}\right) = -87.49 - 2(12.84) = -113.18$$

Then

Phase margin $= -113.18 - (-180) = 66.8°$

EX12.20

(a) $\phi = -180 = -\tan^{-1}\left(\frac{f_{180}}{10^3}\right) - 2\tan^{-1}\left(\frac{f_{180}}{10^5}\right)$

$$f_{180} \cong 10^5 \text{ Hz}$$

$$|T(f_{180})| = \frac{250}{\sqrt{1+\left(\frac{10^5}{10^3}\right)^2}\left[1+\left(\frac{10^5}{10^5}\right)^2\right]} = \frac{250}{(100)(2)} = 1.25$$

$|T| > 1$ at f_{180}

(b) $$T = \frac{250}{\left(1+j\frac{f}{f_{PD}}\right)\left(1+j\frac{f}{10^3}\right)\left(1+j\frac{f}{10^5}\right)^2}$$

$$\phi = -120 = -\tan^{-1}\left(\frac{f}{f_{PD}}\right) - \tan^{-1}\left(\frac{f}{10^3}\right) - 2\tan^{-1}\left(\frac{f}{10^5}\right)$$

Then

$$f \cong 0.577\times 10^3 \text{ Hz}$$

Now

$$|T| = 1 = \frac{250}{\sqrt{1+\left(\frac{0.577\times 10^3}{f_{PD}}\right)^2}\sqrt{1+\left(\frac{0.577\times 10^3}{10^3}\right)^2}(1)}$$

$$\left(\frac{0.577\times 10^3}{f_{PD}}\right) = \frac{250}{1.155}$$

which yields

$$f_{PD} = 2.67 \text{ Hz}$$

EX12.21

$$A_f(0) = \frac{10^5}{1+(0.025)(10^5)} = 40$$

$$f = (10)\left[1+(0.025)(10^5)\right] \cong 25 \text{ kHz}$$

EX12.22

$$\phi = -135 = -\tan^{-1}\left(\frac{f_{135}}{f_{PD}}\right) - 2\tan^{-1}\left(\frac{f_{135}}{10^5}\right) \Rightarrow f_{135} \cong 0.414\times 10^5 \text{ Hz}$$

$$|T(f_{135})| = 1 = \frac{250}{\sqrt{1+\left(\frac{0.414\times 10^5}{f_{PD}}\right)^2}\left[1+\left(\frac{0.414\times 10^5}{10^5}\right)^2\right]}$$

$$\frac{0.414\times 10^5}{f_{PD}} = \frac{250}{1.171} \Rightarrow f_{PD} = 194 \text{ Hz}$$

Test Your Understanding Solutions

TYU12.1

(a) $A_f = \dfrac{A}{1+A\beta}$

$$50 = \frac{A}{1+A(0.019)}$$

or

$$50 = A[1-(50)(0.019)] \Rightarrow A = 10^3$$

(b) $A_f = \dfrac{5\times10^5}{1+(5\times10^5)(0.019)} = 52.63$

TYU12.2

$$\frac{dA_f}{A_f} = \frac{1}{(1+\beta A)}\cdot\frac{dA}{A} = \left(\frac{A_f}{A}\right).\frac{dA}{A}$$

$$\frac{dA}{A} = \frac{dA_f}{A_f}\cdot\left(\frac{A}{A_f}\right) = (0.001)\left(\frac{5\times10^5}{100}\right) \Rightarrow \underline{\frac{dA}{A} = \pm5\%}$$

TYU12.3

(a) $(5\times10^5)(6) = (200\times10^3)A_f(0)$

$A_f(0) = 15$

(b) $(5\times10^5)(6) = (100\times10^3)A_f(0)$

$A_f(0) = 30$

TYU12.4

$$V_\varepsilon = V_S - V_{fb} = 100 - 99 = 1\text{ mV}$$

$$A_g = \frac{I_0}{V_\varepsilon} = \frac{5\text{ mA}}{1\text{ mV}} \Rightarrow \underline{A_g = 5\text{ A/V}}$$

$$\beta = \frac{V_{fb}}{I_0} = \frac{99\text{ mV}}{5\text{ mA}} \Rightarrow \underline{\beta = 19.8\text{ V/A}}$$

$$A_{gf} = \frac{A_g}{1+\beta A_g} = \frac{5}{1+(19.8)(5)} \Rightarrow \underline{A_{gf} = 0.05\text{ A/V} = 50\text{ mA/V}}$$

TYU12.5

$$I_\varepsilon = I_S - I_{fb} = 100 - 99 = 1\ \mu\text{A}$$

$$A_z = \frac{V_0}{I_\varepsilon} = \frac{5\text{ V}}{1\ \mu\text{A}} \Rightarrow \underline{A_z = 5\times10^6\text{ V/A}}$$

$$\beta = \frac{I_{fb}}{V_0} = \frac{99\ \mu\text{A}}{5\text{ V}} \Rightarrow \underline{\beta = 1.98\times10^{-5}\text{ A/V}}$$

$$A_{zf} = \frac{A_z}{1+\beta A_z} = \frac{5\times10^6}{1+(1.98\times10^{-5})(5\times10^6)} \Rightarrow \underline{A_{zf} = 5\times10^4\text{ V/A} = 50\text{ V/mA}}$$

TYU12.6

(a) $r_\pi = \dfrac{h_{FE}V_T}{I_{CQ}} = \dfrac{(120)(0.026)}{1.2} = 2.6 \text{ k}\Omega$

$$A_{\upsilon f} = \frac{\left(\frac{1}{r_\pi} + g_m\right)R_E}{1 + \left(\frac{1}{r_\pi} + g_m\right)R_E} = \frac{(1+h_{FE})R_E}{r_\pi + (1+h_{FE})R_E} = \frac{(121)(1.5)}{2.6 + (121)(1.5)} = 0.985877$$

$$R_{if} = r_\pi + (1+h_{FE})R_E = 2.6 + (121)(1.5) = 184.1 \text{ k}\Omega$$

$$R_{of} = \frac{R_E}{1 + \left(\frac{1}{r_\pi} + g_m\right)R_E} = \frac{(R_E)(r_\pi)}{r_\pi + (1+h_{FE})R_E} = \frac{(1.5)(2.6)}{2.6 + (121)(1.5)} \Rightarrow R_{of} = 21.18\Omega$$

(b) $r_\pi = \dfrac{(180)(0.026)}{1.2} = 3.9 \text{ k}\Omega$

$$A_{\upsilon f} = \frac{(181)(1.5)}{3.9 + (181)(1.5)} = 0.985839$$

$$\frac{\Delta A_{\upsilon f}}{A_{\upsilon f}} \times 100\% = -0.00385\%$$

$$R_{if} = 3.9 + (181)(1.5) = 275.4 \text{ k}\Omega$$

$$\frac{\Delta R_{if}}{R_{if}} \times 100\% = +49.6\%$$

$$R_{of} = \frac{(1.5)(3.9)}{3.9 + (181)(1.5)} \Rightarrow R_{of} = 21.24\Omega$$

$$\frac{\Delta R_{of}}{R_{of}} \times 100\% = +0.283\%$$

TYU12.7

(a) $A_{\upsilon f} = \dfrac{g_m R_S}{1 + g_m R_S}, \qquad g_m = 2\sqrt{K_n I_{DQ}} = 2\sqrt{(0.5)(0.25)} = 0.7071 \text{ mA/V}$

$$A_{\upsilon f} = \frac{(0.7071)(3)}{1 + (0.7071)(3)} = 0.67962$$

$$R_{of} = \frac{R_S}{1 + g_m R_S} = \frac{3}{1 + (0.7071)(3)} = 0.96114 \text{ k}\Omega$$

(b) $g_m = 2\sqrt{(0.5)(1)} = 1.414 \text{ mA/V}$

$$A_{\upsilon f} = \frac{(1.414)(3)}{1 + (1.414)(3)} = 0.80923$$

$$\frac{\Delta A_{\upsilon f}}{A_{\upsilon f}} \times 100\% = +19.1\%$$

$$R_{of} = \frac{3}{1 + (1.414)(3)} = 0.5723 \text{ k}\Omega$$

$$\frac{\Delta R_{of}}{R_{of}} \times 100\% = -40.5\%$$

TYU12.8 Computer Analysis

TYU12.9 Computer Analysis

TYU12.10

(a) (i) $A_{gf} = \dfrac{(h_{FE}A_g)}{1+(h_{FE}A_g)R_E} = \dfrac{(180)(10^2)}{1+(180)(10^2)(1)} = 0.9999444 \text{ mA/V}$

$I_o = A_{gf} \cdot V_i = (0.9999444)(1.5) = 1.4999166 \text{ mA}$

(ii) $V_\in = V_i - I_o R_E = 1.5 - (1.4999166)(1) \Rightarrow V_\in = 83.4\,\mu \text{ V}$

(b) (i) $A_{gf} = \dfrac{(144)(10^2)}{1+(144)(10^2)(1)} = 0.9999306 \text{ mA/V}$

$I_o = A_{gf} \cdot V_i = (0.9999306)(1.5) = 1.4998959 \text{ mA}$

$$\frac{\Delta A_{gf}}{A_{gf}} \times 100\% = \frac{0.9999306 - 0.9999444}{0.9999444} \times 100\% = -0.00138\%$$

$$\frac{\Delta I_o}{I_o} \times 100\% = \frac{1.4998959 - 1.4999166}{1.4999166} \times 100\% = -0.00138\%$$

(ii) $V_\in = 1.5 - (1.4998959)(1) \Rightarrow V_\in = 104\,\mu \text{ V}$

TYU12.11

(a) $R_{TH} = R_1 \| R_2 = 51 \| 5.5 = 4.965 \text{ k}\Omega$

$$V_{TH} = \left(\frac{5.5}{5.5+51}\right)(10) = 0.9735 \text{ V}$$

$$I_{BQ} = \frac{0.9735 - 0.7}{4.965 + (181)(0.5)} = 0.002865 \text{ mA}$$

$I_{CQ} = 0.5157 \text{ mA}$

Then

$$g_m = \frac{0.5157}{0.026} = 19.83 \text{ mA/V}, \quad r_\pi = \frac{(180)(0.026)}{0.5157} = 9.075 \text{ k}\Omega$$

(i) $V_o = -g_m V_\pi R_C$

$$V_\pi = \left(\frac{R_1 \| R_2 \| r_\pi}{R_1 \| R_2 \| r_\pi + R_S}\right) \cdot V_i = \left[\frac{4.965 \| 9.075}{(4.965 \| 9.075) + 10}\right] \cdot V_i = 0.243 V_i$$

$$A_\upsilon = \frac{V_o}{V_i} = -(0.243)(19.83)(10) = -48.187$$

(ii) (1) $\dfrac{V_o}{R_C} + g_m V_\pi + \dfrac{V_o - V_\pi}{R_F} = 0$

(2) $\dfrac{V_\pi - V_i}{R_S} + \dfrac{V_\pi}{R_{TH} \| r_\pi} + \dfrac{V_\pi - V_o}{R_F} = 0$

$$V_\pi \left(\frac{1}{R_S} + \frac{1}{R_{TH} \| r_\pi} + \frac{1}{R_F}\right) = \frac{V_o}{R_F} + \frac{V_i}{R_S}$$

$$V_\pi\left(\frac{1}{10}+\frac{1}{4.965\|9.075}+\frac{1}{60}\right)=\frac{V_o}{60}+\frac{V_i}{10}$$
$$V_\pi=V_o(0.038913)+V_i(0.233487)$$

Now

(1) $$V_o\left(\frac{1}{R_C}+\frac{1}{R_F}\right)+V_\pi\left(g_m-\frac{1}{R_F}\right)=0$$
$$V_o\left(\frac{1}{10}+\frac{1}{60}\right)+\left(19.83-\frac{1}{60}\right)\left[V_o(0.038913)+V_i(0.233487)\right]=0$$
$$V_o(0.887662)+V_i(4.62616)=0$$

Then
$$A_\upsilon=\frac{V_o}{V_i}=-5.2116$$

(b) (i) $$I_{BQ}=\frac{0.9735-0.7}{4.965+(121)(0.5)}=0.004178\ \text{mA}$$
$$I_{CQ}=0.5013\ \text{mA}$$
$$g_m=\frac{0.5013}{0.026}=19.28\ \text{mA/V}\ ,\quad r_\pi=6.224\ \text{k}\Omega$$
$$R_{TH}\|r_\pi=4.965\|6.224=2.7618\ \text{k}\Omega$$
$$V_\pi=\left(\frac{2.7618}{2.7618+10}\right)\cdot V_i=0.2164V_i$$
$$A_\upsilon=-g_mV_\pi R_C=-(19.28)(0.2164)(10)=-41.722$$

(ii) $$V_\pi\left(\frac{1}{10}+\frac{1}{2.7618}+\frac{1}{60}\right)=\frac{V_o}{60}+\frac{V_i}{10}$$
$$V_\pi=V_o(0.034811)+V_i(0.208877)$$

Then
$$V_o(0.116667)+(19.26334)\left[V_o(0.034811)+V_i(0.208877)\right]=0$$
$$V_o(0.787242)+V_i(4.023669)=0$$

Then
$$A_\upsilon=\frac{V_o}{V_i}=-5.1111$$

(c) (i) $$\frac{41.722-48.187}{48.187}\times100\%=-13.4\%$$

(ii) $$\frac{5.1111-5.2116}{5.2116}\times100\%=-1.93\%$$

TYU12.12

(a) $I_{CQ}=0.5157\ \text{mA},\ g_m=19.83\ \text{mA/V},\ r_\pi=9.075\ \text{k}\Omega$

(i) $R_o=R_C=10\ \text{k}\Omega$

(ii) $R_S\|R_{TH}\|r_\pi=10\|4.965\|9.075=2.43\ \text{k}\Omega$

$$I_x=\frac{V_x}{R_C}+g_mV_\pi+\frac{V_x}{R_F+2.43}$$
$$V_\pi=\left(\frac{2.43}{2.43+60}\right)\cdot V_x=(0.03892)V_x$$

$$\frac{I_x}{V_x} = \frac{1}{R_{of}} = \frac{1}{10} + (19.83)(0.03892) + \frac{1}{62.43}$$

or

$$R_{of} = 1.126 \text{ k}\Omega$$

(b) $I_{CQ} = 0.5013$ mA, $g_m = 19.28$ mA/V, $r_\pi = 6.224$ kΩ

$$R_S \| R_{TH} \| r_\pi = 10 \| 4.965 \| 6.224 = 2.164 \text{ k}\Omega$$

(i) $R_o = 10$ kΩ

(ii) $$\frac{I_x}{V_x} = \frac{1}{10} + (19.28)\left(\frac{2.164}{2.164+60}\right) + \frac{1}{62.164} = \frac{1}{R_{of}}$$

or

$$R_{of} = 1.270 \text{ k}\Omega$$

TYU12.13

From Example 12.15, for $h_{FE} = 100$, $T = 4.10$.

Now for $h_{FE} = 150$,

$$R_{TH} = 4.965 \text{ k}\Omega, \quad V_{TH} = 0.9735 \text{ V}$$

$$I_{BQ} = \frac{0.9735 - 0.7}{4.965 + (151)(0.5)} = 0.003399 \text{ mA}$$

$$I_{CQ} = 0.5098 \text{ mA}, \quad g_m = 19.61 \text{ mA/V}, \quad r_\pi = 7.650 \text{ k}\Omega$$

$$R_{eq} = R_S \| R_{TH} \| r_\pi = 10 \| 4.965 \| 7.65 = 2.314 \text{ k}\Omega$$

We find

$$T = (g_m R_C)\left(\frac{R_{eq}}{R_{eq} + R_F + R_C}\right) = (19.61)(10)\left(\frac{2.314}{2.314 + 82 + 10}\right)$$

or

$$T = 4.811$$

$$\text{Percent change} = \frac{4.811 - 4.10}{4.10} \times 100\% = +17.3\%$$

TYU12.14

$$V_t = -V_\epsilon, \quad V_o = -A_\upsilon V_t$$

$$V_r = \left(\frac{R_1 \| R_i}{R_1 \| R_i + R_2}\right) \cdot V_o$$

$$T = -\frac{V_r}{V_t} = A_\upsilon \cdot \frac{1}{1 + \dfrac{R_2}{R_1 \| R_i}} = (10^4) \cdot \frac{1}{1 + \dfrac{20}{5 \| 50}} = 1.85 \times 10^3$$

TYU12.15

$$-135 = -\tan^{-1}\left(\frac{f_{135}}{10^3}\right) - 2\tan^{-1}\left(\frac{f_{135}}{10^5}\right)$$

$$f_{135} \cong 4.25\times10^4 \text{ Hz}$$

$$|T(f_{135})| = 1 = \frac{\beta(3000)}{\sqrt{1+\left(\frac{f_{135}}{10^3}\right)^2}\left[1+\left(\frac{f_{135}}{10^5}\right)^2\right]}$$

$$1 = \frac{\beta(3000)}{\sqrt{1+\left(\frac{4.25\times10^4}{10^3}\right)^2}\left[1+\left(\frac{4.25\times10^4}{10^5}\right)^2\right]} = \frac{\beta(3000)}{(42.51)(1.1806)}$$

Then

$$\beta = 0.0167$$

TYU12.16

$$T = A_i\beta = \frac{A_{i0}\beta}{\left(1+j\cdot\frac{f}{f_1}\right)\left(1+j\cdot\frac{f}{f_2}\right)}$$

Phase

$$= -\left[\tan^{-1}\left(\frac{f}{f_1}\right)+\tan^{-1}\left(\frac{f}{f_2}\right)\right]$$

Phase Margin $= 60° \Rightarrow \text{Phase} = -120°$

$$-120° = -\left[\tan^{-1}\left(\frac{f}{10^4}\right)+\tan^{-1}\left(\frac{f}{10^5}\right)\right]$$

At $f' = 7.66\times10^4$ Hz,

$$\text{Phase} = -\left[\tan^{-1}(7.66)+\tan^{-1}(0.766)\right]$$

$$= -[82.56+37.45]$$

$$= -120°$$

$$|T(f')| = \quad 1 = \frac{(10^5)\beta}{\sqrt{1+(7.66)^2}\times\sqrt{1+(0.766)^2}}$$

$$1 = \frac{(10^5)\beta}{(7.725)(1.26)} \Rightarrow \underline{\beta = 9.73\times10^{-5}}$$

TYU12.17

Phase Margin $= 60° \Rightarrow \text{Phase} = -120°$

Phase $= -120° = -3\tan^{-1}\left(\frac{f'}{10^5}\right)$

$$\tan^{-1}\left(\frac{f'}{10^5}\right) = 40° \Rightarrow f' = 0.839\times10^5 \text{ Hz}$$

$$\left|T(f')\right| = 1 = \frac{\beta(100)}{\left[\sqrt{1+\left(\frac{f'}{10^5}\right)^2}\right]^3}$$

$$= \frac{\beta(100)}{\left[\sqrt{1+(0.839)^2}\right]^3} \Rightarrow \underline{\beta = 0.0222}$$

Chapter 13

Exercise Solutions

EX13.1

$$I_{REF} = \frac{5 - 0.6 - 0.6 - (-5)}{25} = 0.352 \text{ mA}$$

$$I_{C10}(5) = (0.026)\ln\left(\frac{0.352}{I_{C10}}\right)$$

By trial and error

$$I_{C10} \cong 16\,\mu\text{A}$$

Then

$$I_{C1} = I_{C2} = \frac{I_{C10}}{2} = 8\,\mu\text{A}$$

EX13.2

$$I_{REF} = \frac{5 - 0.6 - 0.6 - (-5)}{40} = 0.22 \text{ mA}$$

$$I_{C17} = I_{C13B} = 0.75 I_{REF} = (0.75)(0.22) = 0.165 \text{ mA}$$

$$I_{C16} = \frac{0.165}{200} + \frac{(0.165)(0.1) + 0.6}{50}$$

$$= 0.000825 + 0.01233$$

$$I_{C16} = 13.2\ \mu\text{A}$$

EX13.3

$$I_{C13A} = (0.25)(0.5) = 0.125 \text{ mA}$$

$$I_{R10} = \frac{0.6}{50} = 0.012 \text{ mA}$$

$$I_{C19} \cong I_{C13A} - I_{R10} = 0.125 - 0.012 = 0.113 \text{ mA}$$

$$I_{B19} = \frac{I_{C19}}{\beta} = \frac{0.113}{200} \Rightarrow 0.565\,\mu\text{A}$$

$$I_{C18} = I_{R10} + I_{B19} = 12 + 0.565 = 12.565\,\mu\text{A}$$

$$V_{BE19} = (0.026)\ln\left(\frac{0.113 \times 10^{-3}}{10^{-14}}\right) = 0.60185 \text{ V}$$

$$V_{BE18} = (0.026)\ln\left(\frac{12.565 \times 10^{-6}}{10^{-14}}\right) = 0.54474 \text{ V}$$

$$V_{BB} = 0.60185 + 0.54474 = 1.1466 \text{ V}$$

$$I_{C14} = (3 \times 10^{-14})\exp\left(\frac{1.1466/2}{0.026}\right) \Rightarrow 0.113 \text{ mA}$$

EX13.4

$$r_{o6} = \frac{100}{0.0095} \Rightarrow 10.5\ \text{M}\Omega$$

Then, using results from Example 13.4

$$R_{act1} = r_{o6}\left[1 + g_{m6}(R_2 \,\|\, r_{\pi 6})\right] = 10.5\left[1 + (0.365)(1 \,\|\, 547)\right]$$
$$= 14.3\ \text{M}\Omega$$

$$r_{o4} = \frac{V_A}{I_{C4}} = \frac{100}{0.0095} \Rightarrow 10.5\ \text{M}\Omega$$

$$A_d = -\left(\frac{9.5}{0.026}\right)\left(10.5 \,\|\, 14.3 \,\|\, 4.07\right) = -889$$

EX13.5

$$R_{19} = r_{o13A} = \frac{100}{0.18} = 556\ \text{K}$$

$$R_{i3} = r_{\pi 22} + (1 + \beta_P)[R_{19} \,\|\, R_{20}]$$
$$= 7.22 + (51)(556 \,\|\, 111) \Rightarrow 4.73\ \text{M}\Omega$$

$$R_{act2} = \frac{100}{0.54} = 185\ \text{K}$$

$$R_{o17} = \frac{100}{0.54} = 185\ \text{K}$$

$$A_{v2} = \frac{-(200)(201)(50)(185 \,\|\, 4730 \,\|\, 185)}{4070[50 + [9.63 + (201)(0.1)]]}$$
$$= \frac{-182358786.9}{32450.1}$$
$$A_{v2} = -562$$

EX13.6

$$r_{o17} = \frac{100}{0.54} = 185\ \text{K} \quad r_{o13B} = \frac{100}{0.54} = 185\ \text{K}$$

$$R_{C17} = 185\left[1 + (20.8)(0.1 \,\|\, 9.63)\right]$$

$$R_{C17} = 566\ \text{K}$$

$$R_{e22} = \frac{7.22 + 566 \,\|\, 185}{51} = 2.88\ \text{K}$$

$$R_{C19} = \frac{100}{0.18} = 556\ \text{K}$$

$$R_{e20} = \frac{0.65 + 2.88 \,\|\, 556}{51} = 0.0689$$
$$= 68.9\ \Omega$$

$$R_O = 22 + 68.9 = \underline{90.9\ \Omega}$$

EX13.7

$$C_i = C_1(1+|A_2|) = 30(1+562) = 16890 \text{ pF}$$
$$R_{i2} = 4.07 \text{ M}\Omega$$
$$R_{o1} = R_{act1} \| r_{o4} = 14.3 \| 10.5 = 6.05 \text{ M}\Omega$$

Then $R_{eq} = R_{o1} \| R_{i2} = 6.05 \| 4.07 = 2.43 \text{ M}\Omega$

Then

$$f_{PD} = \frac{1}{2\pi R_{eq} C_i} = \frac{1}{2\pi(2.43\times 10^6)(16890\times 10^{-12})}$$
$$= 3.88 \text{ Hz}$$

EX13.8

$$K_{p5} = \left(\frac{k_p'}{2}\right)\left(\frac{W}{L}\right)_5 = \left(\frac{0.04}{2}\right)(20) = 0.40 \text{ mA/V}^2$$
$$K_{p5}(V_{SG5} + V_{TP})^2 = \frac{5 - V_{SG5} - (-5)}{150}$$
$$60(V_{SG5}^2 - V_{SG5} + 0.25) = 10 - V_{SG5}$$
$$60V_{SG5}^2 - 59V_{SG5} + 5 = 0 \Rightarrow V_{SG5} = 0.8897 \text{ V}$$
$$I_{REF} = I_Q = \frac{10 - 0.8897}{150} \Rightarrow 60.74\,\mu\text{A}$$
$$I_{D7} = I_{D8} = 60.74\,\mu\text{A}$$
$$I_{D1} = I_{D2} = I_{D3} = I_{D4} = 30.37\,\mu\text{A}$$

EX13.9

$$K_{p1} = K_{p2} = \left(\frac{0.04}{2}\right)(20) = 0.40 \text{ mA/V}^2$$
$$r_{o2} = r_{o4} = \frac{1}{\lambda I_{D2}} = \frac{1}{(0.02)(0.03037)} \Rightarrow 1.646 \text{ M}\Omega$$
$$A_d = \sqrt{2K_{p1}I_Q}\,(r_{o2}\|r_{o4}) = \sqrt{2(0.40)(0.06074)}\,(1646\|1646)$$

or

$$A_d = 181.4$$

Now

$$g_{m7} = 2\sqrt{\left(\frac{k_n'}{2}\right)\left(\frac{W}{L}\right)_7 I_{D7}} = 2\sqrt{\left(\frac{0.1}{2}\right)(20)(0.06074)} = 0.4929 \text{ mA/V}$$
$$r_{o7} = r_{o8} = \frac{1}{\lambda I_{D7}} = \frac{1}{(0.02)(0.06074)} = 823.2 \text{ k}\Omega$$
$$A_{\upsilon 2} = g_{m7}(r_{o7}\|r_{o8}) = (0.4929)(823.2\|823.2)$$

or

$$A_{\upsilon 2} = 202.9$$

Then

$$A_\upsilon = A_d A_{\upsilon 2} = (181.4)(202.9) = 36{,}806 \Rightarrow 91.3 \text{ dB}$$

EX13.10

(a) $g_{m1} = 2\sqrt{\left(\frac{k_n'}{2}\right)\left(\frac{W}{L}\right)_1\left(\frac{I_{Q1}}{2}\right)} = 2\sqrt{\left(\frac{0.08}{2}\right)(22.5)\left(\frac{0.2}{2}\right)} = 0.60 \text{ mA/V}$

$$r_{o2} = \frac{1}{(0.01)(0.1)} = 1000 \text{ k}\Omega$$

$$r_{o4} = \frac{1}{(0.015)(0.1)} = 666.7 \text{ k}\Omega$$

$$A_{d1} = g_{m1}(r_{o2}\|r_{o4}) = (0.6)(1000\|666.7) = 240$$

$$g_{m5} = 2\sqrt{\left(\frac{k_p'}{2}\right)\left(\frac{W}{L}\right)_5 I_{D5}} = 2\sqrt{\left(\frac{0.04}{2}\right)(80)(0.2)} = 1.131 \text{ mA/V}$$

$$r_{o5} = \frac{1}{(0.015)(0.2)} = 333.3 \text{ k}\Omega$$

$$r_{o9} = \frac{1}{(0.01)(0.2)} = 500 \text{ k}\Omega$$

$$A_2 = -g_{m5}(r_{o5}\|r_{o9}) = -(1.131)(333.3\|500) = -226.2$$

Then

$$A_\upsilon = A_{d1}A_2 = (240)(-226.2) = -54{,}288$$

(b)

$$K_{n6} = \left(\frac{k_n'}{2}\right)\left(\frac{W}{L}\right)_6 = \left(\frac{0.08}{2}\right)(25) = 1.0 \text{ mA/V}^2$$

$$I_{D6} = K_{n6}(V_{GS6} - V_{TN})^2$$

$$0.04 = (1)(V_{GS6} - 0.7)^2 \Rightarrow V_{GS6} = 0.90 \text{ V} = V_{SG7}$$

Then

$$V_{GS8} = 2(0.9) = 1.8 \text{ V}$$

$$I_{D8} = 0.2 = \left(\frac{0.08}{2}\right)\left(\frac{W}{L}\right)_8 (1.8 - 0.7)^2 \Rightarrow \left(\frac{W}{L}\right)_8 = 4.13$$

EX13.11

$$I_{D1} = I_{D2} = 25\ \mu A$$

$$g_{m1} = g_{m8} = 2\sqrt{\frac{k_p'}{2}\left(\frac{W}{L}\right)I_{DQ}} = 2\sqrt{\left(\frac{40}{2}\right)(25)(25)} \Rightarrow g_{m1} = g_{m8} = 224\ \mu A/V$$

$$g_{m6} = 2\sqrt{\left(\frac{k_n'}{2}\right)\left(\frac{W}{L}\right)I_{DQ}} = 2\sqrt{\left(\frac{80}{2}\right)(25)(25)} \Rightarrow g_{m6} = 316\ \mu A/V$$

$$r_{o1} = r_{o6} = r_{o8} = r_{o10} = \frac{1}{\lambda I_D} = \frac{1}{(0.02)(25)} = 2\ M\Omega$$

$$r_{o4} = \frac{1}{\lambda I_{D4}} = \frac{1}{(0.02)(50)} = 1\ M\Omega$$

$$R_{o8} = g_{m8}(r_{o8}r_{o10}) = (224)(2)(2) = 896\ M\Omega$$

$$R_{o6} = g_{m6}(r_{o6})(r_{o4} \| r_{o1}) = 316(2)(1\|2) = 421\ M\Omega$$

Then

$$A_d = g_{m1}(R_{o6}\|R_{o8}) = 224(421\|896) \Rightarrow \underline{A_d = 64{,}158}$$

EX13.12

(a) $K_p\left(V_{SG}-|V_{TP}|\right)^2=\dfrac{V_{SG}-V_{BE}}{R_1}$

$$(0.15)(V_{SG}-0.8)^2=\frac{V_{SG}-0.6}{10}$$

We obtain

$$1.5V_{SG}^2-3.4V_{SG}+1.56=0\Rightarrow V_{SG}=1.628\ \text{V}$$

Now

$$I_1=I_2=\frac{1.628-0.6}{10}=0.1028\ \text{mA}$$

$$V_{C7}=V^+-V_{EB}-V_{BE}=5-0.6-0.6=3.8\ \text{V}$$

$$V_{C6}=V^-+V_{SG}=-5+1.628=-3.372\ \text{V}$$

$$V_{CB7}=V_{BC6}=V_{C7}-V_{C6}=3.8-(-3.37)=7.17\ \text{V}$$

(b)

Set $V_{CB7}=V_{BC6}=0\Rightarrow V_{C7}=V_{C6}$

$V^+-1.2=V^-+1.628$, Let $V^-=-V^+$

$2V^+=2.828$, So that $V^+=-V^-=1.414\ \text{V}$

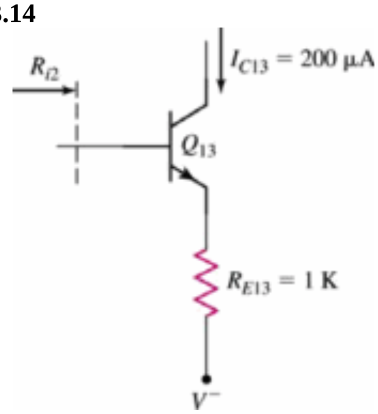
EX13.13

$$A_d=\sqrt{2K_PI_{Q5}}(R_{i2})$$

$$=\sqrt{2(1)(0.2)}(26)$$

$$\underline{A_d=16.4}$$

EX13.14



$$r_{\pi 13} = \frac{\beta V_T}{I_{C13}} = \frac{(200)(0.026)}{0.20}$$
$$= 26 \text{ k}\Omega$$
$$R_{i2} = r_{\pi 13} + (1+\beta)R_{E13} = 26 + 201(1)$$
$$= 227 \text{ k}\Omega$$
$$r_{010} = \frac{1}{\lambda I_{D10}} = \frac{1}{(0.02)(0.1)} = 500 \text{ k}\Omega$$
$$r_{012} = \frac{V_A}{I_{C12}} = \frac{50}{0.1} = 500 \text{ k}\Omega$$
$$g_{m12} = \frac{I_{C12}}{V_T} = \frac{0.1}{0.026} = 3.85 \text{ mA/V}$$
$$r_{\pi 12} = \frac{\beta V_T}{I_{C12}} = \frac{(200)(0.026)}{0.1} = 52 \text{ k}\Omega$$
$$R_{act1} = r_{012}[1 + g_{m12}(r_{\pi 12} \| R_5)]$$
$$= 500[1 + (3.85)(52 \| 0.5)] = 1453 \text{ k}\Omega$$
$$A_d = \sqrt{2K_n I_{Q5}} \cdot \left(r_{o10} \| R_{act1} \| R_{12}\right)$$
$$= \sqrt{2(0.6)(0.2)} \cdot (500 \| 1453 \| 227)$$
$$= (0.490)(141) \Rightarrow \underline{A_d = 69.1}$$

EX13.15

From Example 13.15, $f_{PD} = 265 \text{ Hz}$

$$A_v = A_{di} \cdot A_2 = (16.4)(1923) = 31{,}537$$
$$f_T = f_{PD} \cdot A_v = (265)(31{,}537) = \underline{8.36 \text{ MHz}}$$

Test Your Understanding Solutions

TYU13.1 Computer Analysis

TYU13.2 Computer Analysis

TYU13.3

$$I_{B1} = I_{B2} = \frac{9.5}{200}\mu\text{A} \quad I_{B1} = I_{B2} = 47.5 \text{ nA}$$

TYU13.4

$$V_{iN}(\max) = V^+ - V_{EB}(\text{on}) = 15 - 0.6 = 14.4 \text{ V}$$
$$V_{iN}(\min) \cong 4V_{BE}(\text{on}) + V^+$$
$$= 4(0.6) - 15 = -12.6 \text{ V}$$
$$\underline{-12.6 \le V_{iN}(\text{cm}) \le 14.4 \text{ V}}$$

TYU13.5

a. $V_0(\max) \cong V^+ - 2V_{BE}(\text{on}) = 15 - 2(0.6)$

$V_0(\max) \quad = 13.8 \text{ V}$

$V_0(\min) \quad = 3V_{BE}(\text{on}) + V^- = 3(0.6) - 15$

$V_0(\min) \quad \cong -13.2 \text{ V}$

$\underline{-13.2 \le V_0 \le 13.8 \text{ V}}$

b. $V_0(\max) = 5 - 1.2 = 3.8 \text{ V}$

$V_0(\min) \quad \cong 3V_{BE} + V^- = 3(0.6) - 5 = -3.2 \text{ V}$

$\underline{-3.2 \le V_0 \le 3.8 \text{ V}}$

TYU13.6

$$I_{REF} = \frac{5 - V_{EB12} - V_{BE11} - (-5)}{40}$$

$$V_{EB12} = V_{BE11} = (0.026)\ln\left(\frac{I_{REF}}{5 \times 10^{15}}\right)$$

Then by trial and error, $I_{REF} \cong 0.218$ mA, and $V_{BE11} = V_{EB12} \cong 0.637$ V

$$I_{C10}(5) = (0.026)\ln\left(\frac{0.218}{I_{C10}}\right)$$

By trial and error, $I_{C10} \cong 14.2\,\mu$ A

$$V_{BE10} = V_{BE11} - I_{C10}R_4 = 0.637 - (0.0142)(5) = 0.566 \text{ V}$$

$$I_{C6} = \frac{I_{C10}}{2} = 7.1\,\mu\text{ A}$$

$$V_{BE6} = (0.026)\ln\left(\frac{7.1 \times 10^{-6}}{5 \times 10^{-15}}\right) = 0.548 \text{ V}$$

TYU13.7

$$I_{REF} = \frac{10 - 0.6 - 0.6 - (-10)}{40} \Rightarrow \underline{I_{REF} = 0.47 \text{ mA}}$$

$$I_{C10}R_4 = V_T \ln\left(\frac{I_{REF}}{I_{C10}}\right)$$

$$I_{C10}(5) = (0.026)\ln\left(\frac{0.47}{I_{C10}}\right)$$

By trial and error:

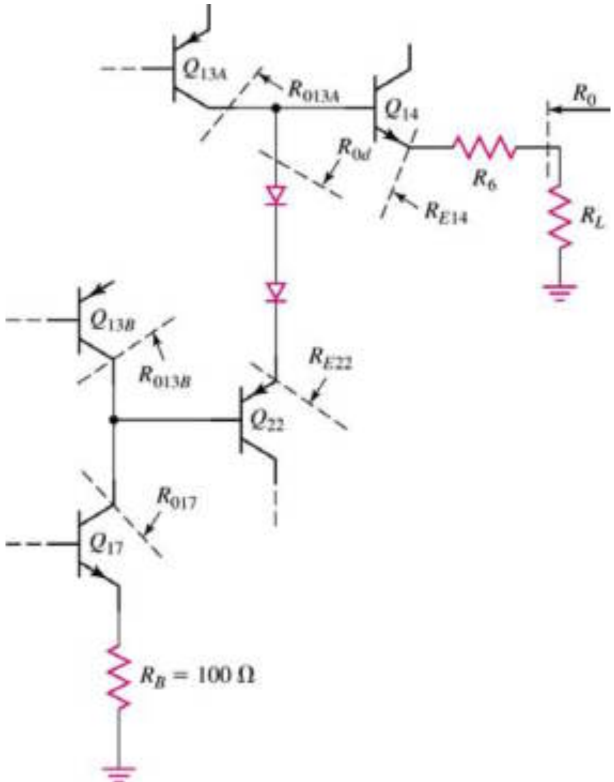
$\Rightarrow \underline{I_{C10} \cong 17.2\ \mu\text{A}}$

$I_{C6} \cong \dfrac{I_{C10}}{2} \Rightarrow \underline{I_{C6} = 8.6\ \mu\text{A}}$

$I_{C13B} = (0.75)I_{REF} \Rightarrow \underline{I_{C13B} = 0.353 \text{ mA}}$

$I_{C13A} = (0.25)I_{REF} \Rightarrow \underline{I_{C13A} = 0.118 \text{ mA}}$

TYU13.8



$$R_0 = R_6 + R_{E14}$$

$$R_{E14} = \frac{r_{\pi 14} + R_{0d} \| R_{013A}}{1+\beta_n}$$

The diode resistance can be found as

$$I_D = I_S \exp\left(\frac{V_D}{V_T}\right)$$

$$\frac{1}{r_d} = \frac{\partial I_D}{\partial V_D} = I_S\left(\frac{1}{V_T}\right)\cdot \exp\left(\frac{V_D}{V_T}\right) = \frac{I_D}{V_T}$$

or

$$r_d = \frac{V_T}{I_D} = \frac{V_T}{I_{C13A}} = \frac{0.026}{0.18} \Rightarrow 144\ \Omega$$

$$R_{E22} = \frac{r_{\pi 22} + R_{017} \| R_{013B}}{1+\beta_P}$$

$$R_{013B} = r_{013B} = 92.6\ \text{k}\Omega$$

$$R_{017} = r_{017}\left[1+g_{m17}(R_8 \| r_{\pi 17})\right] = 283\ \text{k}\Omega$$

From previous calculations

$$R_{E22} = 1.51\ \text{k}\Omega$$

$$R_{0d} = 2r_d + R_{E22} = 2(0.144)+1.51 = 1.80\ \text{k}\Omega$$

$$R_{013A} = r_{013A} = 278\ \text{k}\Omega$$

$$r_{\pi 14} = \frac{\beta_n V_T}{I_{C14}} = \frac{(200)(0.026)}{5} = 1.04\ \text{k}\Omega$$

$$R_{E14} = \frac{1.04 + 1.8 \| 278}{201} \Rightarrow 14.1\ \Omega$$

$$R_0 = R_6 + R_{E14} = 27 + 14.1 \Rightarrow R_0 \cong 41\ \Omega$$

TYU13.9

$$I_{D1} = 20.2 = \left(\frac{40}{2}\right)(12.5)(V_{SG1} + V_{TP})^2 = 250(V_{SG1} - 0.5)^2 \Rightarrow V_{SG1} = 0.7843\text{ V}$$

$$V_{SG5} = 0.9022\text{ V}, \ \Rightarrow V_{SD6}(sat) = 0.9022 - 0.5 = 0.4022\text{ V}$$

Then

$$\upsilon_{CM}(+) = 5 - 0.7843 - 0.4022 = 3.81\text{ V}$$

$$I_{D3} = 20.2 = \left(\frac{100}{2}\right)(6.25)(V_{GS3} - 0.5)^2 \Rightarrow V_{GS3} = 0.7542\text{ V}$$

$$V_{SD1}(sat) = 0.7843 - 0.5 = 0.2843\text{ V}$$

Now

$$\upsilon_{CM}(-) = V^- + V_{GS3} + V_{SD1}(sat) - V_{SG1} = -5 + 0.7542 + 0.2843 - 0.7843 = -4.75\text{ V}$$

Then $\quad -4.75 \le \upsilon_{CM} \le 3.81\text{ V}$

TYU13.10

$$V_{SG8} = V_{SG5} = 0.9022\text{ V}$$

$$V_{SD8}(sat) = 0.9022 - 0.5 = 0.4022\text{ V}$$

$$\upsilon_O(\max) = 5 - 0.4022 = 4.6\text{ V}$$

$$I_{D7} = \left(\frac{k_n'}{2}\right)\left(\frac{W}{L}\right)_7 (V_{GS7} - V_{TN})^2$$

$$40.4 = \left(\frac{100}{2}\right)(12.5)(V_{GS7} - 0.5)^2 \Rightarrow V_{GS7} = 0.7542\text{ V}$$

$$V_{DS7}(sat) = 0.7542 - 0.5 = 0.2542\text{ V}$$

$$\upsilon_O(\min) = -5 + 0.2542 = -4.75\text{ V}$$

Then $\quad -4.75 \le \upsilon_O \le 4.6\text{ V}$

TYU13.11

(a) $0.25(V_{SG5} - 0.5)^2 = \dfrac{10 - V_{SG5}}{100}$

$$25V_{SG5}^2 - 24V_{SG5} - 3.75 = 0 \Rightarrow V_{SG5} = 1.097\text{ V}$$

$$I_{set} = I_Q = \frac{10 - 1.097}{100} \Rightarrow 89.03\,\mu\text{A} = I_{D7} = I_{D8}$$

Then $\ I_{D1} - I_{D4} = 44.52\,\mu\text{A}$

(b) $K_{p1} = K_{p2} = 0.25\text{ mA/V}^2$

$$r_{o2} = r_{o4} = \frac{1}{(0.02)(0.04452)} = 1123\text{ k}\Omega$$

$$A_d = \sqrt{2K_{p1}I_Q}\,(r_{o2}\|r_{o4}) = \sqrt{2(0.25)(0.08903)}\,(1123\|1123) = 118.5$$

$$g_{m7} = 2\sqrt{\left(\frac{0.1}{2}\right)(12.5)(0.08903)} = 0.4718\text{ mA/V}$$

$$r_{o8} = r_{o7} = \frac{1}{(0.02)(0.08903)} = 561.6\text{ k}\Omega$$

$$A_{\upsilon 2} = (0.4718)(561.6 \| 561.6) = 132.5$$

Then $A_\upsilon = (118.5)(132.5) = 15{,}701$

TYU13.12

(a) $g_{m1} = 2\sqrt{\left(\frac{k_n'}{2}\right)\left(\frac{W}{L}\right)_1 I_{DQ}} = 2\sqrt{\left(\frac{0.1}{2}\right)(40)(0.1)} = 0.8944 \text{ mA/V}$

$$r_{o6} = r_{o8} = \frac{1}{(0.02)(0.3)} = 166.7 \text{ k}\Omega$$

$$A_d = Bg_{m1}(r_{o6} \| r_{o8}) = 3(0.8944)(166.7 \| 166.7) = 223.6$$

(b) $R_o = r_{o6} \| r_{o8} = 166.7 \| 166.7 = 83.33 \text{ k}\Omega$

$$f_{PD} = \frac{1}{2\pi R_o (C_L + C_P)} = \frac{1}{2\pi(83.33 \times 10^3)(2 \times 10^{-12})} \Rightarrow f_{PD} = 955 \text{ kHz}$$

$$GBW = (223.6)(955 \times 10^3) \Rightarrow 213.5 \text{ MHz}$$

TYU13.13

(a) $g_{m1} = 2\sqrt{\left(\frac{0.1}{2}\right)(40)(0.1)} = 0.8944 \text{ mA/V}$

$$r_{o6} = r_{o8} = r_{o10} = r_{o12} = \frac{1}{(0.02)(0.3)} = 166.7 \text{ k}\Omega$$

$$g_{m12} = 2\sqrt{\left(\frac{k_n'}{2}\right)\left(\frac{W}{L}\right)_{12} I_{D12}} = 2\sqrt{\left(\frac{0.1}{2}\right)(40)(0.3)} = 1.549 \text{ mA/V}$$

$$g_{m10} = 2\sqrt{\left(\frac{0.04}{2}\right)(40)(0.3)} = 0.9798 \text{ mA/V}$$

$$R_{o10} = g_{m10}(r_{o10} r_{o6}) = (0.9798)(166.7)(166.7) = 27{,}228 \text{ k}\Omega$$

$$R_{o12} = g_{m12}(r_{o12} r_{o8}) = (1.549)(166.7)(166.7) = 43{,}045 \text{ k}\Omega$$

$$A_d = (3)(0.8944)(27228 \| 43045) = 44{,}751$$

(b)

$$R_o = R_{o10} \| R_{o12} = 16{,}678 \text{ k}\Omega$$

$$f_{PD} = \frac{1}{2\pi(16{,}678 \times 10^3)(2 \times 10^{-12})} \Rightarrow 4.77 \text{ kHz}$$

$$GBW = (44{,}751)(4.77 \times 10^3) \Rightarrow 213.5 \text{ MHz}$$

TYU13.14

(a) $A_d = g_{m1}\left(R_{o6} \| R_{o8}\right)$

From Example 13.11,

$g_{m1} = 316\ \mu A/V,\ \ R_{o8} = 316\ M\Omega$

Now

$R_{o6} = g_{m6}(r_{o6})(r_{o4} \| r_{o1})$

$r_{o1} = 1\ M\Omega,\ r_{o4} = 0.5\ M\Omega$

$g_{m6} = \dfrac{I_{C6}}{V_T} = \dfrac{50}{0.026} \Rightarrow 1.923\ mA/V$

$r_{o6} = \dfrac{V_{A6}}{I_{C6}} = \dfrac{80}{50} = 1.6\ M\Omega$

Then

$R_{o6} = (1.923)(1600)(0.5 \| 1) = 1026\ M\Omega$

$A_d = (316)(1026 \| 316) \Rightarrow \underline{A_d = 76{,}343}$

$f_{PD} = \dfrac{1}{2\pi(316 \| 1026) \times 10^6 \times 2 \times 10^{-12}} \Rightarrow \underline{f_{PD} = 329\ Hz}$

(b) $f_{PD} \cdot A_d = (329)(76{,}343) \Rightarrow 25.1\ MHz$

TYU13.15

For Q_7 and R_1

$V_{SG} = V_{BE7} + I_1 R_1 = 0.6 + I_1(5)$

For M_8:

$I_2 = K_p(V_{SG} + V_{TP})^2$

$I_2 = 0.3(V_{SG} - 1.4)^2$

By trial and error:

$\underline{V_{SG} = 2.54\ \text{V}}$

$\underline{I_1 = I_2 = 0.388\ \text{mA}}$

TYU13.16

For J_6 biased in the saturation region

$\Rightarrow I_{C3} = I_{DSS} = 300\ \mu\text{A}$

$Q_1,\ Q_2,\ Q_3$ are matched

$\Rightarrow \underline{I_{C1} = I_{C2} = I_{C3} = 300\ \mu\text{A}}$

Chapter 14

Exercise Solutions

EX14.1

(a) $A_{CL} = \dfrac{-40}{1+\dfrac{1}{A_{OL}}(41)} = \dfrac{-40}{1+\dfrac{41}{2\times 10^5}} = -39.9918$

(b) $A_{CL} = \dfrac{-40}{1+\dfrac{41}{5\times 10^4}} = -39.9672$

(c) Percent change $= \dfrac{39.9672-39.9918}{39.9918}\times 100\% = -0.0615\%$

EX14.2

(a) $\dfrac{1}{R_{if}} = \dfrac{1}{40} + \dfrac{1}{80}\cdot\dfrac{\left(1+5\times 10^4\right)}{(1)} = 0.025 + 625.0$

so that $R_{if} = 1.6\,\Omega$

(b) $\dfrac{1}{R_{if}} = \dfrac{1}{40} + \dfrac{1}{80}\cdot\dfrac{\left(1+5\times 10^4+\dfrac{1}{10}\right)}{\left(1+\dfrac{1}{10}+\dfrac{1}{80}\right)} = 0.025 + \dfrac{1}{80}\cdot\dfrac{\left(5.00011\times 10^4\right)}{(1.1125)}$

so that $R_{if} = 1.78\,\Omega$

EX14.3

$$R_{if} = \frac{40\left(1+10^4\right)+99\left(1+\dfrac{40}{1}\right)}{1+\dfrac{99}{1}}$$

$$\cong \frac{4\times 10^5 + 4.059\times 10^3}{100}$$

$R_{if} = 4.04\times 10^3 \text{ k}\Omega \Rightarrow \underline{R_{if} = 4.04 \text{ M}\Omega}$

EX14.4

$1+\dfrac{R_2}{R_1} = 100$

a. $\dfrac{1}{R_{0f}} = \dfrac{1}{100}\left[\dfrac{10^5}{100}\right] = 10 \Rightarrow \underline{R_{0f} = 0.1\,\Omega}$

b. $\dfrac{1}{R_{0f}} = \dfrac{1}{10}\left[\dfrac{10^5}{100}\right] = 10^2$

$R_{0f} = 10^{-2} \text{ k}\Omega \Rightarrow \underline{R_{0f} = 10\,\Omega}$

EX14.5

(a) $f_T = (2\times10^5)(5) = (30)f_{3-dB} \Rightarrow f_{3-dB} = 33.3 \text{ kHz}$

(b) $\upsilon_O = A_{CLO}\cdot\upsilon_I = (30)(100\sin(2\pi f t))\,\mu \text{ V}$

or

$$\upsilon_O = 3\sin(2\pi f t) \text{ mV}$$

(c) (i) $\upsilon_{O,peak} \cong 3 \text{ mV}$

(ii) $\upsilon_O = \dfrac{3}{\sqrt{1+\left(\dfrac{50}{33.3}\right)^2}} = 1.663 \text{ mV}$

(iii) $\upsilon_O = \dfrac{3}{\sqrt{1+\left(\dfrac{200}{33.3}\right)^2}} = 0.493 \text{ mV}$

EX14.6

(a) $\upsilon_O = (SR)\cdot t$

(i) $\upsilon_O = (1.25)(2) = 2.5 \text{ V}$

(ii) $\upsilon_O = (1.25)(4) = 5 \Rightarrow \upsilon_O = 4 \text{ V}$

(iii) $\upsilon_O = 4 \text{ V}$

(b) $\upsilon_O = 4 = (1.25)(t) \Rightarrow t = 3.2\,\mu \text{ s}$

EX14.7

(a) $f_{\max} = \dfrac{SR}{2\pi V_{PO}} = \dfrac{0.63\times10^6}{2\pi(0.25)} \Rightarrow 401 \text{ kHz}$

(b) $f_{\max} = \dfrac{0.63\times10^6}{2\pi(2)} \Rightarrow 50.1 \text{ kHz}$

(c) $f_{\max} = \dfrac{0.63\times10^6}{2\pi(8)} \Rightarrow 12.5 \text{ kHz}$

EX14.8

$$V_{OS} = V_T \ln\left(\frac{I_{S2}}{I_{S1}}\right)$$

$$\frac{2}{26} = \ln\left(\frac{I_{S2}}{I_{S1}}\right)$$

Then

$$I_{S2} = I_{S1}\exp\left(\frac{2}{26}\right) = 2.16\times10^{-15} \text{ A}$$

$$\text{Percent change} = \frac{2.16-2}{2}\times100\% = 8\%$$

EX14.9

We need

$i_{C1} = i_{C2}$, $v_{EC3} = v_{EC4} = 0.6$ V, and $v_{CE1} = v_{CE2} = 10$ V

By Equation (14.60(a))

$$i_{C1} = I_{S1}\left[\exp\left(\frac{v_{BE1}}{V_T}\right)\right]\left(1+\frac{10}{50}\right)$$

$$= I_{S3}\left[\exp\left(\frac{v_{EB3}}{V_T}\right)\right]\left(1+\frac{0.6}{50}\right)$$

By Equation (14.60(b))

$$i_{C2} = I_{S2}\left[\exp\left(\frac{v_{BE2}}{V_T}\right)\right]\left(1+\frac{10}{50}\right)$$

$$= I_{S4}\left[\exp\left(\frac{v_{EB4}}{V_T}\right)\right]\left(1+\frac{0.6}{50}\right)$$

$I_{S1} = I_{S2},$ take the ratio:

$$\exp\left(\frac{v_{BE1}-v_{BE2}}{V_T}\right) = \frac{I_{S3}}{I_{S4}}$$

$$v_{BE1}-v_{BE2} = V_{0S} \quad = V_T \ln\left(\frac{I_{S3}}{I_{S4}}\right)$$

$$= 0.026\cdot\ln(1.05)$$

$$\Rightarrow \underline{V_{0S} = 1.27 \text{ m V}}$$

EX14.10

$$V_{OS} = \frac{1}{2}\cdot\sqrt{\frac{I_Q}{2K_n}}\cdot\left(\frac{\Delta K_n}{K_n}\right)$$

$$0.020 = \frac{1}{2}\cdot\sqrt{\frac{150}{2(50)}}\cdot\left(\frac{\Delta K_n}{50}\right)$$

$$\Rightarrow \underline{\Delta K_n = 1.63\mu A/V^2}$$

$$\Rightarrow \frac{\Delta K_n}{K_n} = \frac{1.63}{50} \Rightarrow \underline{3.26\%}$$

EX14.11

Want $\left(\frac{R_5}{R_5+R_4}\right)V^+ = 5 \text{ m V}$

$R_5 \| R_4$ so $\frac{R_5}{R_4}\cdot V^+ = 0.005$

$$R_5 = \frac{(0.005)(100)}{10} = 0.05 \text{ k}\Omega$$

$$\Rightarrow \underline{R_5 = 50\ \Omega}$$

EX14.12

$$R_1' = 25 \| 1 = 0.9615 \text{ k}\Omega$$
$$R_2' = 75 \| 1 = 0.9868 \text{ k}\Omega$$

For $I_Q = 100\ \mu\text{A} \Rightarrow i_{C1} = i_{C2} = 50\ \mu\text{A}$

From Equation (14.75)

$$(0.026)\ln\left(\frac{50\times10^{-6}}{10^{-14}}\right)+(0.050)(0.9615)$$
$$=(0.026)\ln\left(\frac{i_{C2}}{I_{S4}}\right)+(0.050)(0.9868)$$
$$0.58065+0.048075$$
$$=(0.026)\ln\left(\frac{i_{C2}}{I_{S4}}\right)+0.04934$$
$$\ln\left(\frac{i_{C2}}{I_{S4}}\right)=22.284$$
$$\frac{50\times10^{-6}}{I_{S4}}=4.7625\times10^{9}$$
$$\underline{I_{S4} \cong 1.05\times10^{-14}\text{ A}}$$

EX14.13

(a) (i) Yes

(ii) $R_3 = R_1 \| R_2 = 20 \| 120 = 17.14\ \text{k}\Omega$

(b) (i) Yes

(ii) $\upsilon_O = 0 = I_{B1}R_2 - I_{B2}R_3\left(1+\dfrac{R_2}{R_1}\right)$

$$(0.75)(120) = (0.85)R_3\left(1+\frac{120}{20}\right) \Rightarrow R_3 = 15.13\ \text{k}\Omega$$

Test Your Understanding Solutions

TYU14.1

$$v_{1CM}(\max) = V^+ - V_{SD1}(sat) - V_{SG1}$$
$$v_{1CM}(\min) = V^- + V_{DS4}(sat) + V_{SD1}(sat) - V_{SG1}$$

We have:

$$I_{REF} = 100\ \mu A,\ k'_n = 80\ \mu A/V^2,\ k'_p = 40\ \mu A/V^2,$$
$$\left(\frac{W}{L}\right) = 25$$

For M_1:

$$I_D = 50 = \left(\frac{40}{2}\right)(25)(V_{SG1} + V_{TP})^2$$

So $50 = 500(V_{SG1} - 0.5)^2 \Rightarrow V_{SG1} = 0.816\ V$

$$V_{SD1}(sat) = 0.816 - 0.5 = 0.316\ V$$

Then

$$v_{CM}(\max) = V^+ - 0.316 - 0.816 = V^+ - 1.13\,V$$

For M_4:

$$I_D = 100 = \left(\frac{80}{2}\right)(25)(V_{GS4} - V_{TN})^2$$

So $100 = 1000(V_{GS4} - 0.5)^2 \Rightarrow V_{GS4} = 0.816\ V$

$$V_{DS4}(sat) = 0.816 - 0.5 = 0.316\,V$$
$$V_{CM}(\min) = V^- + 0.316 + 0.316 - 0.816 = V^- - 0.184$$

So

$$\underline{V^- - 0.184 \le v_{CM} \le V^+ - 1.13\ V}$$

TYU14.2

$$v_o(\max) = V^+ - V_{SD8}(sat) - V_{SG10}$$
$$v_o(\min) = V^- + V_{DS4}(sat) + V_{DS6}(sat)$$

Now

$$V_{SG8} = V_{SG10} = \sqrt{\frac{50}{(40/2)(25)}} + 0.5 = 0.816\ V$$
$$V_{SD8}(sat) = V_{SD10}(sat) = 0.316\,V$$

So $v_o(\max) = V^+ - 0.316 - 0.816 = V^+ - 1.13$

Also

$$V_{GS6} = \sqrt{\frac{50}{(80/2)(25)}} + 0.5 = 0.724\,V$$
$$V_{GS4} = \sqrt{\frac{100}{(80/2)(25)}} + 0.5 = 0.816\,V$$
$$V_{DS6}(sat) = 0.724 - 0.5 = 0.224\ V$$
$$V_{DS4}(sat) = 0.816 - 0.5 = 0.316\,V$$

So

$$v_o(\min) = V^- + 0.316 + 0.224 = V^- + 0.54$$

Then

$$\underline{V^- + 0.54 \le v_o \le V^+ - 1.13\,V}$$

TYU14.3

(a) $-\dfrac{R_2}{R_1} = -\dfrac{250}{25} = -10.0$

$$A_{CL} = -(1-0.001)(10.0) = -9.99$$

Now

$$-9.99 = \frac{-10}{1+\dfrac{11}{A_{OL}}} \Rightarrow A_{OL} = 10{,}989$$

(b) $A_{CL} = -(1-0.0005)(10) = -9.995$

We find

$$-9.995 = \frac{-10}{1+\dfrac{11}{A_{OL}}} \Rightarrow A_{OL} = 21{,}989$$

TYU14.4

a. $$A_{CL} = \frac{A_{CL}(\infty)}{1+\left[\dfrac{A_{CL}(\infty)}{A_{0L}}\right]}$$

$$A_{CL}(\infty) = 1+\frac{R_2}{R_1} = 1+\frac{495}{5} = 100$$

$$A_{CL} = \frac{100}{1+\dfrac{100}{10^5}} \Rightarrow \quad \underline{A_{CL} = 99.90}$$

$$\underline{A_{CL}(\infty) = 100}$$

b. $$\frac{dA_{CL}}{A_{CL}} = 10\times\frac{100}{10^5} = \underline{0.01\%}$$

$$A_{CL} = 99.90-(0.0001)(99.90)$$

$$\Rightarrow \underline{A_{CL} = 99.89}$$

TYU14.5

(a) $$\frac{A_{CL}}{A_{CL}(\infty)} = \frac{1}{1+\dfrac{A_{CL}(\infty)}{A_{OL}}}$$

$$0.999 = \frac{1}{1+\dfrac{A_{CL}(\infty)}{2\times10^4}} \Rightarrow A_{CL}(\infty) = 20.02$$

(b) $$0.9995 = \frac{1}{1+\dfrac{A_{CL}(\infty)}{2\times10^4}} \Rightarrow A_{CL}(\infty) = 10.005$$

TYU14.6

$$\frac{i_i}{I_1} = \left(\frac{R_{if}}{R_i}\right)$$

a. $$\frac{i_I}{i_1} = \frac{0.1}{10^4} = \underline{1\times 10^{-5}}$$

b. $$\frac{i_I}{i_1} = \frac{10}{10^4} = \underline{1\times 10^{-3}}$$

TYU14.7

Voltage follower $R_2 = 0,\ R_1 = \infty$

$$R_{if} = R_i\left(1 + A_{0L}\right) = 10\left(1 + 5\times 10^5\right)$$

$$\cong 5\times 10^6\ \text{k}\Omega \Rightarrow \underline{R_{if} = 5000\ \text{M}\Omega}$$

TYU14.8

(a) (i) $f_T = \left(5\times 10^4\right)(15) = (25) f_{3-dB}$

or $f_{3-dB} = f_{\max} = 30\ \text{kHz}$

(ii) $V_{PO} = \dfrac{SR}{2\pi f_{\max}} = \dfrac{0.8\times 10^6}{2\pi\left(30\times 10^3\right)} = 4.24\ \text{V}$

(b) (i) $f_T = \left(5\times 10^5\right)(10) = (25) f_{3-dB} \Rightarrow f_{3-dB} = 200\ \text{kHz}$

(ii) $V_{PO} = \dfrac{SR}{2\pi f_{\max}} = \dfrac{0.8\times 10^6}{2\pi\left(200\times 10^3\right)} = 0.637\ \text{V}$

TYU14.9

a. $$v_0 = I_{B1} R_3 = \left(10^{-6}\right)\left(200\times 10^3\right)$$

$$\Rightarrow \underline{v_0 = 0.20\ \text{V}}$$

b. $$R_4 = R_1 \| R_2 \| R_3 = 100 \| 50 \| 200$$

$$\Rightarrow \underline{R_4 = 28.6\ \text{k}\Omega}$$

Chapter 15

Exercise Solutions

EX15.1

$$f_{3-dB} = \frac{1}{2\pi RC} \Rightarrow RC = \frac{1}{2\pi f_{3-dB}} = \frac{1}{2\pi\left(25\times 10^3\right)} = 6.366\times 10^{-6}$$

Set $C_3 = 50\ \text{pF} = 1.414C \Rightarrow C = 35.36\ \text{pF}$

$C_4 = (0.707)C = 25\ \text{pF}$

Then $R = \dfrac{6.366\times 10^{-6}}{C} = \dfrac{6.366\times 10^{-6}}{35.36\times 10^{-12}} \Rightarrow R = 180\ \text{k}\Omega$

EX15.2

(a) $R_{eq} = \dfrac{1}{f_c C} = \dfrac{1}{\left(100\times 10^3\right)\left(1.2\times 10^{-12}\right)} \Rightarrow R_{eq} = 8.33\ \text{M}\Omega$

(b) $C = \dfrac{1}{f_c R_{eq}} = \dfrac{1}{\left(50\times 10^3\right)\left(50\times 10^6\right)} \Rightarrow C = 0.4\ \text{pF}$

EX15.3

Low-frequency gain: $T = -\dfrac{C_1}{C_2} = -\dfrac{30}{5} = \underline{-6}$

$$f_{3dB} = \frac{f_C C_2}{2\pi C_F} = \frac{\left(100\times 10^3\right)\left(5\times 10^{-12}\right)}{2\pi\left(12\times 10^{-12}\right)} \Rightarrow \underline{f_{3dB} = 6.63\ \text{kHz}}$$

EX15.4

$$f_o = \frac{1}{2\pi\sqrt{3}RC} \Rightarrow RC = \frac{1}{2\pi\sqrt{3}\left(22.5\times 10^3\right)} = 4.084\times 10^{-6}$$

Set $R = 10\ \text{k}\Omega$

$C = \dfrac{4.084\times 10^{-6}}{10\times 10^3} \Rightarrow C = 408\ \text{pF}$

$R_2 = 8R = 80\ \text{k}\Omega$

EX15.5

$f_0 = \dfrac{1}{2\pi RC} \Rightarrow C = \dfrac{1}{2\pi f_0 R}$

$C = \dfrac{1}{2\pi(800)\left(10^4\right)} \Rightarrow \underline{C \cong 0.02\ \mu\text{F}}$

$R_2 = 2R_1 = 2(10) \Rightarrow \underline{R_2 = 20\ \text{k}\Omega}$

EX15.6

$$V_{TH} = \left(\frac{R_1}{R_1 + R_2}\right) \cdot V_H$$

Set $R_1 = 10\ \text{k}\Omega$

Then $0.5 = \left(\dfrac{10}{10 + R_2}\right)(9) \Rightarrow R_2 = 170\ \text{k}\Omega$

EX15.7

$$V_{TH} - V_{TL} = \left(\frac{R_1}{R_1 + R_2}\right)(V_H - V_L)$$

$$0.10 = \left(\frac{R_1}{R_1 + R_2}\right)(10 - [-10])$$

$$1 + \frac{R_2}{R_1} = \frac{20}{0.10} = 200 \Rightarrow \underline{\frac{R_2}{R_1} = 199}$$

$$V_S = \left(\frac{R_2}{R_1 + R_2}\right) V_{REF}$$

$$V_{REF} = \left(1 + \frac{R_1}{R_2}\right) V_S = \left(1 + \frac{1}{199}\right)(1) \Rightarrow \underline{V_{REF} = 1.005\ \text{V}}$$

$$I = \frac{V_H - V_{BE}(\text{on}) - V_\gamma}{R + 0.1}$$

$$R + 0.1 = \frac{10 - 0.7 - 0.7}{0.2} = 43\ \text{k}\Omega$$

$$\underline{R = 42.9\ \text{k}\Omega}$$

EX15.8

At $t = 0^-$ let $\upsilon_O = -5\ \text{V}$ so $\upsilon_X = -2.5\ \text{V}$: For $t > 0$

$$\upsilon_X = 10 + (-2.5 - 10)\exp\left(\frac{-t}{\tau_X}\right)$$

When $\upsilon_X = 5\ \text{V}$, output switches

$$5 = 10 - 12.5\exp\left(\frac{-t_1}{\tau_X}\right)$$

$$\exp\left(\frac{-t_1}{\tau_X}\right) = \frac{10-5}{12.5} = \frac{5}{12.5}$$

$$\exp\left(\frac{+t_1}{\tau_X}\right) = \frac{12.5}{5} \Rightarrow t_1 = \tau_X \ln\left(\frac{12.5}{5}\right) \Rightarrow t_1 = \tau_X (0.916)$$

During the next part of the cycle

$$\upsilon_X = -5 + [5 - (-5)]\exp\left(\frac{-t}{\tau_X}\right)$$

When $\upsilon_X = -2.5\ \text{V}$, output switches

$$-2.5 = -5 + 10\exp\left(\frac{-t_2}{\tau_X}\right)$$

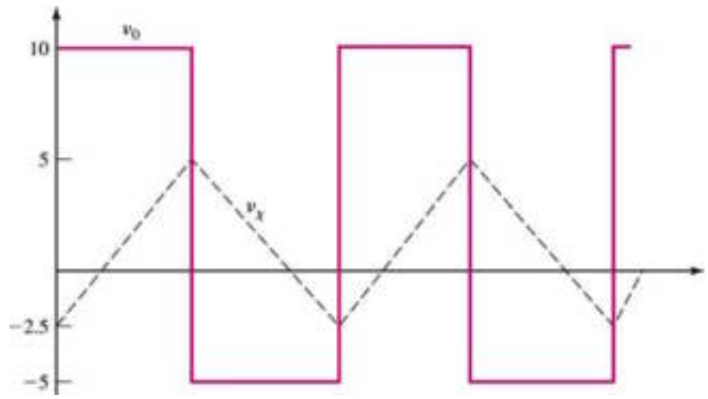
$$\exp\left(\frac{-t_2}{\tau_X}\right) = \frac{5-2.5}{10} = \frac{2.5}{10}$$

$$\exp\left(\frac{+t_2}{\tau_X}\right) = \frac{10}{2.5} \Rightarrow t_2 = \tau_X \ln\left(\frac{10}{2.5}\right) \Rightarrow t_2 = \tau_X (1.39)$$

$$\text{Period } = t_1 + t_2 = T = (0.916 + 1.39)\tau_X = 2.31\tau_X \text{ , Frequency} = f = \frac{1}{2.31\tau_X}$$

$$\tau_X = (50\times 10^3)(0.01\times 10^{-6}) = 5\times 10^{-4}\ \text{s} \Rightarrow f = 866\ \text{Hz}$$

$$\text{Duty cycle} = \frac{t_1}{t_1+t_2}\times 100\% = \frac{0.916}{0.916+1.39}\times 100\% \Rightarrow \text{Duty cycle} = 39.7\%$$



EX15.9

a.

$$\tau_X = R_X C_X$$

$$\upsilon_Y = \left(\frac{R_1}{R_1+R_2}\right)\cdot \upsilon_O = \left(\frac{10}{10+90}\right)(12) = 1.2\ \text{V}$$

$$\beta = \left(\frac{R_1}{R_1+R_2}\right) = 0.10$$

$$T = \tau_X \ln\left(\frac{1+V_\gamma/V_P}{1-\beta}\right) = \tau_X \ln\left(\frac{1+(0.7)/(12)}{1-0.10}\right)$$

$$T = 50\times 10^{-6} = \tau_X \ln(1.18) = \tau_X (0.162)$$

$$R_X = \frac{50\times 10^{-6}}{(0.1\times 10^{-6})(0.162)} \Rightarrow R_X = 3.09\ \text{k}\Omega$$

b. Recovery time

$$\upsilon_X = V_P + (-1.2 - V_P)\exp\left(\frac{-t}{\tau_X}\right)$$

When $\upsilon_X = V_\gamma \quad t = t_2$

$$0.7 = 12 + (-1.2 - 12)\exp\left(\frac{-t_2}{\tau_X}\right)$$

$$\exp\left(\frac{-t_2}{\tau_X}\right) = \frac{12 - 0.7}{13.2} = 0.856$$

$$t_2 = \tau_X \ln\left(\frac{1}{0.856}\right) = \tau_X(0.155)$$

$$\tau_X = (3.09\times10^3)(0.1\times10^{-6}) = 3.09\times10^{-4}\text{ s}, \Rightarrow t_2 = 48.0\ \mu\text{s}$$

EX15.10

(a) $T = 1.1RC = (1.1)(20\times10^3)(0.012\times10^{-6}) \Rightarrow T = 0.264$ ms

(b) $RC = \dfrac{T}{1.1} = \dfrac{120\times10^{-6}}{1.1} = 1.09\times10^{-4}$

If $C = 0.01\,\mu$F, then $R = \dfrac{1.09\times10^{-4}}{0.01\times10^{-6}} \Rightarrow R = 10.9\ \text{k}\Omega$

EX15.11

$$f = \frac{1}{0.693(R_A + 2R_B)C} = \frac{1}{(0.693)[20 + 2(80)]\times10^3\times(0.01\times10^{-6})} \Rightarrow \underline{f = 802\text{ Hz}}$$

$$\text{Duty cycle} = \frac{R_A + R_B}{R_A + 2R_B}\times100\% = \frac{20 + 80}{20 + 2(80)}\times100\% \Rightarrow \underline{\text{Duty cycle} = 55.6\%}$$

EX15.12

$$\overline{P} = \frac{1}{2}\cdot\frac{V_P^2}{R_L}$$

$$V_P = \sqrt{2R_L\overline{P}} = \sqrt{2(8)(1)} \Rightarrow \underline{V_P = 4\text{ V}}$$

a.
$$I_P = \frac{V_P}{R_L} = \frac{4}{8} \Rightarrow \underline{I_P = 0.5\text{ A}}$$

$V_{CE} = 12 - 4 = 8$ V

b. $I_C \approx 0.5$ A

So $P = I_C \cdot V_{CE} = (0.5)(8) \Rightarrow \underline{P = 4\text{ W}}$

EX15.13

(a) (i) $V_P = \sqrt{2R_L \overline{P}_L} = \sqrt{2(20)(5)} = 14.14 \text{ V}$

$$I_P = \frac{V_P}{R_L} = \frac{14.14}{20} = 0.707 \text{ A}$$

(ii) $V_S = \dfrac{\pi R_L P_S}{V_P}$, We have $P_S = 5 \text{ W}$

$$V_S = \frac{\pi(20)(5)}{14.14} = 22.2 \text{ V}$$

(b) (i) $V_P = \sqrt{2(8)(10)} = 12.65 \text{ V}$

$$I_P = \frac{12.65}{8} = 1.58 \text{ A}$$

(ii) $V_S = \dfrac{\pi(8)(10)}{12.65} = 19.9 \text{ V}$

EX15.14

Line $\text{regulation} = \dfrac{dV_0}{dV^+} = \dfrac{dV_0}{dV_Z} \cdot \dfrac{dV_Z}{dV^+}$

Now

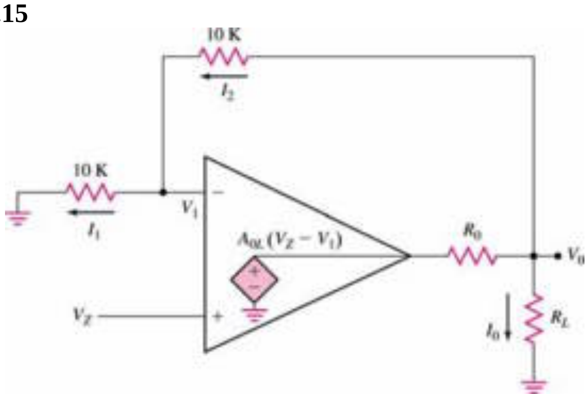
$$\frac{dV_0}{dV_Z} = \left(1 + \frac{10}{10}\right) = 2$$

$$\frac{dV_Z}{dV^+} = \left(\frac{r_Z}{r_Z + R_1}\right) = \frac{10}{10 + 4400} = 0.00227$$

So Line $\text{regulation} = (2)(0.00227) = 0.00454$

0.454%

EX15.15



$$\frac{V_1}{10} = \frac{V_0 - V_1}{10} \Rightarrow V_1\left(\frac{1}{10} + \frac{1}{10}\right) = \frac{V_0}{10}$$

$$V_1\left(\frac{2}{10}\right) = \frac{V_0}{10} \Rightarrow V_0 = 2V_1 \Rightarrow V_1 = \frac{V_0}{2}$$

$$\frac{V_0 - V_1}{10} + \frac{V_0}{R_L} + \frac{V_0 - A_{0L}\left(V_Z - V_1\right)}{R_0} = 0$$

$$\frac{V_0}{10} + \frac{V_0}{R_L} + \frac{V_0}{R_0} - \frac{A_{0L}V_Z}{R_0} = \frac{V_1}{10} - \frac{A_{0L}V_1}{R_0}$$

$$= \frac{V_0}{2(10)} - \frac{A_{0L}V_0}{2R_0}$$

$$\frac{V_0}{10} + I_0 + \frac{V_0}{0.5} - \frac{1000(6.3)}{0.5} = \frac{V_0}{20} - \frac{(1000)V_0}{2(0.5)}$$

$$V_0[0.10 + 2.0 - 0.05 + 1000] + I_0 = 12{,}600$$

$$V_0(1002.05) + I_0 = 12{,}600$$

For $I_0 = 1 \text{ mA} \Rightarrow V_0 = 12.5732$

For $I_0 = 100 \text{ mA} \Rightarrow V_0 = 12.4744$

$$\text{Load reg} = \frac{V_0(\text{NL}) - V_0(\text{FL})}{V_0(\text{NL})} \times 100\%$$

$$= \frac{12.5732 - 12.4744}{12.5732} \times 100\%$$

$$\underline{\text{Load reg} = 0.786\%}$$

EX15.16

a.

$$I_{C3} = \frac{V_Z - 3V_{BE}(\text{on})}{R_1 + R_2 + R_3}$$

$$I_{C3} = \frac{5.6 - 3(0.6)}{3.9 + 3.4 + 0.576} = \frac{3.8}{7.88} \Rightarrow \underline{I_{C3} = 0.482 \text{ mA}}$$

$$I_{C4}R_4 = V_T \ \ln\left(\frac{I_{C3}}{I_{C4}}\right)$$

$$I_{C4}(0.1) = (0.026) \ \ln\left(\frac{0.482}{I_{C4}}\right)$$

By trial and error

$$\underline{I_{C4} = 0.213 \text{ mA}}$$

$$V_{B7} = 2(0.6) + (0.482)(3.9) \Rightarrow \underline{V_{B7} = 3.08 \text{ V}}$$

b.

$$\left(\frac{R_{13}}{R_{13}+R_{12}}\right)V_0 = V_{B8} = V_{B7}$$

$$\left(\frac{2.23}{2.23+R_{12}}\right)(5) = 3.08$$

$$(2.23)(5) = (3.08)(2.23) + (3.08)R_{12}$$

$$11.15 = 6.868 = 3.08R_{12} \Rightarrow \underline{R_{12} = 1.39\ \text{k}\Omega}$$

Test Your Understanding Solutions

TYU15.1

(a) $$f_{3-dB} = \frac{1}{2\pi RC} \Rightarrow RC = \frac{1}{2\pi f_{3-dB}} = \frac{1}{2\pi(200)} = 7.958\times10^{-4}$$

For example, let $C = 0.01\,\mu\text{F}$

Then $$R = \frac{7.958\times10^{-4}}{0.01\times10^{-6}} \Rightarrow R = 79.58\ \text{k}\Omega$$

$$R_1 = \frac{79.58}{3.546} = 22.44\ \text{k}\Omega$$

$$R_2 = \frac{79.58}{1.392} = 57.17\ \text{k}\Omega$$

$$R_3 = \frac{79.58}{0.2024} = 393.2\ \text{k}\Omega$$

(b) (i) $$|T| = \frac{1}{\sqrt{1+\left(\frac{200}{100}\right)^6}} = 0.124 \Rightarrow -18.1\ \text{dB}$$

(ii) $$|T| = \frac{1}{\sqrt{1+\left(\frac{200}{300}\right)^6}} = 0.959 \Rightarrow -0.365\ \text{dB}$$

TYU15.2

(a) $$RC = \frac{1}{2\pi f_{3-dB}} = \frac{1}{2\pi(30\times10^3)} = 5.305\times10^{-6}$$

For example, let $R = 100\ \text{k}\Omega$

Then $$C = \frac{5.305\times10^{-6}}{100\times10^3} \Rightarrow C = 53.05\ \text{pF}$$

$$C_1 = 1.082C = 57.4\ \text{pF}$$

$$C_2 = 0.9241C = 49.02\ \text{pF}$$

$$C_3 = 2.613C = 138.6\ \text{pF}$$

$$C_4 = 0.3825C = 20.29\ \text{pF}$$

(b) $$(0.99)=\frac{1}{\sqrt{1+\left(\dfrac{f}{30}\right)^{8}}}\Rightarrow\left(\frac{f}{30}\right)^{8}=0.020304$$

which yields $f=18.43\ \text{kHz}$

TYU15.3

1-pole $$|T|=\frac{1}{\sqrt{1+\left(\dfrac{12}{10}\right)^{2}}}\Rightarrow -3.87\ \text{dB}$$

2-pole $$|T|=\frac{1}{\sqrt{1+\left(\dfrac{12}{10}\right)^{4}}}\Rightarrow -4.88\ \text{dB}$$

3-pole $$|T|=\frac{1}{\sqrt{1+\left(\dfrac{12}{10}\right)^{6}}}\Rightarrow -6.0\ \text{dB}$$

4-pole $$|T|=\frac{1}{\sqrt{1+\left(\dfrac{12}{10}\right)^{8}}}\Rightarrow -7.24\ \text{dB}$$

TYU15.4

$$f_cC=\frac{1}{R_{eq}}=\frac{1}{25\times10^{6}}=4\times10^{-8}$$

For example, let $f_c=50\ \text{kHz}$,

$$C=\frac{4\times10^{-8}}{50\times10^{3}}\Rightarrow C=0.8\ \text{pF}$$

TYU15.5

$$f_o=\frac{1}{2\pi\sqrt{6}RC}\Rightarrow C=\frac{1}{2\pi\sqrt{6}\left(15\times10^{3}\right)\left(20\times10^{3}\right)}\Rightarrow C=217\ \text{pF}$$

$$R_2=29R=(29)(15)=435\ \text{k}\Omega$$

TYU15.6

$$f_0=\frac{1}{2\pi\sqrt{L\cdot\left(\dfrac{C_1C_2}{C_1+C_2}\right)}}=\frac{1}{2\pi\sqrt{(10^{-6})\left[\dfrac{(10^{-9})^2}{2\times10^{-9}}\cdot\right]}}\Rightarrow \underline{f_0=7.12\ \text{MHz}}$$

$$\frac{C_2}{C_1}=g_mR$$

$$g_m=\frac{C_2}{C_1}\cdot\frac{1}{R}=\frac{1}{4\times10^{3}}\Rightarrow \underline{g_m=0.25\ \text{mA/V}}$$

We have

$$g_m = 2\left(\frac{k'}{2}\right)\left(\frac{W}{L}\right)(V_{GS} - V_{Th})$$

$$k' \cong 20\ \mu\text{A}/\text{V}^2, V_{GS} - V_{Th} \cong 1\ \text{V}$$

So $\frac{W}{L} = \frac{0.25\times10^{-3}}{(20\times10^{-6})(1)} = 12.5$

and a value of $W/L = 12.5$ is certainly reasonable.

TYU15.7

$$V_{TH} = -\left(\frac{R_1}{R_2}\right)\cdot V_L$$

$$0.2 = -\left(\frac{R_1}{R_2}\right)(-12)$$

Set $R_2 = 200\ \text{k}\Omega$

Then $\frac{R_1}{200} = \frac{0.2}{12} \Rightarrow R_1 = 3.33\ \text{k}\Omega$

TYU15.8

a.

$$V_S = \left(\frac{R_2}{R_1+R_2}\right)V_{REF} = \left(\frac{10}{1+10}\right)(2)$$

$$\underline{V_S = 1.82\ \text{V}}$$

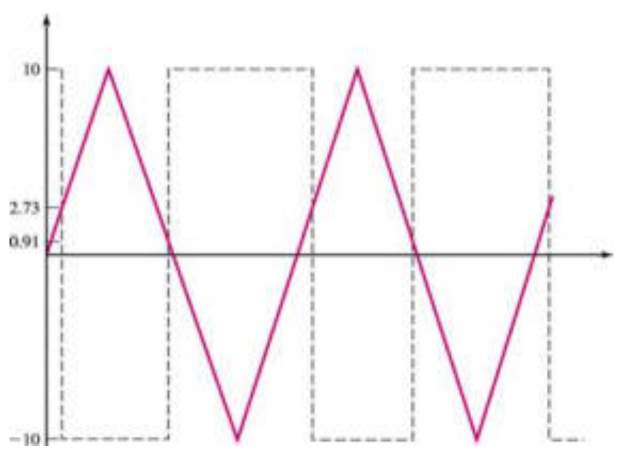
$$V_{TH} = V_S + \left(\frac{R_1}{R_1+R_2}\right)V_H = 1.82 + \left(\frac{1}{1+10}\right)(10)$$

$$\underline{V_{TH} = 2.73\ \text{V}}$$

$$V_{TL} = V_S + \left(\frac{R_1}{R_1+R_2}\right)V_L = 1.82 + \left(\frac{1}{1+10}\right)(-10)$$

$$\underline{V_{TL} = 0.91\ \text{V}}$$

b.



TYU15.9

$$V_{TH} - V_{TL} = \frac{R_1}{R_2}(V_H - V_L)$$

$$0.5 = \frac{R_1}{R_2}[9-(-9)] = 18\left(\frac{R_1}{R_2}\right)$$

Set $R_1 = 10\ \text{k}\Omega$,

Then $R_2 = \dfrac{(18)(10)}{0.5} = 360\ \text{k}\Omega$

Now $V_S = \left(1+\dfrac{R_1}{R_2}\right)\cdot V_{REF}$

$$-2 = \left(1+\frac{10}{360}\right)\cdot V_{REF} \Rightarrow V_{REF} = -1.946\ \text{V}$$

TYU15.10

(a) $f = \dfrac{1}{2.2 R_X C_X} = \dfrac{1}{(2.2)(20\times10^3)(0.05\times10^{-6})} = 454.5\ \text{Hz}$

50% duty cycle

(b) $R_X = \dfrac{1}{(2.2) f C_X} = \dfrac{1}{(2.2)(1.2\times10^3)(0.05\times10^{-6})} \Rightarrow R_X = 7.576\ \text{k}\Omega$

TYU15.11

$$\beta = \frac{R_1}{R_1+R_2} = \frac{20}{20+40} = 0.333$$

$$\tau_X = R_X C_X = (10^4)(0.01\times10^{-6}) = 1\times10^{-4}\ \text{s}$$

$$T = \tau_X \ln\left(\frac{1+V_\gamma/V_P}{1-\beta}\right) = (10^{-4})\ln\left(\frac{1+(0.7)/8}{1-0.333}\right) \Rightarrow T = 48.9\ \mu\text{s}$$

Recovery time

$$\upsilon_Y = \left(\frac{R_1}{R_1+R_2}\right)\cdot\upsilon_O = \left(\frac{20}{20+40}\right)(8) = 2.667\ \text{V}$$

$$0.7 = 8 + (-2.667-8)\exp\left(\frac{-t_2}{\tau_X}\right)$$

$$\exp\left(\frac{-t_2}{\tau_X}\right) = \frac{8-0.7}{10.66} = 0.6844$$

$$t_2 = \tau_X \ln\left(\frac{1}{0.6844}\right) \Rightarrow t_2 = 37.9\ \mu\text{s}$$

TYU15.12

$$f = \frac{1}{(0.693)(R_A + 2R_B)C} \Rightarrow R_A + 2R_B = \frac{1}{(0.693)fC} = \frac{1}{(0.693)(10^3)(0.01\times10^{-6})}$$

$$R_A + 2R_B = 1.443\times10^5$$

$$\text{Duty cycle} = 55\% = \frac{(R_A + R_B)}{(R_A + 2R_B)}\times100\%$$

$$0.55 = \frac{1.443\times10^5 - R_B}{1.443\times10^5}$$

$$R_B = (1.443\times10^5)(1-0.55) \Rightarrow R_B = 64.9 \text{ k}\Omega \quad \text{and} \quad R_A = 14.43 \text{ k}\Omega$$

TYU15.13

(a) (i) For A_1: $A_{\upsilon1} = \left(1+\frac{R_2}{R_1}\right) = \left(1+\frac{40}{20}\right) = 3$

For A_2: $A_{\upsilon2} = -\frac{R_4}{R_3} = -\frac{60}{20} = -3$

(ii) $V_L(peak) = 12 - (-12) = 24 \text{ V}$

$$I_L(peak) = \frac{24}{0.5} = 48 \text{ mA}$$

$$P_L(avg) = \left(\frac{24}{\sqrt{2}}\right)\left(\frac{0.048}{\sqrt{2}}\right) = 0.576 \text{ W}$$

(iii) $\upsilon_{O1}(peak) = 12 \Rightarrow \upsilon_I(peak) = \frac{12}{3} = 4 \text{ V}$

(b) Need $A_{\upsilon1} = 6 = \left(1+\frac{R_2}{20}\right) \Rightarrow R_2 = 100 \text{ k}\Omega$

$$A_{\upsilon2} = -6 = -\frac{R_4}{20} \Rightarrow R_4 = 120 \text{ k}\Omega$$

Chapter 16

Exercise Solutions

EX16.1

(a) $\upsilon_O = V_{DD} - i_D R_D = V_{DD} - \left(\frac{k_n'}{2}\right)\left(\frac{W}{L}\right) R_D \left[2(\upsilon_I - V_{TN})\upsilon_O - \upsilon_O^2\right]$

$$0.1 = 3 - \left(\frac{0.1}{2}\right)(4) R_D \left[2(3-0.5)(0.1) - (0.1)^2\right] \Rightarrow R_D = 29.6 \text{ k}\Omega$$

(b) $i_{D,\max} = \dfrac{3-0.1}{29.6} = 0.0980 \text{ mA}$

$P_{D,\max} = (0.098)(3) = 0.294 \text{ mW}$

(c) From Equation (16.9),

$$\left(\frac{0.1}{2}\right)(4)(29.6) V_{Ot}^2 + V_{Ot} - 3 = 0$$

$$5.92 V_{Ot}^2 + V_{Ot} - 3 = 0 \Rightarrow V_{Ot} = 0.632 \text{ V}$$

$$V_{Ot} = V_{It} - V_{TN} \Rightarrow V_{It} = 1.132 \text{ V}$$

EX16.2

(a) (i) $\upsilon_O = V_{DD} - V_{TNL} = 3 - 0.4 = 2.6 \text{ V}$

(ii) From Equation (16.21),

$$\left(\frac{0.1}{2}\right)(16)\left[2(2.6-0.4)\upsilon_O - \upsilon_O^2\right] = \left(\frac{0.1}{2}\right)(2)(3 - \upsilon_O - 0.4)^2$$

which yields

$$9\upsilon_O^2 - 40.4\upsilon_O + 6.76 = 0 \Rightarrow \upsilon_O = 0.174 \text{ V}$$

(b) $i_{D,\max} = \left(\dfrac{0.1}{2}\right)(2)(3 - 0.174 - 0.4)^2 = 0.589 \text{ mA}$

$P_{D,\max} = (0.589)(3) = 1.766 \text{ mW}$

(c) $V_{It} = \dfrac{3 - 0.4 + 0.4\left(1+\sqrt{8}\right)}{1+\sqrt{8}} = 1.08 \text{ V}$

$V_{Ot} = 1.08 - 0.4 = 0.68 \text{ V}$

EX16.3

(a) From Equation (16.27(b)),

$$\frac{6}{2}\left[2(3-0.4)\upsilon_O - \upsilon_O^2\right] = \left[-(-0.8)\right]^2$$

or $3\upsilon_O^2 - 15.6\upsilon_O + 0.64 = 0 \Rightarrow \upsilon_O = 0.0414 \text{ V}$

(b) $i_{D,\max} = \left(\dfrac{0.1}{2}\right)(2)\left[-(-0.8)\right]^2 = 0.064 \text{ mA}$

$P_{D,mas} = (0.064)(3) = 0.192 \text{ mW}$

(c) $\sqrt{\dfrac{6}{2}}\left(V_{It}-0.4\right)=-\left(-0.8\right)\Rightarrow V_{It}=0.862\ \text{V}$

Driver: $V_{It}=0.862\ \text{V},\ \ V_{Ot}=0.462\ \text{V}$

Load: $V_{It}=0.862\ \text{V},\ \ V_{Ot}=3-0.8=2.2\ \text{V}$

EX16.4

$$V_{OH}=2.5-\left\{0.5+\left(0.3\right)\left[\sqrt{0.73+V_{OH}}-\sqrt{0.73}\right]\right\}$$

$$V_{OH}-2.2563=-\left(0.3\right)\sqrt{0.73+V_{OH}}$$

$$V_{OH}^2-4.5126V_{OH}+5.09098=\left(0.09\right)\left(0.73+V_{OH}\right)$$

$$V_{OH}^2-4.60264V_{OH}+5.02528=0\Rightarrow V_{OH}=1.781\ \text{V}$$

EX16.5

(a) (i) $\dfrac{K_D}{K_L}\left[2\left(\upsilon_I-V_{TND}\right)\upsilon_O-\upsilon_O^2\right]=\left(-V_{TNL}\right)^2$

$$\left(\frac{5}{1}\right)\left[2\left(1.8-0.4\right)\upsilon_O-\upsilon_O^2\right]=\left[-\left(-0.6\right)\right]^2$$

$$5\upsilon_O^2-14\upsilon_O+0.36=0\Rightarrow \upsilon_O=26\ \text{mV}$$

(ii) $2\left(\dfrac{K_D}{K_L}\right)\left[2\left(\upsilon_I-V_{TND}\right)\upsilon_O-\upsilon_O^2\right]=\left(-V_{TNL}\right)^2$

$$2\left(\frac{5}{1}\right)\left[2\left(1.8-0.4\right)\upsilon_O-\upsilon_O^2\right]=\left[-\left(-0.6\right)\right]^2$$

$$10\upsilon_O^2-28\upsilon_O+0.36=0\Rightarrow \upsilon_O=12.9\ \text{mV}$$

(b) $i_{D,\max}=K_L\left(-V_{TNL}\right)^2=\left(\dfrac{100}{2}\right)\left(1\right)\left[-\left(-0.6\right)\right]^2=18\,\mu\text{A}$

$$P=i_{D,\max}\cdot V_{DD}=\left(18\right)\left(1.8\right)=32.4\,\mu\text{W}$$

EX16.6

(a) $\left(\dfrac{K_D}{3K_L}\right)\left[2\left(\upsilon_I-V_{TND}\right)\upsilon_O-\upsilon_O^2\right]=\left(-V_{TNL}\right)^2$

$$\frac{12}{\left(3\right)\left(1\right)}\left[2\left(2.5-0.4\right)\upsilon_O-\upsilon_O^2\right]=\left[-\left(-0.6\right)\right]^2$$

$$4\upsilon_O^2-16.8\upsilon_O+0.36=0\Rightarrow \upsilon_O=21.5\ \text{mV}$$

(b) $\dfrac{4}{\left(3\right)\left(1\right)}\left[2\left(2.5-0.4\right)\upsilon_O-\upsilon_O^2\right]=\left[-\left(-0.6\right)\right]^2$

$$1.333\upsilon_O^2-5.6\upsilon_O+0.36=0\Rightarrow \upsilon_O=65.3\ \text{mV}$$

EX16.7

(a)
$$V_{It} = \frac{V_{DD}}{2} = \frac{2.1}{2} = 1.05 \text{ V}$$
$$V_{OPt} = V_{It} - V_{TD} = 1.05 - (-0.4) = 1.45 \text{ V}$$
$$V_{ONt} = V_{It} - V_{TN} = 1.05 - 0.4 = 0.65 \text{ V}$$

(b)
$$V_{It} = \frac{2.1 + (-0.4) + \sqrt{0.5}(0.4)}{1 + \sqrt{0.5}} = 1.16 \text{ V}$$
$$V_{OPt} = 1.16 + 0.4 = 1.56 \text{ V}$$
$$V_{ONt} = 1.16 - 0.4 = 0.76 \text{ V}$$

(c)
$$V_{It} = \frac{2.1 + (-0.4) + \sqrt{2}(0.4)}{1 + \sqrt{2}} = 0.938 \text{ V}$$
$$V_{OPt} = 0.938 + 0.4 = 1.338 \text{ V}$$
$$V_{ONt} = 0.538 \text{ V}$$

EX16.8

$$P = f \cdot C_L \cdot V_{DD}^2$$
$$\left(0.10\times 10^{-6}\right) = f\left(0.5\times 10^{-12}\right)(3)^2$$
$$f = 2.22\times 10^4 \text{ Hz} \Rightarrow \underline{f = 22.2 \text{ kHz}}$$

EX16.9

(a)
$$V_{It} = \frac{V_{DD} + V_{TP} + \sqrt{\dfrac{K_n}{K_p}}\cdot V_{TN}}{1 + \sqrt{\dfrac{K_n}{K_p}}} = \frac{1.8 - 0.4 + (0.4)\sqrt{\dfrac{200}{80}}}{1 + \sqrt{\dfrac{200}{80}}} \Rightarrow V_{It} = 0.7874 \text{ V}$$
$$V_{OPt} = V_{It} - V_{TP} = 0.7874 + 0.4 = 1.187 \text{ V}$$
$$V_{ONt} = V_{It} - V_{TN} = 0.7874 - 0.4 = 0.3874 \text{ V}$$

(b)
$$\frac{K_n}{K_p} = \frac{200}{80} = 2.5$$
$$V_{IL} = 0.4 + \frac{(1.8 - 0.4 - 0.4)}{(2.5 - 1)}\left[2\sqrt{\frac{2.5}{2.5 + 3}} - 1\right] \Rightarrow V_{IL} = 0.6323 \text{ V}$$
$$V_{IH} = 0.4 + \frac{(1.8 - 0.4 - 0.4)}{(2.5 - 1)}\left[\frac{2(2.5)}{\sqrt{3(2.5) + 1}} - 1\right] \Rightarrow V_{IH} = 0.8767 \text{ V}$$
$$V_{OHU} = \frac{1}{2}\{(1 + 2.5)(0.6323) + 1.8 - (2.5)(0.4) + 0.4\} \Rightarrow V_{OHU} = 1.7065 \text{ V}$$
$$V_{OLU} = \frac{(0.8767)(1 + 2.5) - 1.8 - (2.5)(0.4) + 0.4}{2(2.5)} \Rightarrow V_{OLU} = 0.1337 \text{ V}$$

(c)
$$NM_L = 0.6323 - 0.1337 = 0.4986 \text{ V}$$
$$NM_H = 1.7065 - 0.8767 = 0.8298 \text{ V}$$

EX16.10

3 PMOS in series and 3 NMOS in parallel.

Worst Case: Only one NMOS is ON in Pull-down mode $\Rightarrow$ same as the CMOS inverter $\Rightarrow W_n = W$.

All 3 PMOS are on during pull-up mode $\Rightarrow W_p = 3(2W) = 6W$.

EX16.11

NMOS: Worst Case, M_{NA}, M_{NB} on, $W_n = 2(W)$ or M_{NC}, M_{ND} or M_{NC}, M_{NE} on $\Rightarrow W_n = 2(W)$.

PMOS: M_{PA} and M_{PC} on or M_{PA} and M_{PB} on $\Rightarrow W_P = 2(2W) = 4\text{W}$

If M_{PD} and M_{PE} on, need $W_P = 2(4W) = 8\text{W}$

EX16.12

(a) $\upsilon_O = \phi - V_{TN} = 2.5 - 0.4 = 2.1 \text{ V}$

(b) For $\upsilon_{DS} = 0$, $\upsilon_O = 1.8 \text{ V}$

(c) $\upsilon_O = \phi - V_{TN} = 2.5 - 0.4 = 2.1 \text{ V}$

(d) $\upsilon_O = \phi - V_{TN} = 1.5 - 0.4 = 1.1 \text{ V}$

EX16.13

(a) $\upsilon_I' = \phi - V_{TN} = 3.3 - 0.5 = 2.8 \text{ V}$

$$\frac{K_D}{K_L}\left[2(\upsilon_I' - V_{TN})\upsilon_O - \upsilon_O^2\right] = \left[V_{DD} - \upsilon_O - V_{TN}\right]^2$$

$$\frac{K_D}{K_L}\left[2(2.8 - 0.5)(0.1) - (0.1)^2\right] = [3.3 - 0.1 - 0.5]^2$$

which yields

$$\frac{K_D}{K_L} = 16.2$$

(b) $\upsilon_I' = \phi - V_{TN} = 2.8 - 0.5 = 2.3 \text{ V}$

$$\frac{K_D}{K_L}\left[2(2.3 - 0.5)(0.1) - (0.1)^2\right] = [3.3 - 0.1 - 0.5]^2$$

which yields

$$\frac{K_D}{K_L} = 20.8$$

EX16.14

$16\,K \Rightarrow 16384$ cells

Total $\text{Power} = 125\ mW = (2.5)I_T \Rightarrow I_T = 50\ mA$

Then, for each cell, $I = \dfrac{50\ mA}{16384} \Rightarrow I = 3.05\ \mu A$

Now, $I \cong \dfrac{V_{DD}}{R}$ or $R = \dfrac{V_{DD}}{I} = \dfrac{2.5}{3.05} \Rightarrow \underline{R = 0.82\ M\Omega}$

Test Your Understanding Solutions

TYU16.1

$$P_{D,\max} = i_{D,\max} \cdot V_{DD}$$

$$0.50 = i_{D,\max}(1.8) \Rightarrow i_{D,\max} = 0.2778 \text{ mA}$$

$$i_{D,\max} = 0.2778 = \left(\frac{0.1}{2}\right)\left(\frac{W}{L}\right)_L (1.8 - 0.12 - 0.4)^2 \Rightarrow \left(\frac{W}{L}\right)_L = 3.39$$

$$\frac{K_D}{K_L}\left[2(1.4-0.4)(0.12)-(0.12)^2\right] = (1.8-0.12-0.4)^2 \Rightarrow \frac{K_D}{K_L} = 7.26$$

$$\frac{K_D}{K_L} = 7.26 = \frac{(W/L)_D}{(W/L)_L} = \frac{(W/L)_D}{3.39} \Rightarrow \left(\frac{W}{L}\right)_D = 24.6$$

TYU16.2

$$P_{D,\max} = i_{D,\max} \cdot V_{DD}$$

$$0.2 = i_{D,\max}(1.8) \Rightarrow i_{D,\max} = 0.111 \text{ mA}$$

$$i_{D,\max} = 0.111 = \left(\frac{0.1}{2}\right)\left(\frac{W}{L}\right)_L [-(-0.6)]^2 \Rightarrow \left(\frac{W}{L}\right)_L = 6.17$$

$$\frac{K_D}{K_L} = \frac{[-(-0.6)]^2}{2(1.8-0.4)(0.08)-(0.08)^2} = 1.654 = \frac{(W/L)_D}{(W/L)_L} = \frac{(W/L)_D}{6.17}$$

so $\left(\frac{W}{L}\right)_D = 10.2$

TYU16.3

(a) $I = (0.098)(100{,}000) \text{ mA}, \Rightarrow I = 9.8 \text{ A}$

$P = (0.294)(100{,}000) \text{ mW}, \Rightarrow P = 29.4 \text{ W}$

(b) $I = (0.589)(100{,}000) \text{ mA}, \Rightarrow I = 58.9 \text{ A}$

$P = (1.766)(100{,}000) \text{ mW}, \Rightarrow P = 176.6 \text{ W}$

(c) $I = (0.064)(100{,}000) \text{ mA}, \Rightarrow I = 6.4 \text{ A}$

$P = (0.194)(100{,}000) \text{ mW}, \Rightarrow P = 19.2 \text{ W}$

TYU16.4

(a) $P = i_D \cdot V_{DD}$

$$50 = i_D(2.5) \Rightarrow i_D = 20\,\mu\text{A}$$

$$i_D = 20 = \left(\frac{100}{2}\right)\left(\frac{W}{L}\right)_L [-(-0.6)]^2 \Rightarrow \left(\frac{W}{L}\right)_L = 1.11$$

$$\frac{K_D}{K_L}\left[2(2.5-0.4)(0.05)-(0.05)^2\right] = [-(-0.6)]^2 \Rightarrow \frac{K_D}{K_L} = 1.735$$

$$\frac{K_D}{K_L} = 1.735 = \frac{(W/L)_D}{(W/L)_L} = \frac{(W/L)_D}{1.11} \Rightarrow \left(\frac{W}{L}\right)_D = 1.93$$

(b) $3(1.735)\left[2(2.5-0.4)V_{OL} - V_{OL}^2\right] = [-(-0.6)]^2$

$$5.205V_{OL}^2 - 21.861V_{OL} + 0.36 = 0 \Rightarrow V_{OL} = 16.5 \text{ mV}$$

TYU16.5

(a) $$\frac{1}{2}\cdot\frac{(W/L)_D}{(W/L)_L}\left[2(2.1-0.4)(0.08)-(0.08)^2\right]=(2.5-0.08-0.4)^2 \Rightarrow \left(\frac{W}{L}\right)_D=15.4$$

(b) $$i_{D,\max}=\left(\frac{100}{2}\right)(0.5)(2.5-0.08-0.4)^2=102\,\mu\text{ A}$$

$$P=i_{D,\max}\cdot V_{DD}=(102)(2.5)=255\,\mu\text{ W}$$

TYU16.6

(a) $$\frac{1}{2}\frac{(W/L)_D}{(W/L)_L}\left[2(2.5-0.4)(0.08)-(0.08)^2\right]=\left[-(-0.6)\right]^2 \Rightarrow \left(\frac{W}{L}\right)_D=1.09$$

(b) $$i_{D,\max}=\left(\frac{100}{2}\right)(0.5)\left[-(-0.6)\right]^2=9\,\mu\text{ A}$$

$$P=i_{D,\max}\cdot V_{DD}=(9)(2.5)=22.5\,\mu\text{ W}$$

TYU16.7

a.

$$K_n=K_p=50\ \mu A/V^2$$

$$V_{It}=2.5\text{ V}$$

$$i_D(\max)=K_n(V_{It}-V_{TN})^2=50(2.5-0.8)^2 \Rightarrow \underline{i_D(\max)=145\ \mu\text{A}}$$

b.

$$K_n=K_p=200\ \mu A/V^2$$

$$V_{It}=2.5\text{ V}$$

$$i_D(\max)=(200)(2.5-0.8)^2 \Rightarrow \underline{i_D(\max)=578\ \mu\text{A}}$$

TYU16.8

(a) $$V_{It}=\frac{5+(-2)+0.8}{1+1}=1.9\text{ V}$$

$$V_{OPt}=V_{It}-V_{TP}=1.9-(-2)=3.9\text{ V}$$

$$V_{ONt}=V_{It}-V_{TN}=1.9-0.8=1.1\text{ V}$$

(b) $$V_{IL}=0.8+\frac{3}{8}\left[5+(-2)-0.8\right]=1.625\text{ V}$$

$$V_{IH}=0.8+\frac{5}{8}\left[5+(-2)-0.8\right]=2.175\text{ V}$$

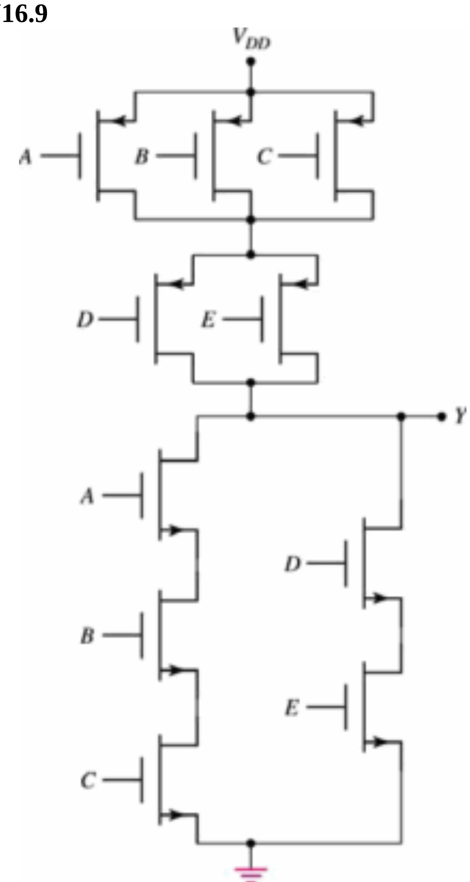
$$V_{OLU}=\frac{1}{2}\left[2(2.175)-5-0.8-(-2)\right]=0.275\text{ V}$$

$$V_{OHU}=\frac{1}{2}\left[2(1.625)+5-0.8-(-2)\right]=4.725\text{ V}$$

(c) $$NM_L=1.625-0.275=1.35\text{ V}$$

$$NM_H=4.725-2.175=2.55\text{ V}$$

TYU16.9



TYU16.10

NMOS – 2 transistors in series

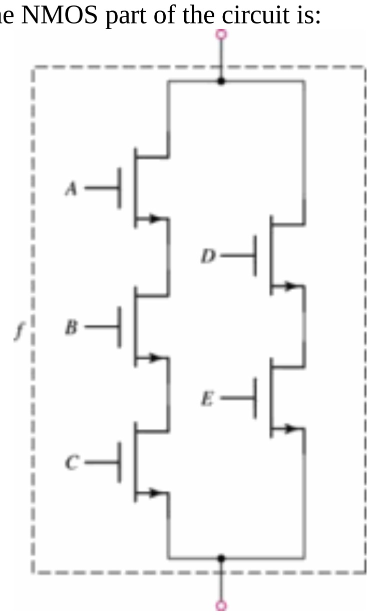
$W_n = 2(W) = 2\text{W}$

PMOS – 2 transistors in series

$W_p = 2(2W) = 4\text{W}$

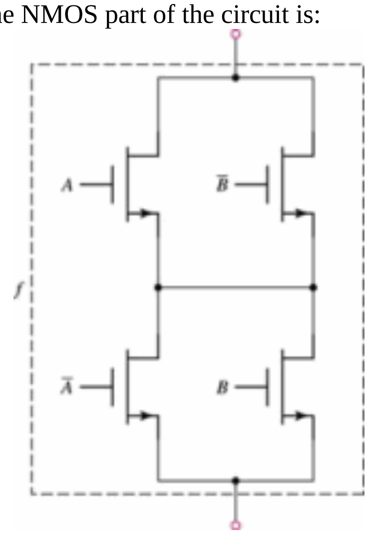
TYU16.11

The NMOS part of the circuit is:



TYU16.12

The NMOS part of the circuit is:



TYU16.13

Insert Figure X-TYU16.13

TYU16.14

For NMOS, $\phi - \upsilon_O \ge 0.4$ V or $\phi - \upsilon_I \ge 0.4$ V

At $\upsilon_I = 2.1$ V, $2.1 = 2.5 - 0.2t \Rightarrow t = 2$ s

NMOS conducting for $2 \le t \le 12.5$ s

For PMOS, $\upsilon_I - 0 \ge 0.4$ V

At $\upsilon_I = 0.4$ V, $0.4 = 2.5 - 0.2t \Rightarrow t = 10.5$ s

PMOS conducting for $0 \le t \le 10.5$ s

TYU16.15

(a) $1\,K \Rightarrow 32 \times 32$ array

Each row and column requires a 5-bit word $\Rightarrow$ 6 transistors per row and column, $\Rightarrow 32 \times 6 + 32 \times 6 = 384$ transistors plus buffer transistors.

(b) $4\,K \Rightarrow 64 \times 64$ array

Each row and column requires a 6-bit word $\Rightarrow$ 7 transistors per row and column $\Rightarrow 64 \times 7 + 64 \times 7 = 896$ transistors plus buffer transistors.

(c) $16\,K \Rightarrow 128 \times 128$ array

Each row and column requires a 7-bit word $\Rightarrow$ 8 transistors per row and column $\Rightarrow 128 \times 8 + 128 \times 8 = 2048$ transistors plus buffer transistors.

TYU16.16

From Equation (16.82)

$$\frac{(W/L)_{nA}}{(W/L)_{n1}} = \frac{2\left(V_{DD}V_{TN}\right) - 3V_{TN}^2}{\left(V_{DD} - 2V_{TN}\right)^2} = \frac{2(2.5)(0.4) - 3(0.4)^2}{\left(2.5 - 2(0.4)\right)^2} = 0.526$$

From Equation (16.84)

$$\frac{(W/L)_{p}}{(W/L)_{nB}} = \frac{k_n'}{k_p'} \cdot \frac{2\left(V_{DD}V_{TN}\right) - 3V_{TN}^2}{\left(V_{DD} + V_{TP}\right)^2} = (2.5)\left[\frac{2(2.5)(0.4) - 3(0.4)^2}{(2.5 - 0.4)^2}\right] = 0.862$$

So $\left(\frac{W}{L}\right)$ of transmission gate device must be < 0.526 times the $\left(\frac{W}{L}\right)$ of the NMOS transistors in the inverter cell. The $\left(\frac{W}{L}\right)$ of the PMOS transistors must be < 0.862 times the $\left(\frac{W}{L}\right)$ of the transmission gate devices. Then the $\left(\frac{W}{L}\right)$ of the PMOS devices must be < 0.453 times $\left(\frac{W}{L}\right)$ of NMOS devices in cell.

TYU16.17

Initial voltage across the storage capacitor $= V_{DD} - V_{TN} = 3 - 0.5 = 2.5\ V$.

Now

$$-I = C\frac{dV}{dt} \text{ or } V = -\frac{I}{C} \cdot t + K$$

where $K = 2.5\ V$, $t = 1.5\ ms$, $V = \frac{2.5}{2} = 1.25\ V$, and $C = 0.05\ pF$. Then

$$1.25 = 2.5 - \frac{I(1.5 \times 10^{-3})}{(0.05 \times 10^{-12})} \Rightarrow$$

$$\underline{I = 4.17 \times 10^{-11}\,A \Rightarrow I = 41.7\ pA}$$

Chapter 17

Exercise Solutions

EX17.1

(a) $i_E = \dfrac{-0.7-(-1.8)}{R_E} = 0.11 \Rightarrow R_E = 10 \text{ k}\Omega$

$i_{C1} = i_{C2} = \dfrac{i_E}{2} = 0.055 \text{ mA}$

$R_C = \dfrac{1.8-1.45}{0.055} = 6.364 \text{ k}\Omega$

(b) (i) $\upsilon_1 = 0.5 \text{ V}, \ \upsilon_E = 0.5-0.7 = -0.2 \text{ V}$

$i_E = \dfrac{-0.2-(-1.8)}{10} = 0.16 \text{ mA}$

$\upsilon_{O1} = 1.8-(0.16)(6.364) = 0.782 \text{ V}$

$\upsilon_{O2} = 1.8 \text{ V}$

(ii) $\upsilon_1 = -0.5 \text{ V}, \ i_E = 0.11 \text{ mA}$

$\upsilon_{O1} = 1.8 \text{ V}$

$\upsilon_{O2} = 1.8-(0.11)(6.364) = 1.1 \text{ V}$

(c) (i) $i_E = 0.16 \text{ mA}, \ P = (0.16)[1.8-(-1.8)] = 0.576 \text{ mW}$

(ii) $i_E = 0.11 \text{ mA}, \ P = (0.11)[1.8-(-1.8)] = 0.396 \text{ mW}$

EX17.2

$P(i_{CXY} + i_{CR} + i_3 + i_4)(5.2)$

$v_X = v_Y = \text{logic } 1 \Rightarrow i_{CXY} = 3.22 \text{ mA}$

$i_{CR} = 0$

$i_3 = \dfrac{-0.7+5.2}{1.5} = 3 \text{ mA}$

$i_4 = \dfrac{-1.4+5.2}{1.5} = 2.53 \text{ mA}$

a. $P = (3.22+0+3+2.53)(5.2) \Rightarrow \underline{P = 45.5 \text{ mW}}$

$v_X = v_Y = \text{logic } 0 \Rightarrow i_{CXY} = 0$

$i_{CR} = 2.92 \text{ mA}$

$i_3 = 2.53 \text{ mA}$

$i_4 = 3 \text{ mA}$

b. $P = (0+2.92+2.53+3)(5.2) \Rightarrow \underline{P = 43.9 \text{ mW}}$

EX17.3

$$\upsilon_{B5} = -1 + 0.7 = -0.3 \text{ V}$$

$$R_1 = \frac{0.3}{0.5} = 0.6 \text{ k}\Omega$$

$$R_2 = \frac{-0.3 - 1.4 - (-3.3)}{0.5} = 3.2 \text{ k}\Omega$$

$$R_5 = \frac{-1 - (-3.3)}{0.5} = 4.6 \text{ k}\Omega$$

EX17.4

$$I_{MAX} = 1 = \frac{-0.7 - (-5.2)}{R_3} \Rightarrow R_3 = R_4 = 4.5 \text{ K}$$

$$i_{CXY} = \frac{-0.7 - 0.7 - (-5.2)}{1.18} = 3.22 \text{ mA}$$

$$i_5 = i_1 = 1.40 \text{ mA}$$

$$i_3 = 1.0 \text{ mA}$$

$$i_4 = \frac{-1.4 - (-5.2)}{4.5} = 0.844 \text{ mA}$$

$$P = (3.22 + 1.4 + 1.4 + 1.0 + 0.844)(5.2) = 40.8 \text{ mW}$$

EX17.5

$$i_L = \left(\frac{v_{oR} - 0.7 - (-5.2)}{(1.18)(51)}\right)(10)$$

$$i_3 = \frac{v_{oR} - (-5.2)}{1.5}$$

$$\left[\frac{0 - (V_{oR} + 0.7)}{0.24}\right](51) = \frac{v_{oR} + 5.2}{1.5} + \left(\frac{v_{oR} + 4.5}{(1.18)(51)}\right)(10)$$

$$-v_{oR}\left[\left(\frac{51}{0.24}\right) + \frac{1}{1.5} + \frac{1-(6)}{(1.18)(51)}\right] = \frac{(0.7)(51)}{0.24} + \frac{5.2}{1.5} + \frac{4.5(10)}{(1.18)(51)}$$

$$-v_{oR}[212.50 + 0.6667 + 0.166168] = 148.75 + 3.4666 + 0.747757$$

$$-v_{oR}[213.3328] = 152.9644$$

$$v_{oR} = -0.7170$$

EX17.6

$$r_{\pi 3} = \frac{(100)(0.026)}{1} = 2.6 \text{ K}$$

$$g_{m3} = \frac{1}{0.026} = 38.46 \text{ mA/V}$$

$$I_{b3} = \frac{V_n}{R_{C2} + r_{\pi 3} + (1+\beta)R_3} = \frac{V_n}{0.24 + 2.6 + (101)(4.5)}$$

$$I_{b3} = \frac{V_n}{457.34}$$

$$V_O = -I_{b3}(R_{C2} + r_{\pi 3}) = -\left(\frac{V_n}{457.34}\right)(0.24 + 2.6)$$

$$\underline{V_O = -0.00621\ V_n}$$

$$V_O' = (1+\beta)I_{b3}R_3 = (101)\left(\frac{V_n}{457.34}\right)(4.5)$$

$$\underline{V_O' = 0.9938\ V_n}$$

EX17.7

$$P = I_Q \cdot V_{CC} \Rightarrow 0.2 = I_Q(1.7) \Rightarrow \underline{I_Q = 117.6\ \mu\text{A}}$$

$$Q_R \text{ on } \Rightarrow v_0 = 1.7 - I_Q R_C = 1.7 - 0.4 \Rightarrow R_C = \frac{0.4}{0.1176} \Rightarrow \underline{R_C = 3.40\ \text{k}\Omega}$$

$$V_R = \frac{1.7 + 1.3}{2} \Rightarrow \underline{V_R = 1.5\ \text{V}}$$

EX17.8

(a)

$$v_X = v_Y = 5\ V$$

$$v_1 = V_{BE}(sat) + 2V_Y = 0.8 + 2(0.7) = 2.2\ V$$

$$i_1 = \frac{5 - 2.2}{4} = 0.70\ mA$$

$$i_{RC} = \frac{V_{CC} - V_{CE}(sat)}{R_C} = \frac{5 - 0.1}{4} = 1.225\ mA$$

$$P = (i_1 + i_{RC})V_{CC} = (0.70 + 1.225)(5)$$

or $\underline{P = 9.625\ mW}$

$$v_X = v_Y = 0 \Rightarrow v_1 = 0.70\ V$$

$$i_1 = \frac{V_{CC} - v_1}{R_1} = \frac{5 - 0.70}{4} = 1.075\ mA$$

(b) $P = i_1 \cdot V_{CC} = (1.075)(5) \Rightarrow \underline{P = 5.375\ mW}$

EX17.9

(a) $\upsilon_X = \upsilon_Y = 0.1\ \text{V}$

$$\upsilon_{B1} = 0.1 + 0.8 = 0.9\ \text{V}$$

$$i_1 = i_{B1} = \frac{5 - 0.9}{12} = 0.342\ \text{mA}$$

$$i_{C1} \cong 0, \quad i_{B2} = i_{C2} = 0, \quad i_{Bo} = i_{Co} = 0$$

(b) $\upsilon_X = \upsilon_Y = 5 \text{ V}$

$\upsilon_{B1} = 0.8 + 0.8 + 0.7 = 2.3 \text{ V}$

$i_1 = i_{B1} = \dfrac{5 - 2.3}{12} = 0.225 \text{ mA}$

$i_{B2} = |i_{C1}| = (1 + 0.2) i_{B1} = 0.27 \text{ mA}$

$\upsilon_{C2} = 0.8 + 0.1 = 0.9 \text{ V}$

$i_2 = i_{C2} = \dfrac{5 - 0.9}{4} = 1.025 \text{ mA}$

$i_{E2} = i_{B2} + i_{C2} = 0.27 + 1.025 = 1.295 \text{ mA}$

$i_{Bo} = i_{E2} - \dfrac{0.8}{R_B} = 1.295 - \dfrac{0.8}{2} = 0.895 \text{ mA}$

$i_3 = i_{Co} = \dfrac{5 - 0.1}{6} = 0.8167 \text{ mA}$

EX17.10

(a) $\upsilon_X = \upsilon_Y = 3.6 \text{ V}$

$i_1 = \dfrac{5 - (0.8 + 0.8 + 0.7)}{12} = 0.225 \text{ mA}$

$i_{B2} = (1 + 0.2)(0.225) = 0.27 \text{ mA}$

$i_{C2} = \dfrac{5 - (0.8 + 0.1)}{4} = 1.025 \text{ mA}$

$i_{Bo} = 0.27 + 1.025 - \dfrac{0.8}{2} = 0.895 \text{ mA}$

$i'_L = \dfrac{5 - (0.1 + 0.8)}{12} = 0.3417 \text{ mA}$

$i_L(\max) = \beta i_{Bo} = N i'_L$

$(25)(0.895) = N(0.3417) \Rightarrow N = 65$

(b) $i_L(\max) = 12 = N i'_L = N(0.3417) \Rightarrow N = 35$

EX17.11

(a) $i_C = \dfrac{5 - 0.4}{2.25} = 2.044 \text{ mA}$

$i'_C = \dfrac{2 + 2.044}{1 + \dfrac{1}{15}} = 3.791 \text{ mA}$

$i'_B = \dfrac{i'_C}{\beta} = \dfrac{3.791}{15} = 0.253 \text{ mA}$

$i_D = i_B - i'_B = 2 - 0.253 = 1.747 \text{ mA}$

(b) $i_C = 2.044 + 10 = 12.044 \text{ mA}$

$$i'_C = \frac{2 + 12.044}{1 + \frac{1}{15}} = 13.166 \text{ mA}$$

$$i'_B = \frac{13.166}{15} = 0.878 \text{ mA}$$

$i_D = 2 - 0.878 = 1.122 \text{ mA}$

(c) $i_D = 0$, $i'_B = 2 \text{ mA}$, $i'_C = (2)(15) = 30 \text{ mA}$

$i_L = 30 - 2.044 \cong 28 \text{ mA}$

EX17.12

(a) $v_1 = 0.4 + 0.3 = 0.7$, $i_1 = \dfrac{5 - 0.7}{40} = 0.1075 \text{ mA}$

All transistor currents are zero.

$P = (0.1075)(5 - 0.4) \Rightarrow 495 \ \mu\text{W}$

(b) $v_1 = 1.4 \text{ V}$, $i_1 = i_{B2} = \dfrac{5 - 1.4}{40} = 0.090 \text{ mA}$

$v_{C2} = 0.7 + 0.4 = 1.1 \text{ V}$, $i_2 = i_{C2} = \dfrac{5 - 1.1}{12} = 0.325 \text{ mA}$

$i_{B0} \approx i_{B2} + i_{C2} = 0.09 + 0.325 = 0.415 \text{ mA}$

$i_{C0} \approx 0$

$P = (i_1 + i_2)(5) = (0.09 + 0.325)(5) = 2.08 \text{ mW}$

Test Your Understanding Solutions

TYU17.1

(a) $i_E = 0.8 = \dfrac{0.75 - 0.7 - (-1.8)}{R_E} \Rightarrow R_E = 2.31 \text{ k}\Omega$

$R_{C2} = \dfrac{1.8 - 1.1}{0.8} = 0.875 \text{ k}\Omega$

(b) $i_E = \dfrac{1.1 - 0.7 - (-1.8)}{2.3125} = 0.951 \text{ mA}$

$R_{C1} = \dfrac{1.8 - 1.1}{0.95135} = 0.736 \text{ k}\Omega$

TYU17.2

logic $1 = -0.7$ V

Q_1 and Q_2 on when $v_X = v_Y = -0.7$ V

$i_E = \dfrac{-0.7 - 0.7 - (-5.2)}{R_E} = 2.5 \Rightarrow \underline{R_E = 1.52 \text{ k}\Omega}$

$v_{\text{NOR}} = -1.5 \Rightarrow R_{C1} = \dfrac{0 - (-1.5 + 0.7)}{2.5} \Rightarrow \underline{R_{C1} = 320\ \Omega}$

$V_R = \dfrac{-1.5 - 0.7}{2} \Rightarrow \underline{V_R = -1.1 \text{ V}}$

Q_R on $\Rightarrow i_E = \dfrac{-1.1 - 0.7 - (-5.2)}{1.52} = 2.237 \text{ mA}$

$R_{C2} = \dfrac{0 - (-1.5 + 0.7)}{2.237} \Rightarrow \underline{R_{C2} = 358\ \Omega}$

$R_3 = R_4 = \dfrac{-0.7 - (-5.2)}{2.5} \Rightarrow \underline{R_3 = R_4 = 1.8 \text{ k}\Omega}$

TYU17.3

State	A	B	C	Q_{01}	Q_{02}	Q_{03}	Q_1	Q_2	Q_R	v_0
1	0	0	0	off	off	off	off	on	on	0
2	1	0	0	“on”	off	off	off	on	on	0
3	0	1	0	off	on	off	off	on	“off”	1
4	0	0	1	off	off	on	on	off	on	0
5	1	1	0	on	on	off	off	on	off	1
6	1	0	1	on	off	on	on	off	“off”	1
7	0	1	1	off	on	on	on	off	on	0
8	1	1	1	on	on	on	on	off	off	1

$$\underbrace{(A \text{ AND } C)}_{\text{true for}} \text{ OR } \underbrace{(B \text{ AND } \bar{C})}_{\text{true for}}$$

$$\underbrace{\text{states 6 and 8 } \text{ states 3 and 5}}_{\text{Output goes high for these 4 states}}$$

TYU17.4

A	B	C	v_0
0	0	0	0
1	0	0	1
0	1	0	1
0	0	1	1
1	1	0	0
1	0	1	0
0	1	1	0
1	1	1	1

$$\Rightarrow (A \oplus B) \oplus C$$

TYU17.5

(a) $i_1 = \dfrac{5-(0.1+0.7)}{15} = 0.28 \text{ mA}$

$i_2 = i_R = i_B = i_{RC} = 0$

$\upsilon_O = 5 \text{ V}$

(b) Same as part (a).

(c) $i_2 = i_1 = \dfrac{5-(0.8+0.7+0.7)}{15} = 0.1867 \text{ mA}$

$i_R = \dfrac{0.8}{15} = 0.0533 \text{ mA}$

$i_B = 0.1867 - 0.0533 = 0.1334 \text{ mA}$

$i_{RC} = \dfrac{5-0.1}{6} = 0.8167 \text{ mA}$

$\upsilon_O = 0.1 \text{ V}$

TYU17.6

(a) $i_B = 0.1134 \text{ mA}, \quad i_{RC} = 0.8167 \text{ mA}$

$i'_L = \dfrac{5-(0.1+0.7)}{15} = 0.28 \text{ mA}$

$i_{RC} + N i'_L = \beta i_B$

$0.8167 + N(0.28) = (30)(0.1134) \Rightarrow N = 9$

(b) $i_{C,\max} = \beta i_B = (30)(0.1134) = 3.4 < 12 \text{ mA}$

$\Rightarrow N = 9$

TYU17.7

From EX17.9, $i_{Bo} = 0.895 \text{ mA}, \quad i_3 = 0.8167 \text{ mA}$

$\upsilon_O = 0.1 \text{ V}$, so $\upsilon'_{B1} = 0.1 + 0.8 = 0.9 \text{ V}$

$i'_L = \dfrac{5-0.9}{12} = 0.3417 \text{ mA}$

$i_{Co,\max} = \beta i_{Bo} = i_3 + N i'_L$

$(25)(0.895) = 0.8167 + N(0.3417)$

$N = 63.1 \Rightarrow N = 63$

TYU17.8

Q_1 in saturation

$i_{B1} = \frac{5-0.9}{6} \Rightarrow \underline{i_{B1} = 0.683 \text{ mA}}$

$\underline{|i_{C1}| = i_{B2} = i_{C2} = 0}$

$\underline{i_{B0} = i_{C0} = 0}$

$v_{B4} = 0.1 + 0.7 = 0.8 \text{ V}$

$i_{B4} = \frac{0.1}{(21)(4)} \Rightarrow \underline{i_{B4} = 1.19\ \mu\text{A}}$

$\underline{i_{C4} = 23.8\ \mu\text{A}}$

$\underline{i_{B3} = i_{C3} = 0}$

TYU17.9

(a) $v_X = v_Y = 0.4,\ \ v_{B1} = 0.4 + 0.7 = 1.1 \text{ V}$

$i_1 = \frac{5-1.1}{2.8} = 1.393 \text{ mA}$

$P = i_1(5-0.4) = (1.393)(5-0.4) = 6.41 \text{ mW}$

(b) $v_X = v_Y = 3.6 \text{ V}$

$v_{B1} = 2.1,\ \ i_1 = \frac{5-2.1}{2.8} = 1.036 \text{ mA}$

$v_{C2} = 0.7 + 0.4 = 1.1 \text{ V},\ \ i_2 = \frac{5-1.1}{0.76} = 5.132 \text{ mA}$

$v_{E4} = 1.1 - 0.7 = 0.4 \text{ V},\ \ i_{R4} = \frac{0.4}{3.5} = 0.1143 \text{ mA}$

$i_{R3} = \left(\frac{\beta}{1+\beta}\right) i_{R4} = \left(\frac{25}{26}\right)(0.1143) = 0.1099 \approx 0.11 \text{ mA}$

$P = (i_1 + i_2 + i_{R3})(5) = (1.036 + 5.132 + 0.11)(5)$

or

$P = 31.4 \text{ mW}$

TYU17.10

(a) $\upsilon_X = 0.4 \text{ V},\ \upsilon_{E1} = 0.4 + 0.7 = 1.1 \text{ V}$

$i_{R1} = \frac{5-1.1}{40} \Rightarrow 97.5\ \mu\text{A}$

Q_2 cutoff, $i_{R2} = 0$

(b) $\upsilon_X = 3.6 \text{ V},\ \ \upsilon_{E1} = 3(0.7) = 2.1 \text{ V}$

$i_{R1} = \frac{5-2.1}{40} \Rightarrow 72.5\ \mu\text{A}$

$\upsilon_{C2} = 2(0.7) + 0.4 = 1.8 \text{ V}$

$i_{R2} = \frac{5-1.8}{50} \Rightarrow 64\ \mu\text{A}$

TYU17.11

(a) $\upsilon_X = 0.4 \text{ V}, \quad \upsilon_{E1} = 0.4 + 0.7 = 1.1 \text{ V}$

$$i_{R1} = \frac{3.5 - 1.1}{40} \Rightarrow 60\,\mu\text{A}$$

$$i_{R2} = 0$$

(b) $\upsilon_X = 2.1 \text{ V}, \quad \upsilon_{E1} = 2.1 \text{ V}$

$$i_{R1} = \frac{3.5 - 2.1}{40} \Rightarrow 35\,\mu\text{A}$$

$$\upsilon_{C2} = 1.8 \text{ V}$$

$$i_{R2} = \frac{3.5 - 1.8}{50} \Rightarrow 34\,\mu\text{A}$$