Chapter 13

Exercise Solutions

E13.3

$$V_{IN}(\max) = V^+ - V_{EB}(\text{on}) = 15 - 0.6 = 14.4 \text{ V}$$

$$V_{IN}(\min) \cong 4V_{BE}(\text{on}) + V^+$$

$$= 4(0.6) - 15 = -12.6 \text{ V}$$

$$\underline{-12.6 \le V_{IN}(\text{cm}) \le 14.4 \text{ V}}$$

E13.4

a. $V_0(\max) \cong V^+ - 2V_{BE}(\text{on}) = 15 - 2(0.6)$

$$V_0(\max) = 13.8 \text{ V}$$

$$V_0(\min) = 3V_{BE}(\text{on}) + V^- = 3(0.6) - 15$$

$$V_0(\min) \cong -13.2 \text{ V}$$

$$\underline{-13.2 \le V_0 \le 13.8 \text{ V}}$$

b. $V_0(\max) = 5 - 1.2 = 3.8 \text{ V}$

$$V_0(\min) \cong 3V_{BE} + V^- = 3(0.6) - 5 = -3.2 \text{ V}$$

$$\underline{-3.2 \le V_0 \le 3.8 \text{ V}}$$

E13.5

$$I_{C1} = I_{C2} \cong 9.5\ \mu\text{A}$$

$$I_{B1} = I_{B2} = \frac{9.5\ \mu\text{A}}{200} = 0.0475\ \mu\text{A}$$

$$\Rightarrow \underline{I_{B1} = I_{B2} = 47.5 \text{ nA}}$$

E13.6

$$I_{REF} \cong \frac{15 - 2(0.6) - (-15)}{40} = 0.72 \text{ mA}$$

$$V_{BE} = V_T \ln\left(\frac{I_{REF}}{I_S}\right) = (0.026)\ln\left(\frac{0.72 \times 10^{-3}}{10^{-14}}\right)$$

$$= 0.650 \text{ V}$$

So

$$I_{REF} = \frac{30 - 2(0.65)}{40} \Rightarrow \underline{I_{REF} = 0.718 \text{ mA}}$$

$$\underline{V_{BE11} = 0.650 \text{ V}}$$

$$I_{C10}R_4 = V_T \ln\left(\frac{I_{REF}}{I_{C10}}\right)$$

$$I_{C10}(5) = (0.026)\ln\left(\frac{0.718}{I_{C10}}\right)$$

By trial and error: $I_{C10} = 18.9\ \mu\text{A}$

$$V_{BE10} = V_{BE11} - I_{C10}R_4 = 0.650 - (0.0189)(5)$$

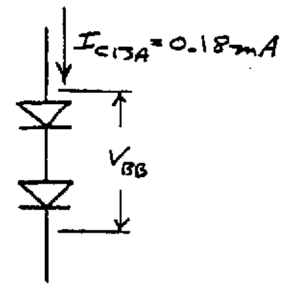
$$\Rightarrow \underline{V_{BE10} \cong 0.556 \text{ V}}$$

$$I_{C6} \cong \frac{I_{C10}}{2} = \frac{18.9}{2} = 9.45\ \mu\text{A}$$

$$V_{BE6} = V_T \ln\left(\frac{I_{C6}}{I_S}\right) = (0.026)\ln\left(\frac{9.45 \times 10^{-6}}{10^{-14}}\right)$$

$$\Rightarrow \underline{V_{BE6} = 0.537 \text{ V}}$$

E13.7



$$0.18 \times 10^{-3} = 10^{-14} \exp\left(\frac{V_D}{V_T}\right)$$

$$V_D = V_T \ln\left(\frac{0.18 \times 10^{-3}}{10^{-14}}\right)$$

$$= (0.026)\ln\left(\frac{0.18 \times 10^{-3}}{10^{-14}}\right)$$

$$V_D = 0.6140$$

$$\underline{V_{BB} = 2V_{DD} \cong 1.228 \text{ V}}$$

$$I_{C14} = I_{C20} = I_S \exp\left(\frac{V_{BB}/2}{V_T}\right)$$

$$= 3 \times 10^{-14} \exp\left(\frac{0.6140}{0.026}\right)$$

$$\underline{I_{C14} = I_{C20} = 0.541 \text{ mA}}$$

E13.8

$$I_{REF} = \frac{10 - 0.6 - 0.6 - (-10)}{40}$$

$$\Rightarrow \underline{I_{REF} = 0.47 \text{ mA}}$$

$$I_{C10}R_4 = V_T \ln\left(\frac{I_{REF}}{I_{C10}}\right)$$

$$I_{C10}(5) = (0.026)\ln\left(\frac{0.47}{I_{C10}}\right)$$

By trial and error:

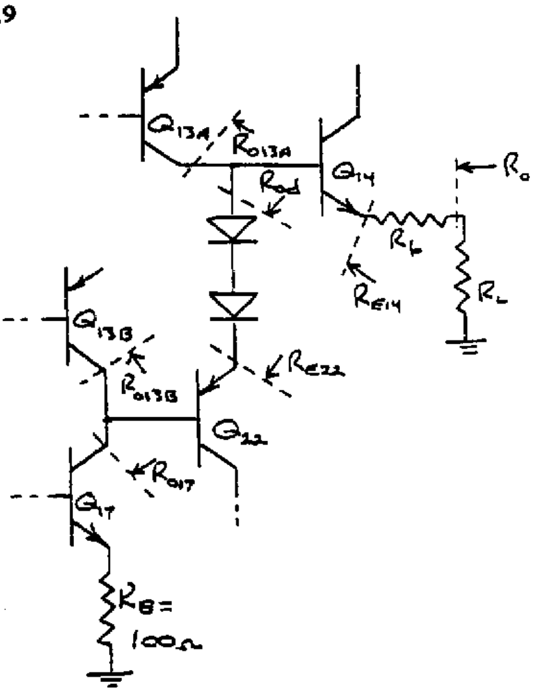
$$\Rightarrow \underline{I_{C10} \cong 17.2\ \mu\text{A}}$$

$$I_{C6} \cong \frac{I_{C10}}{2} \Rightarrow \underline{I_{C6} = 8.6\ \mu\text{A}}$$

$$I_{C13B} = (0.75)I_{REF} \Rightarrow \underline{I_{C13B} = 0.353 \text{ mA}}$$

$$I_{C13A} = (0.25)I_{REF} \Rightarrow \underline{I_{C13A} = 0.118 \text{ mA}}$$

E13.9



$R_0 = R_6 + R_{E14}$

$$R_{E14} = \frac{r_{\pi 14} + R_{0d} \| R_{013A}}{1 + \beta_n}$$

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

$$r_d = \frac{V_T}{I_D} = \frac{V_T}{I_{C13A}} = \frac{0.026}{0.18} \Rightarrow 144\ \Omega$$

$$R_{E22} = \frac{r_{\pi 22} + R_{017} \| R_{013B}}{1 + \beta_P}$$

$R_{013B} = r_{013B} = 92.6\ \text{k}\Omega$

$R_{017} = r_{017}[1 + g_{m17}(R_8 \| r_{\pi 17})] = 283\ \text{k}\Omega$

From previous calculations

$R_{E22} = 1.51\ \text{k}\Omega$

$R_{0d} = 2r_d + R_{E22} = 2(0.144) + 1.51 = 1.80\ \text{k}\Omega$

$R_{013A} = r_{013A} = 278\ \text{k}\Omega$

$$r_{\pi 14} = \frac{\beta_n V_T}{I_{C14}} = \frac{(200)(0.026)}{5} = 1.04\ \text{k}\Omega$$

$$R_{E14} = \frac{1.04 + 1.8 \| 278}{201} \Rightarrow 14.1\ \Omega$$

$R_0 = R_6 + R_{E14} = 27 + 14.1$

$\Rightarrow \underline{R_0 \cong 41\ \Omega}$

E13.10

For Q_6 we have $V_{SG5} = V_{SG6} = 1.06$ V

So

$$V_{SD6}(\text{sat}) = 1.06 - 0.5 = 0.56\ \text{V}$$

For M_1 and M_2

$$I_D = \frac{I_Q}{2} = K_p(V_{SG1} + V_{TP})^2$$

$$\frac{0.0397}{2} = 0.125(V_{SG1} - 0.5)^2$$

$$\Rightarrow V_{SG1} = 0.898\ \text{V}$$

So maximum input voltage

$$= V^+ - V_{SD6}(\text{sat}) - V_{SG1}$$
$$= 5 - 0.56 - 0.898$$
$$\Rightarrow \underline{V_{IN}(\max) = 3.54\ \text{V}}$$

For M_3,

$K_p = (6.25)(20) = 125\ \mu A/V^2$

$$I_{D3} = \frac{I_Q}{2} = \frac{39.7}{2}\ \mu\text{A}$$

$$\frac{39.7}{2} = 125(V_{GS3} - V_{TN})^2$$

$V_{TN} = 0.5V \Rightarrow$

$V_{GS3} = 0.898$ V

$V_{SD1}(\text{sat}) = 0.898 - 0.5 = 0.398$ V

$$V_{IN}(\min) = V^- + V_{GS3} + V_{SD1}(\text{sat}) - V_{SG1}$$
$$= -5 + 0.898 + 0.398 - 0.898$$
$$\underline{V_{IN}(\min) = -4.60\ \text{V}}$$
$$\underline{-4.60 \le V_{IN}(\text{cm}) \le 3.54\ \text{V}}$$

E13.11

$V_0(\max) = V^+ - V_{SD8}(\text{sat})$

$V_{SG8} = V_{SG5} = 1.06$ V

$V_{SD8}(\text{sat}) = 1.06 - 0.5 = 0.56$ V

$$V_0(\max) = 5 - 0.56 = 4.44\ \text{V}$$

$V_0(\min) = V^- + V_{DS7}(\text{sat})$

$V_{GS7} = 1.06 \Rightarrow V_{DS7}(\text{sat}) = 1.06 - 0.5 = 0.56$

$$V_0(\min) = -5 + 0.56 = -4.44$$
$$\underline{-4.44 \le V_0 \le 4.44\ \text{V}}$$

E13.12

(a) For M_5, $K_{p5} = 125\ \mu A/V^2$

$$K_{p5}(V_{SG5}+V_{TP})^2 = \frac{V^+ - V^- - V_{SG5}}{R_{set}}$$

$$0.125(V_{SG5}-0.5)^2 = \frac{5+5-V_{SG5}}{100}$$

$$12.5(V_{SG5}^2 - V_{SG5} + 0.25) = 10 - V_{SG5}$$

$$12.5V_{SG5}^2 - 11.5V_{SG5} - 6.875 = 0$$

$$V_{SG5} = \frac{11.5 \pm \sqrt{(11.5)^2 + 4(12.5)(6.875)}}{2(12.5)}$$

$$V_{SG5} = 1.33\ \text{V}$$

Then

$$I_{REF} = I_Q = I_{D8} = I_{D7} = \frac{10-1.33}{100} \Rightarrow 86.7\ \mu\text{A}$$

$$I_{D1} = I_{D2} = I_{D3} = I_{D4} = \frac{I_Q}{2} = 43.35\ \mu\text{A}$$

(b) $K_{p1} = K_{p2} = 125\ \mu A/V^2$

$$r_{o2} = r_{o4} = \frac{1}{\lambda I_D} = \frac{1}{(0.02)(0.04335)} = 1153\ k\Omega$$

Input stage gain

$$A_d = \sqrt{2K_{p1}I_Q}\cdot(r_{o2}\|r_{o4})$$

$$= \sqrt{2(0.125)(0.0867)}\cdot(1153\|1153) \Rightarrow$$

$$A_d = 84.9$$

Transconductance of M_7

$$g_{m7} = 2\sqrt{K_{n7}I_{D7}} = 2\sqrt{(0.250)(0.0867)}$$

$$= 0.294\ mA/V$$

$$r_{o7} = r_{o8} = \frac{1}{\lambda I_{D7}} = \frac{1}{(0.02)(0.0867)} = 577\ k\Omega$$

Second stage gain

$$A_{v2} = g_{m7}(r_{o7}\|r_{o8}) = (0.294)(577\|577) \Rightarrow$$

$$A_{v2} = 84.8$$

Overall gain $= A_d \cdot A_{v2} = (84.9)(84.8) \Rightarrow$

$$A = 7{,}200$$

E13.13

$$I_{D1} = I_{D2} = 25\ \mu A$$

$$g_{m1} = g_{m8} = 2\sqrt{\frac{k_p'}{2}\left(\frac{W}{L}\right)I_{DQ}} = 2\sqrt{\left(\frac{40}{2}\right)(25)(25)} \Rightarrow$$

$$g_{m1} = g_{m8} = 224\ \mu A/V$$

$$g_{m6} = 2\sqrt{\left(\frac{k_n'}{2}\right)\left(\frac{W}{L}\right)I_{DQ}} = 2\sqrt{\left(\frac{80}{2}\right)(25)(25)} \Rightarrow$$

$$g_{m6} = 316\ \mu A/V$$

$$r_{o1} = r_{o6} = r_{o8} = r_{o10} = \frac{1}{\lambda I_D} = \frac{1}{(0.02)(25)} = 2\ M\Omega$$

$$r_{o4} = \frac{1}{\lambda I_{D4}} = \frac{1}{(0.02)(50)} = 1\ M\Omega$$

$$R_{o8} = g_{m8}(r_{o8}r_{o10}) = (224)(2)(2) = 896\ M\Omega$$

$$R_{o6} = g_{m6}(r_{o6})(r_{o4}\|r_{o1}) = 316(2)(1\|2) = 421\ M\Omega$$

Then

$$A_d = g_{m1}(R_{o6}\|R_{o8}) = 224(421\|896) \Rightarrow$$

$$A_d = 64{,}158$$

E13.14

(a) $A_d = Bg_{m1}(r_{o6}\|r_{o8})$

$$g_{m1} = 2\sqrt{\left(\frac{k_n'}{2}\right)\left(\frac{W}{L}\right)I_{D1}} = 2\sqrt{\left(\frac{80}{2}\right)(20)(50)}$$

$$g_{m1} = 400\ \mu A/V$$

$$r_{o6} = \frac{1}{\lambda_p I_{D6}} = \frac{1}{(0.02)(150)} = 0.333\ M\Omega$$

$$r_{o8} = \frac{1}{\lambda_n I_{D8}} = \frac{1}{(0.02)(150)} = 0.333\ M\Omega$$

$$A_d = 3(400)(0.333\|0.333) \Rightarrow \quad A_d = 200$$

(b) $f_{PD} = \dfrac{1}{2\pi R_o(C_L + C_F)}$

where $R_o = r_{o6}\|r_{o8} = 0.333\|0.333\ M\Omega$

$$f_{PD} = \frac{1}{2\pi(0.333\|0.333)x10^6x2x10^{-12}} \Rightarrow$$

$$f_{PD} = 477\ kHz$$

$$f_{PD}\cdot A_d = (477x10^3)(200) \Rightarrow 95.4\ MHz$$

E13.15

(a) From Exercise 13.14, $g_{m1} = 400\ \mu A/V$

$$r_{o6} = r_{o8} = r_{o10} = r_{o12} = 0.333\ M\Omega$$

$$g_{m10} = 2\sqrt{\left(\frac{k_p'}{2}\right)\left(\frac{W}{L}\right)I_{D10}} = 2\sqrt{\left(\frac{40}{2}\right)(20)(150)} \Rightarrow$$

$$g_{m10} = 490\ \mu A/V$$

$$g_{m12} = 2\sqrt{\left(\frac{k_n'}{2}\right)\left(\frac{W}{L}\right)I_{D12}} = 2\sqrt{\left(\frac{80}{2}\right)(20)(150)} \Rightarrow$$

$$g_{m12} = 693\ \mu A/V$$

$$R_{o10} = g_{m10}(r_{o10}r_{o6}) = (490)(0.333)(0.333) = 54.3\ M\Omega$$

$$R_{o12} = g_{m12}(r_{o12}r_{o8}) = (693)(0.333)(0.333) = 76.8\ M\Omega$$

$$A_d = Bg_{m1}(R_{o10}\|R_{o12}) = 3(400)(54.3\|76.8) \Rightarrow$$

$$A_d = 38{,}172$$

(b) $R_o = R_{o10}\|R_{o12} = 54.3\|76.8 = 31.8\ M\Omega$

$$f_{PD} = \frac{1}{2\pi(31.8x10^6)(2x10^{-12})} = 2.50\ kHz$$

$$f_{PD}\cdot A_d = (2.5x10^3)(38{,}172) \Rightarrow 95.4\ MHz$$

E13.16

(a) $A_d = g_{m1}(R_{o6} \| R_{o4})$

From Example 13.10,

$g_{m1} = 316\ \mu A/V$, $R_{o4} = 316\ M\Omega$

Now

$R_{o6} = g_{m6}(r_{o6})(r_{o4} \| r_{o1})$

$r_{o1} = 1\ M\Omega$, $r_{o4} = 0.5\ M\Omega$

$$g_{m6} = \frac{I_{C6}}{V_T} = \frac{50}{0.026} \Rightarrow 1.923\ mA/V$$

$$r_{o6} = \frac{V_{A6}}{I_{C6}} = \frac{80}{50} = 1.6 M\Omega$$

Then

$R_{o6} = (1.923)(1600)(0.5\|1) = 1026\ M\Omega$

$A_d = (316)(1026\|316) \Rightarrow \underline{A_d = 76{,}343}$

(b) $$f_{PD} = \frac{1}{2\pi(316\|1026)x10^6 x2x10^{-12}} \Rightarrow$$

$\underline{f_{PD} = 329\ Hz}$

$f_{PD} \cdot A_d = (329)(76{,}343) \Rightarrow 25.1\ MHz$

E13.17

$$V^+ - V^- = V_{EB1} + V_{EB6} + V_{BE7} + I_1 R_1$$
$$= 0.6 + 0.6 + 0.6 + (0.24)(8) = 3.72\ \text{V}$$

So

$$\underline{V^+ = -V^- = 1.86\ \text{V}}$$

E13.18

For Q_7 and R_1

$$V_{SG} = V_{BE7} + I_1 R_1 = 0.6 + I_1(5)$$

For M_8 :

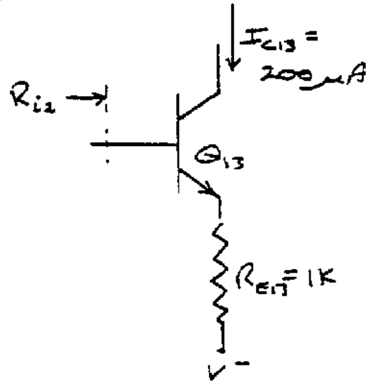
$$I_2 = K_p(V_{SG} + V_{TP})^2$$
$$I_2 = 0.3(V_{SG} - 1.4)^2$$

By trial and error:

$\underline{V_{SG} = 2.54\ \text{V}}$

$\underline{I_1 = I_2 = 0.388\ \text{mA}}$

E13.19



$$r_{\pi 13} = \frac{\beta V_T}{I_{C13}} = \frac{(200)(0.026)}{0.20}$$
$$= 26\ \text{k}\Omega$$

$$R_{i2} = r_{\pi 13} + (1+\beta)R_{E13} = 26 + 201(1)$$
$$= 227\ \text{k}\Omega$$

$$r_{o10} = \frac{1}{\lambda I_{D10}} = \frac{1}{(0.02)(0.1)} = 500\ \text{k}\Omega$$

$$r_{o12} = \frac{V_A}{I_{C12}} = \frac{50}{0.1} = 500\ \text{k}\Omega$$

$$g_{m12} = \frac{I_{C12}}{V_T} = \frac{0.1}{0.026} = 3.85\ \text{mA/V}$$

$$r_{\pi 12} = \frac{\beta V_T}{I_{C12}} = \frac{(200)(0.026)}{0.1} = 52\ \text{k}\Omega$$

$$R_{act1} = r_{o12}[1 + g_{m12}(r_{\pi 12} \| R_5)]$$
$$= 500[1 + (3.85)(52\|0.5)] = 1453\ \text{k}\Omega$$

$$A_d = \sqrt{2K_n I_{Q5}} \cdot (r_{o10} \| R_{act1} \| R_{i2})$$
$$= \sqrt{2(0.6)(0.2)} \cdot (500\|1453\|227)$$
$$= (0.490)(141) \Rightarrow \underline{A_d = 69.1}$$

E13.20

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 13

Problem Solutions

13.3

(a) $A_d = g_{m1}(r_{o2} \| r_{o4} \| R_{i6})$

$g_{m1} = \frac{I_{C1}}{V_T} = \frac{20}{0.026} \Rightarrow 0.769\ mA/V$

$r_{o2} = \frac{V_{A2}}{I_{C2}} = \frac{80}{20} = 4\ M\Omega$

$r_{o4} = \frac{V_{A4}}{I_{C2}} = \frac{80}{20} = 4\ M\Omega$

$R_{i6} = r_{\pi 6} + (1+\beta_n)[R_1 \| r_{\pi 7}]$

$r_{\pi 7} = \frac{(120)(0.026)}{0.2} = 15.6\ k\Omega$

$I_{C6} \cong \frac{V_{BE}(on)}{R_1} = \frac{0.6}{20} = 0.030\ mA$

$r_{\pi 6} = \frac{(120)(0.026)}{0.030} = 104\ k\Omega$

Then

$R_{i6} = 104 + (121)[20 \| 15.6] \Rightarrow 1.16\ M\Omega$

Then

$A_d = 769(4\|4\|1.16) \Rightarrow \underline{A_d = 565}$

Now

$V_o = -I_{c7} r_{o7} = -(\beta_n I_{b7}) r_{o7} = -\beta_n r_{o7}\left(\frac{R_1}{R_1 + r_{\pi 7}}\right) I_{e6}$

$= -\beta_n(1+\beta_n) r_{o7}\left(\frac{R_1}{R_1 + r_{\pi 7}}\right) I_{b6}$ and $I_{b6} = \frac{V_{o1}}{R_{i6}}$

Then

$A_{v2} = \frac{V_o}{V_{o1}} = \frac{-\beta_n(1+\beta_n) r_{o7}}{R_{i6}}\left(\frac{R_1}{R_1 + r_{\pi 7}}\right)$

$r_{o7} = \frac{V_A}{I_{C7}} = \frac{80}{0.2} = 400\ k\Omega$

So

$A_{v2} = \frac{-(120)(121)(400)}{1160}\left(\frac{20}{20+15.6}\right) \Rightarrow$

$\underline{A_{v2} = -2813}$

Overall gain $= A_d \cdot A_{v2} = (565)(-2813) \Rightarrow$

$\underline{A = -1.59x10^6}$

(b) $R_{id} = 2r_{\pi 1}$ and $r_{\pi 1} = \frac{(80)(0.026)}{0.020} = 104\ k\Omega$

$\underline{R_{id} = 208\ k\Omega}$

(c) $f_{PD} = \frac{1}{2\pi R_{eq} C_M}$ and

$C_M = (10)(1+2813) = 28{,}140\ pF$

$R_{eq} = r_{o2} \| r_{o4} \| R_{i6} = 4\|4\|1.16 = 0.734\ M\Omega$

$f_{PD} = \frac{1}{2\pi(0.734x10^6)(28{,}140x10^{-12})} = 7.71\ Hz$

Gain-Bandwidth Product $= (7.71)(1.59x10^6) \Rightarrow$

$\underline{12.3\ MHz}$

13.4

a. Q_3 acts as the protection device.

b. Same as part (a).

13.5

If we assume $V_{BE}(\text{on}) = 0.7$ V, then

$$V_{in} = 0.7 + 0.7 + 50 + 5$$

So breakdown voltage $\approx$ $\underline{56.4\ \text{V}}$.

13.6

(a) $I_{REF} = \frac{15 - 0.6 - 0.6 - (-15)}{R_5} = 0.50$

$\underline{\Rightarrow R_5 = 57.6\ k\Omega}$

$I_{C10} R_4 = V_T \ln\left(\frac{I_{REF}}{I_{C10}}\right)$

$R_4 = \frac{0.026}{0.030}\ln\left(\frac{0.50}{0.030}\right) \Rightarrow \underline{R_4 = 2.44\ k\Omega}$

(b) $I_{REF} = \frac{5 - 0.6 - 0.6 - (-5)}{57.6} \Rightarrow \underline{I_{REF} = 0.153\ mA}$

$I_{C10}(2.44) = (0.026)\ln\left(\frac{0.153}{I_{C10}}\right)$

By trial and error, $\underline{I_{C10} \cong 21.1\ \mu A}$

13.7

(a) $I_{REF} \cong 0.50\ mA$

$V_{BE} = V_T \ln\left(\frac{I_{REF}}{I_S}\right) = (0.026)\ln\left(\frac{0.50x10^{-3}}{10^{-14}}\right) \Rightarrow$

$\underline{V_{BE11} = 0.641\,V = V_{BE12}}$

Then

$R_5 = \frac{15 - 0.641 - 0.641 - (-15)}{0.50} \Rightarrow \underline{R_5 = 57.4\ k\Omega}$

$R_4 = \frac{0.026}{0.030}\ln\left(\frac{0.50}{0.030}\right) \Rightarrow R_4 = 2.44\ k\Omega$

$V_{BE10} = 0.026\ln\left(\frac{0.030x10^{-3}}{10^{-14}}\right) \Rightarrow V_{BE10} = 0.567\,V$

(b) From Problem 13.6, $I_{REF} \cong 0.15\,mA$

$$V_{BE11} = V_{EB12} = 0.026\ln\left(\frac{0.15x10^{-3}}{10^{-14}}\right) = 0.609\,V$$

Then $I_{REF} = \dfrac{5 - 0.609 - 0.609 - (-5)}{57.4} \Rightarrow$

$\underline{I_{REF} = 0.153\,mA}$

Then $\underline{I_{C10} \cong 21.1\,\mu A}$ from Problem 13.6

13.8

a. $I_{REF} = \dfrac{5 - 0.6 - 0.6 - (-5)}{40}$

$$\Rightarrow \underline{I_{REF} = 0.22 \text{ mA}}$$

$$I_{C10}R_4 = V_T \ln\left(\frac{I_{REF}}{I_{C10}}\right)$$

$$I_{C10}(5) = (0.026)\ln\left(\frac{0.22}{I_{C10}}\right)$$

By trial and error;

$$\underline{I_{C10} \cong 14.2\ \mu\text{A}}$$

$$I_{C6} \cong \frac{I_{C10}}{2} \Rightarrow \underline{I_{C6} = 7.10\ \mu\text{A}}$$

$$I_{C17} = 0.75 I_{REF} \Rightarrow \underline{I_{C17} = 0.165 \text{ mA}}$$

$$I_{C13A} = 0.25 I_{REF} \Rightarrow \underline{I_{C13A} = 0.055 \text{ mA}}$$

b. Using Example 13.4

$$r_{\pi 17} = 31.5 \text{ k}\Omega$$

$$R'_E = 50\|[31.5 + (201)(0.1)] = 50\|51.6 = 25.4 \text{ k}\Omega$$

$$r_{\pi 16} = \frac{\beta_n V_T}{I_{C16}} \text{ and}$$

$$I_{C16} = \frac{0.165}{200} + \frac{(0.165)(0.1) + 0.6}{50} = 0.0132 \text{ mA}$$

$$r_{\pi 16} = 394 \text{ k}\Omega$$

Then

$$R_{i2} = 394 + (201)(25.4) \Rightarrow 5.5 \text{ M}\Omega$$

$$r_{\pi 6} = 732 \text{ k}\Omega$$

$$g_{m6} = \frac{0.00710}{0.026} = 0.273 \text{ mA/V}$$

$$r_{o6} = \frac{50}{0.0071} = 7.04 \text{ M}\Omega$$

Then

$$R_{act1} = 7.04[1 + (0.273)(1\|732)] = 8.96 \text{ M}\Omega$$

$$r_{o4} = \frac{50}{0.0071} = 7.04 \text{ M}\Omega$$

Then

$$A_d = -\left(\frac{7.1}{0.026}\right)(7.04\|8.96\|5.5)$$

or

$\underline{A_d = -627}$ Gain of differential amp stage

Using Example 13.5, and neglecting the input resistance to the output stage:

$$R_{act2} = \frac{V_A}{I_{C13B}} = \frac{50}{0.165} = 303 \text{ k}\Omega$$

$$A_{v2} = \frac{-(200)(201)(50)(303)}{(5500)[50 + 31.5 + (201)(0.1)]}$$

or

$\underline{A_{v2} = -1090}$ Gain of second stage

13.9

$$I_{C10} = 19\ \mu\text{A}$$

From Equation (13.6)

$$I_{C10} = 2I\left[\frac{\beta_P^2 + 2\beta_P + 2}{\beta_P^2 + 3\beta_P + 2}\right] = 2I\left[\frac{(10)^2 + 2(10) + 2}{(10)^2 + 3(10) + 2}\right]$$

$$= 2I\left[\frac{122}{132}\right]$$

So

$$2I = (19)\left(\frac{132}{122}\right) = 20.56\ \mu\text{A}$$

$$\underline{I_{C2} = I = 10.28\ \mu\text{A}}$$

$$I_{C9} = \frac{2I}{\left(1 + \frac{2}{\beta_P}\right)} = \frac{20.56}{\left(1 + \frac{2}{10}\right)} \Rightarrow \underline{I_{C9} = 17.13\ \mu\text{A}}$$

$$I_{B9} = \frac{I_{C9}}{\beta_P} = \frac{17.13}{10} \Rightarrow \underline{I_{B9} = 1.713\ \mu\text{A}}$$

$$I_{B4} = \frac{I}{(1 + \beta_P)} = \frac{10.28}{11} \Rightarrow \underline{I_{B4} = 0.9345\ \mu\text{A}}$$

$$I_{C4} = I\left(\frac{\beta_P}{1 + \beta_P}\right) = (10.28)\left(\frac{10}{11}\right)$$

$$\Rightarrow \underline{I_{C4} = 9.345\ \mu\text{A}}$$

13.10

$$V_{B5} - V^- = V_{BE}(\text{on}) + I_{C5}(1)$$

$$= 0.6 + (0.0095)(1) = 0.6095$$

$$I_{C7} = \frac{0.6095}{50} \Rightarrow I_{C7} = 12.2\ \mu\text{A}$$

$I_{C8} = I_{C9} = 19\ \mu A$

$I_{REF} = 0.72$ mA

$I_{E13} = I_{REF} = 0.72$ mA

$I_{C14} = 138\ \mu A$

$$\text{Power} = (V^+ - V^-)[I_{C7} + I_{C8} + I_{C9} + I_{REF} + I_{E13} + I_{C14}]$$
$$= 30[0.0122 + 0.019 + 0.019 + 0.72 + 0.72 + 0.138]$$
$$\Rightarrow \underline{\text{Power} = 48.8 \text{ mW}}$$

Current supplied by V^+ and V^-

$$= I_{C7} + I_{C8} + I_{C9} + I_{REF} + I_{E13} + I_{C14}$$
$$= \underline{1.63 \text{ mA}}$$

13.11

(a) $v_{cm}(\min) = -15 + 0.6 + 0.6 + 0.6 + 0.6 = -12.6\,V$

$v_{cm}(\max) = +15 - .6 = 14.4\,V$

So $-12.6 \le v_{cm} \le 14.4\,V$

(b) $v_{cm}(\min) = -5 + 4(0.6) = -2.6\,V$

$v_{cm}(\max) = 5 - 0.6 = 4.4\,V$

So $-2.6 \le v_{cm} \le 4.4\,V$

13.12

If $v_O = V^- = -15$ V, the base voltage of Q_{14} is pulled low, and Q_{18} and Q_{19} are effectively cut off. As a first approximation

$$I_{C14} = \frac{0.6}{0.027} = 22.2 \text{ mA}$$
$$I_{B14} = \frac{22.2}{200} = 0.111 \text{ mA}$$

Then

$$I_{C15} = I_{C13A} - I_{B14} = 0.18 - 0.111 = 0.069 \text{ mA}$$

Now

$$V_{BE15} = V_T \ln\left(\frac{I_{C15}}{I_S}\right)$$
$$= (0.026)\ln\left(\frac{0.069 \times 10^{-3}}{10^{-14}}\right)$$
$$= 0.589 \text{ V}$$

As a second approximation

$$I_{C14} = \frac{0.589}{0.027} \Rightarrow \underline{I_{C14} = 21.8 \text{ mA}}$$
$$I_{B14} = \frac{21.8}{200} = 0.109 \text{ mA}$$

and

$$I_{C15} = 0.18 - 0.109 \Rightarrow \underline{I_{C15} = 0.071 \text{ mA}}$$

13.13

a. Neglecting base currents:

$I_D = I_{BIAS}$

Then

$$V_{BB} = 2V_D = 2V_T \ln\left(\frac{I_D}{I_S}\right)$$
$$= 2(0.026)\ln\left(\frac{0.25 \times 10^{-3}}{2 \times 10^{-14}}\right)$$

or

$$\underline{V_{BB} = 1.2089 \text{ V}}$$

$$I_{CN} = I_{CP} = I_S \exp\left(\frac{V_{BB}/2}{V_T}\right)$$
$$= 5 \times 10^{-14} \exp\left(\frac{1.2089}{2(0.026)}\right)$$

So

$$\underline{I_{CN} = I_{CP} = 0.625 \text{ mA}}$$

b. For $v_I = 5$ V, $\underline{v_O \cong 5 \text{ V}}$

$$\underline{i_L \cong \frac{5}{4} = 1.25 \text{ mA}}$$

As a first approximation

$$I_{CN} \approx i_L = 1.25 \text{ mA}$$
$$V_{BEN} = (0.026)\ln\left(\frac{1.25 \times 10^{-3}}{5 \times 10^{-14}}\right) = 0.6225 \text{ V}$$

Neglecting base currents,

$$\underline{V_{BB} = 1.2089 \text{ V}}$$

Then $V_{EBP} = 1.2089 - 0.6225 = 0.5864$ V

$$I_{CP} = 5 \times 10^{-14} \exp\left(\frac{0.5864}{0.026}\right) \Rightarrow I_{CP} = 0.312 \text{ mA}$$

As a second approximation,

$$I_{CN} = i_L + I_{CP} = 1.25 + 0.31 \Rightarrow \underline{I_{CN} \cong 1.56 \text{ mA}}$$
$$V_{BEN} = (0.026)\ln\left(\frac{1.56 \times 10^{-3}}{5 \times 10^{-14}}\right) = 0.62826 \text{ V}$$

$$V_{EBP} = 1.2089 - 0.62826 = 0.5806 \text{ V}$$
$$I_{CP} = 5 \times 10^{-14} \exp\left(\frac{0.5806}{0.026}\right) \Rightarrow \underline{I_{CP} = 0.25 \text{ mA}}$$

13.14

$$R_1 + R_2 = \frac{V_{BB}}{(0.1)I_{BIAS}} = \frac{1.157}{0.018} = 64.28 \text{ k}\Omega$$
$$V_{BE} = V_T \ln\left(\frac{I_C}{I_S}\right) = (0.026)\ln\left(\frac{(0.9)I_{BIAS}}{I_S}\right)$$
$$= (0.026)\ln\left(\frac{0.162 \times 10^{-3}}{10^{-14}}\right)$$

$V_{BE} = 0.6112$ V

$V_{BE} = \left(\frac{R_2}{R_1 + R_2}\right) V_{BB}$

$0.6112 = \left(\frac{R_2}{64.28}\right)(1.157)$

So

$\underline{R_2 = 33.96 \text{ k}\Omega}$

Then

$\underline{R_1 = 30.32 \text{ k}\Omega}$

13.15

(a) $A_d = -g_m(r_{o4} \| r_{o6} \| R_{i2})$

From example 13.4

$g_m = \frac{9.5}{0.026} = 365\ \mu A/V$, $r_{o4} = 5.26\ M\Omega$

Now

$r_{o6} = r_{o4} = 5.26\ M\Omega$

Assuming $R_s = 0$, we find

$R_{i2} = r_{\pi 16} + (1+\beta_n)R'_E$

$= 329 + (201)(50 \| 9.63) \Rightarrow 1.95\ M\Omega$

Then

$A_d = -(365)(5.26 \| 5.26 \| 1.95) \Rightarrow \underline{A_d = -409}$

(b) From Equation (13.20),

$$A_{v2} = \frac{-\beta_n(1+\beta_n)R_9(R_{act2} \| R_{i3} \| R_{017})}{R_{i2}\{R_9 + [r_{\pi 17} + (1+\beta_n)R_8]\}}$$

For $R_s = 0$, $R_{i2} = 1.95\ M\Omega$

Using the results of Example 13.5

$$A_{v2} = \frac{-200(201)(50)(92.6 \| 4050 \| 92.6)}{(1950)\{50 + 9.63\}} \Rightarrow$$

$\underline{A_{v2} = -792}$

13.16

Let $I_{C10} = 40\ \mu$A, then $I_{C1} = I_{C2} = 20\ \mu$A. Using Example 13.5.

$R_{i2} = 4.07$ MΩ

$r_{\pi 6} = \frac{(200)(0.026)}{0.020} = 260$ kΩ

$g_{m6} = \frac{0.020}{0.026} = 0.769$ mA/V

$r_{o6} = \frac{50}{0.02} \Rightarrow 2.5$ MΩ

Then

$R_{act1} = 2.5[1 + (0.769)(1 \| 260)] = 4.42$ MΩ

$r_{o4} = \frac{50}{0.02} \Rightarrow 2.5$ MΩ

Then

$$A_d = -\left(\frac{I_{CQ}}{V_T}\right)(r_{o4} \| R_{act1} \| R_{i2})$$

$$= -\left(\frac{20}{0.026}\right)(2.5 \| 4.42 \| 4.07)$$

So

$\underline{A_d = -882}$

13.17

Now

$R_{e14} = \frac{r_{\pi 14} + R_{01}}{1 + \beta_P}$ and $R_0 = R_6 + R_{e14}$

Assume series resistance of Q_{18} and Q_{19} is small. Then

$R_{01} = r_{013A} \| R_{e22}$

where $R_{e22} = \frac{r_{\pi 22} + R_{017} \| r_{013B}}{1 + \beta_P}$

and $R_{017} = r_{017}[1 + g_{m17}(R_8 \| r_{\pi 17})]$

Using results from Example 13.6,

$r_{\pi 17} = 9.63$ kΩ $\quad r_{\pi 22} = 7.22$ kΩ

$g_{m17} = 20.8$ mA/V $\quad r_{017} = 92.6$ kΩ

Then

$R_{017} = 92.6[1 + (20.8)(0.1 \| 9.63)] = 283$ kΩ

$r_{013B} = \frac{50}{0.54} = 92.6$ kΩ

Then

$R_{e22} = \frac{7.22 + 283 \| 92.6}{51} = 1.51$ kΩ

$R_{01} = r_{013A} \| R_{e22} = 278 \| 1.51 = 1.50$ kΩ

$r_{\pi 14} = \frac{(50)(0.026)}{2} = 0.65$ kΩ

Then

$R_{e14} = \frac{0.65 + 1.50}{51} = 0.0422$ kΩ

or

$R_{e14} = 42.2\ \Omega$

Then

$R_0 = 42.2 + 27 \Rightarrow \underline{R_0 = 69.2\ \Omega}$

13.18

$$R_{id} = 2\left[r_{\pi 1} + (1+\beta_n)\left(\frac{r_{\pi 3}}{1+\beta_P}\right)\right]$$

Assume $\beta_n = 200$ and $\beta_P = 10$

Then

$$r_{\pi 1} = \frac{(200)(0.026)}{0.0095} = 547 \text{ k}\Omega$$
$$r_{\pi 3} = \frac{(10)(0.026)}{0.0095} = 27.4 \text{ k}\Omega$$

Then

$$R_{id} = 2\left[547 + \frac{(201)(27.4)}{11}\right]$$

or

$$R_{id} = 2.095 \text{ M}\Omega$$

13.19

We can write

$$A(f) = \frac{A_0}{\left(1+j\frac{f}{f_{PD}}\right)\left(1+j\frac{f}{f_1}\right)} = \frac{356,796}{\left(1+j\frac{f}{5.43}\right)\left(1+j\frac{f}{f_1}\right)}$$

Phase:

$$\phi = -\tan^{-1}\left(\frac{f}{5.43}\right) - \tan^{-1}\left(\frac{f}{f_1}\right)$$

For a phase margin $= 70°$, $\phi = -110°$

So

$$-110° = -\tan^{-1}\left(\frac{f}{5.43}\right) - \tan^{-1}\left(\frac{f}{f_1}\right)$$

Assuming $f \gg 5.43$, we have

$$\tan^{-1}\left(\frac{f}{f_1}\right) = 20° \Rightarrow \frac{f}{f_1} = 0.364$$

At this frequency, $|A(f)| = 1$, so

$$1 = \frac{356,796}{\sqrt{1+\left(\frac{f}{5.43}\right)^2}\cdot\sqrt{1+(0.364)^2}} = \frac{335,275}{\sqrt{1+\left(\frac{f}{5.43}\right)^2}}$$

or $\frac{f}{5.43} = 335,275 \Rightarrow f = 1.82$ MHz

Then, second pole at

$$f_1 = \frac{f}{0.364} \Rightarrow \underline{f_1 = 5 \text{ MHz}}$$

13.20

a. Original g_{m1} and g_{m2}

$$K_{p1} = K_{p2} = \left(\frac{W}{L}\right)\left(\frac{\mu_p C_{ox}}{2}\right) = (12.5)(10) = 125\ \mu A/V^2$$

So

$$g_{m1} = g_{m2} = 2\sqrt{K_{p1}\left(\frac{I_Q}{2}\right)} = 2\sqrt{(0.125)(10)} = 0.09975 \text{ mA/V}$$

If $\left(\frac{W}{L}\right)$ is increased to 50, then

$$K_{p1} = K_{p2} = (50)(10) = 500\ \mu A/V^2$$

So

$$g_{m1} = g_{m2} = 2\sqrt{(0.5)(0.0199)} = 0.1995 \text{ mA/V}$$

b. Gain of first stage

$$A_d = g_{m1}(r_{o2}\|r_{o4}) = (0.1995)(5025\|5025)$$

or

$$\underline{A_d = 501}$$

Voltage gain of second stage remains the same, or

$$A_{v2} = 251$$

Then $A_v = A_d \cdot A_{v2} = (501)(251)$

or

$$\underline{A_d = 125,751}$$

13.22

a. $K_p = (10)(20) = 200\ \mu A/V^2 = 0.2\ mA/V^2$

$$I_{REF} = I_{SET} = \frac{10 - V_{SG} - (-10)}{200} = k_P(V_{SG} - 1.5)^2$$

$$20 - V_{SG} = (0.2)(200)(V_{SG}^2 - 3V_{SG} + 2.25)$$

$$40V_{SG}^2 - 119V_{SG} + 70 = 0$$

$$V_{SG} = \frac{119 \pm \sqrt{(119)^2 - 4(40)(70)}}{2(40)}$$
$$\Rightarrow \underline{V_{SG} = 2.17 \text{ V}}$$

Then

$$I_{REF} = \frac{20 - 2.17}{200} \Rightarrow \underline{I_{REF} = 89.2\ \mu A}$$

M_5, M_6, M_8 matched transistors so that

$$\underline{I_Q = I_{D7} = I_{REF} = 89.2\ \mu A}$$

b. Small-signal voltage gain of input stage:

$$A_d = \sqrt{2K_{p1}I_Q}\cdot(r_{o2}\|r_{o4})$$

$$r_{o2} = \frac{1}{\lambda_P I_D} = \frac{1}{(0.02)\left(\frac{89.2}{2}\right)} = 1.12\ \text{M}\Omega$$

$$r_{o4} = \frac{1}{\lambda_n I_D} = \frac{1}{(0.01)\left(\frac{89.2}{2}\right)} = 2.24\ \text{M}\Omega$$

Then

$$A_d = \sqrt{2(200)(89.2)}\cdot(1.12\|2.24)$$

or

$$\underline{A_d = 141}$$

Small-signal voltage gain of second stage:

$$A_{v2} = g_{m7}(r_{o7}\|r_{o8})$$

$$K_{n7} = (20)(20) = 400\ \mu A/V^2$$

So

$$g_{m7} = 2\sqrt{K_{n7}I_{D7}} = 2\sqrt{(0.4)(0.0892)} = 0.378\ \text{mA/V}$$

$$r_{o8} = \frac{1}{\lambda_P I_{D7}} = \frac{1}{(0.02)(0.0892)} = 561\ \text{k}\Omega$$

$$r_{o7} = \frac{1}{\lambda_n I_{D7}} = \frac{1}{(0.01)(0.0892)} = 1121\ \text{k}\Omega$$

So

$$A_{v2} = (0.378)(1121\|561) \Rightarrow \underline{A_{v2} = 141}$$

Then overall voltage gain

$$A_v = A_d\cdot A_{v2} = (141)(141) \Rightarrow \underline{A_v = 19,881}$$

13.23

Small-signal voltage gain of input stage:

$$A_d = \sqrt{2K_{p1}I_Q}\cdot(r_{o2}\|r_{o4})$$

$$K_{p1} = (10)(10) = 100\ \mu A/V^2$$

$$r_{o2} = \frac{1}{\lambda_P\left(\frac{I_Q}{2}\right)} = \frac{1}{(0.01)\left(\frac{0.2}{2}\right)} = 1000\ \text{k}\Omega$$

$$r_{o4} = \frac{1}{\lambda_n\left(\frac{I_Q}{2}\right)} = \frac{1}{(0.005)\left(\frac{0.2}{2}\right)} = 2000\ \text{k}\Omega$$

Then

$$A_d = \sqrt{2(0.1)(0.2)}\cdot(1000\|2000)$$

or

$$\underline{A_d = 133}$$

Small-signal voltage gain of second stage:

$$A_{v2} = g_{m7}(r_{o7}\|r_{o8})$$

$$K_{n7} = (20)(20) = 400\ \mu A/V^2$$

So

$$g_{m7} = 2\sqrt{K_{n7}I_{D7}} = 2\sqrt{(0.4)(0.2)} = 0.566\ \text{mA/V}$$

$$r_{o8} = \frac{1}{\lambda_P I_{D7}} = \frac{1}{(0.01)(0.2)} = 500\ \text{k}\Omega$$

$$r_{o7} = \frac{1}{\lambda_n I_{D7}} = \frac{1}{(0.005)(0.2)} = 1000\ \text{k}\Omega$$

So

$$A_{v2} = (0.566)(1000\|500) \Rightarrow \underline{A_{v2} = 189}$$

Then overall voltage gain is

$$A_v = A_d\cdot A_{v2} = (133)(189) \Rightarrow \underline{A_v = 25,137}$$

13.24

$$f_{PD} = \frac{1}{2\pi R_{eq}C_i}$$

where $R_{eq} = r_{o4}\|r_{o2}$ and $C_i = C_1(1+|A_{v2}|)$

We can find that

$$A_{v2} = 251 \text{ and } r_{o4} = r_{o2} = 5.025\ \text{M}\Omega$$

Now

$$R_{eq} = 5.025\|5.025 = 2.51\ \text{M}\Omega$$

and

$$C_i = 12(1+251) = 3024\ \text{pF}$$

So

$$f_{PD} = \frac{1}{2\pi(2.51\times10^6)(3024\times10^{-12})}$$

or

$$\underline{f_{PD} = 21.0\ \text{Hz}}$$

13.25

$$f_{PD} = \frac{1}{2\pi R_{eq}C_i}$$

where $R_{eq} = r_{o4}\|r_{o2}$

From Problem 13.22,

$r_{o2} = 1.12\ \text{M}\Omega$, $r_{o4} = 2.24\ \text{M}\Omega$ and $A_{v2} = 141$

So

$$8 = \frac{1}{2\pi(1.12\|2.24) \times 10^6 \times C_i}$$

or

$C_i = 2.66 \times 10^{-8} = C_1(1 + |A_{v2}|) = C_1(142)$

or

$$\underline{C_1 = 188 \text{ pF}}$$

13.26

$R_0 = r_{o7} \| r_{o8}$

We can find that

$$r_{o7} = r_{o8} = 2.52 \text{ M}\Omega$$

Then

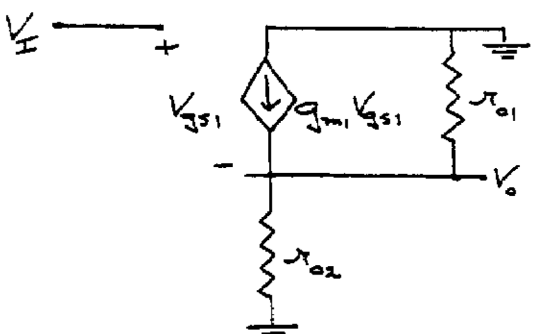
$R_0 = 2.52 \| 2.52$

or

$$\underline{R_0 = 1.26 \text{ M}\Omega}$$

13.27

a.



$V_0 = (g_{m1} V_{gs1})(r_{01} \| r_{02})$

$V_I = V_{gs1} + V_0$

Then $V_0 = g_{m1}(r_{01} \| r_{02})(V_I - V_0)$

or

$$\underline{A_v = \frac{g_{m1}(r_{01} \| r_{02})}{1 + g_{m1}(r_{01} \| r_{02})}}$$

b. $I_X + g_{m1} V_{gs1} = \frac{V_X}{r_{02}} + \frac{V_X}{r_{01}}$ and $V_{gs1} = -V_X$

$$\underline{R_0 = \frac{1}{g_{m1}} \| r_{01} \| r_{02}}$$

13.28

(a) $A_d = g_{m1}(R_{o6} \| R_{o8})$

$g_{m1} = 2\sqrt{K_n I_{DQ}} = 2\sqrt{(0.5)(0.025)} \Rightarrow 224\ \mu A/V$

$g_{m1} = g_{m8}$

$g_{m6} = 2\sqrt{(0.5)(0.025)} \Rightarrow 224\ \mu A/V$

$r_{o1} = r_{o6} = r_{o8} = r_{o10} = \frac{1}{\lambda I_{DQ}} = \frac{1}{(0.015)(25)} = 2.67\ M\Omega$

$r_{o4} = \frac{1}{\lambda I_{D4}} = \frac{1}{(0.015)(50)} \Rightarrow 1.33\ M\Omega$

Now

$R_{o8} = g_{m8}(r_{o8} r_{o10}) = (224)(2.67)(2.67) = 1597\ M\Omega$

$R_{o6} = g_{m6}(r_{o6})(r_{o4} \| r_{o1}) = (224)(2.67)(2.67 \| 1.33) \Rightarrow$

$R_{o6} = 531\ M\Omega$

Then

$A_d = (224)(531 \| 1597) \Rightarrow \underline{A_d = 89{,}264}$

(b) $R_o = R_{o6} \| R_{o8} = 531 \| 1597 \Rightarrow \underline{R_o = 398\ M\Omega}$

(c) $f_{PD} = \frac{1}{2\pi R_o C_L} = \frac{1}{2\pi(398 x 10^6)(5 x 10^{-12})} \Rightarrow$

$\underline{f_{PD} = 80\ Hz}$

$GBW = (89{,}264)(80) \Rightarrow \underline{GBW = 7.14\ MHz}$

13.29

(a) $r_{o1} = r_{o8} = r_{o10} = \frac{1}{\lambda_p I_D} = \frac{1}{(0.02)(25)} = 2\ M\Omega$

$r_{o6} = \frac{1}{\lambda_n I_D} = \frac{1}{(0.015)(25)} = 2.67\ M\Omega$

$r_{o4} = \frac{1}{\lambda_n I_{D4}} = \frac{1}{(0.015)(50)} = 1.33\ M\Omega$

$g_{m1} = 2\sqrt{\left(\frac{35}{2}\right)\left(\frac{W}{L}\right)_1 (25)} = 41.8\sqrt{\left(\frac{W}{L}\right)_1} = g_{m8}$

$g_{m6} = 2\sqrt{\left(\frac{80}{2}\right)\left(\frac{W}{L}\right)_6 (25)} = 63.2\sqrt{\left(\frac{W}{L}\right)_6}$

$R_o = R_{o6} \| R_{o8} = [g_{m6}(r_{o6})(r_{o4} \| r_{o1})] \| [g_{m8}(r_{o8} r_{o10})]$

Define $X_1 = \sqrt{\left(\frac{W}{L}\right)_1}$ and $X_6 = \sqrt{\left(\frac{W}{L}\right)_6}$

Then $R_o = [63.2 X_6 (2.67)(1.33 \| 2)] \| [41.8 X_1 (2)(2)]$

$= 134.8 X_6 \| 167.2 X_1 = \frac{22{,}539 X_1 X_6}{134.8 X_6 + 167.2 X_1}$

$A_d = g_{m1} R_o = (41.8 X_1)\left(\frac{22{,}539 X_1 X_6}{134.8 X_6 + 167.2 X_1}\right)$

$= 10{,}000$

Now $X_6 = \sqrt{\left(\frac{W}{L}\right)_6} = \sqrt{\frac{1}{2.2}\left(\frac{W}{L}\right)_1} = 0.674 X_1$

We then find

$$X_1^2 = \left(\frac{W}{L}\right)_1 = 4.06 = \left(\frac{W}{L}\right)_p$$

and

$$\left(\frac{W}{L}\right)_n = 1.85$$

13.30

Let $V^+ = 5\,V$, $V^- = -5\,V$

$P = I_T(10) = 3 \Rightarrow I_T = 0.3\ mA$

$\Rightarrow I_{REF} = 0.1\ mA = 100\ \mu A$

$$r_{o1} = r_{o8} = r_{o10} = \frac{1}{(0.02)(50)} = 1\ M\Omega$$

$$r_{o6} = \frac{1}{(0.015)(50)} = 1.33\ M\Omega$$

$$r_{o4} = \frac{1}{(0.015)(100)} = 0.667\ M\Omega$$

$$g_{m1} = 2\sqrt{\left(\frac{35}{2}\right)\left(\frac{W}{L}\right)_1(50)} = 59.2X_1 = g_{m8}$$

where $X_1 = \sqrt{\left(\frac{W}{L}\right)_1}$

Assume all width-to-length ratios are the same.

$$g_{m6} = 2\sqrt{\left(\frac{80}{2}\right)\left(\frac{W}{L}\right)(50)} = 89.4X_1$$

Now

$$R_o = R_{o6}\|R_{o8} = \left[g_{m6}(r_{o6})(r_{o4}\|r_{o1})\right]\|\left[g_{m8}(r_{o8}r_{o10})\right]$$

$$= \left[89.4X_1(1.33)(0.667\|1)\right]\|\left[59.2X_1(1)(1)\right]$$

$$= \left[47.6X_1\right]\|\left[59.2X_1\right] = \frac{(47.6X_1)(59.2X_1)}{47.6X_1 + 59.2X_1}$$

So $R_o = 26.4X_1$

Now

$A_d = g_{m1}R_o = (59.2X_1)(26.4X_1) = 25{,}000$

So that $X_1^2 = \dfrac{W}{L} = 16$ for all transistors

13.31

(a) $A_d = Bg_{m1}(r_{o6}\|r_{o8})$

$$r_{o6} = r_{o8} = \frac{1}{\lambda I_{DQ}} = \frac{1}{(0.015)(90)} = 0.741\ M\Omega$$

$$g_{m1} = 2\sqrt{\left(\frac{k_n'}{2}\right)\left(\frac{W}{L}\right)I_{D1}} = 2\sqrt{(500)(30)} = 245\ \mu A/V$$

$A_d = (3)(245)(0.741\|0.741) \Rightarrow A_d = 272$

(b) $R_o = r_{o6}\|r_{o8} = 0.741\|0.741 \Rightarrow R_o = 371\ k\Omega$

(c) $f_{PD} = \dfrac{1}{2\pi R_oC} = \dfrac{1}{2\pi(371\times10^3)(5\times10^{-12})} \Rightarrow$

$f_{PD} = 85.8\ kHz$

$GBW = (272)(85.8\times10^3) \Rightarrow GBW = 23.3\ MHz$

13.32

(a) $r_{o6} = \dfrac{1}{(0.02)(2.5)(40)} = 0.5\ M\Omega$

$$r_{o8} = \frac{1}{(0.015)(2.5)(40)} = 0.667\ M\Omega$$

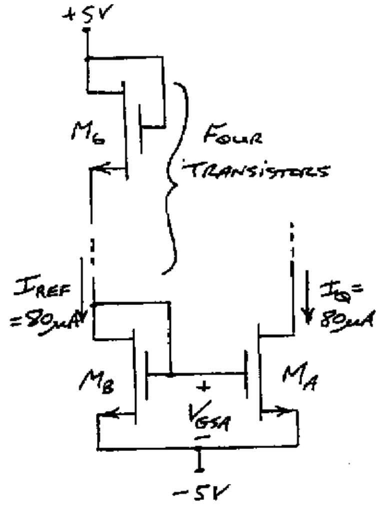
$A_d = Bg_{m1}(r_{o6}\|r_{o8})$

$400 = (2.5)g_{m1}(0.5\|0.667) \Rightarrow g_{m1} = 560\ \mu A/V$

$$g_{m1} = 560 = 2\sqrt{\left(\frac{80}{2}\right)\left(\frac{W}{L}\right)(40)} \Rightarrow \left(\frac{W}{L}\right) = 49$$

Assume all (W/L) ratios are the same except for M_5 and M_6. $\left(\frac{W}{L}\right)_5 = \left(\frac{W}{L}\right)_6 = 122.5$

(b) Assume the bias voltages are $V^+ = 5\,V$, $V^- = -5\,V$.



Assume $\left(\frac{W}{L}\right)_A = \left(\frac{W}{L}\right)_B = 49$

$$I_Q = \left(\frac{80}{2}\right)(49)(V_{GSA} - 0.5)^2 = 80 \Rightarrow V_{GSA} = 0.702\ V$$

Then

$$I_{REF} = 80 = \left(\frac{80}{2}\right)\left(\frac{W}{L}\right)_C(V_{GSC} - 0.5)^2$$

For four transistors

$$V_{GSC} = \frac{10 - 0.702}{4} = 2.325\,V$$

$$80 = \left(\frac{80}{2}\right)\left(\frac{W}{L}\right)_C (2.325 - 0.5)^2 \Rightarrow \underline{\left(\frac{W}{L}\right)_C = 0.60}$$

(c) $f_{3-dB} = \dfrac{1}{2\pi R_o C}$ $\quad R_o = 0.5\|0.667 = 0.286\ M\Omega$

$$f_{3-dB} = \frac{1}{2\pi(286x10^3)(3x10^{-12})} = 185\ kHz$$

$$GBW = (400)(185x10^3) \Rightarrow 74\ MHz$$

13.33

(a) From previous results, we can write

$$R_{o10} = g_{m10}(r_{o10}r_{o6})$$

$$R_{o12} = g_{m12}(r_{o12}r_{o8})$$

$$A_d = Bg_{m1}(R_{o10}\|R_{o12})$$

Now

$$r_{o10} = r_{o6} = \frac{1}{\lambda_p B(I_Q/2)} = \frac{1}{(0.02)(2.5)(40)} = 0.5\ M\Omega$$

$$r_{o12} = r_{o8} = \frac{1}{\lambda_n B(I_Q/2)} = \frac{1}{(0.015)(2.5)(40)} = 0.667\ M\Omega$$

Assume all transistors have the same width-to-length ratios except for M_5 and M_6.

Let $\left(\frac{W}{L}\right) = X^2$

Then

$$g_{m10} = 2\sqrt{\left(\frac{k_p'}{2}\right)\left(\frac{W}{L}\right)_{10}(I_{DQ10})} = 2\sqrt{\left(\frac{35}{2}\right)X^2(2.5)(40)}$$

$$= 83.67X$$

$$g_{m12} = 2\sqrt{\left(\frac{k_n'}{2}\right)\left(\frac{W}{L}\right)_{12}(I_{DQ12})} = 2\sqrt{\left(\frac{80}{2}\right)X^2(2.5)(40)}$$

$$= 126.5X$$

$$g_{m1} = 2\sqrt{\left(\frac{80}{2}\right)X^2(40)} = 80X$$

Then

$$R_{o10} = (83.67X)(0.5)(0.5) = 20.9X\ M\Omega$$

$$R_{o12} = (126.5X)(0.667)(0.667) = 56.3X\ M\Omega$$

We want

$$20{,}000 = (2.5)(80X)[20.9X\|56.3X]$$

$$= 200X\left[\frac{(20.9X)(56.3X)}{20.9X + 56.3X}\right] = 3048X^2$$

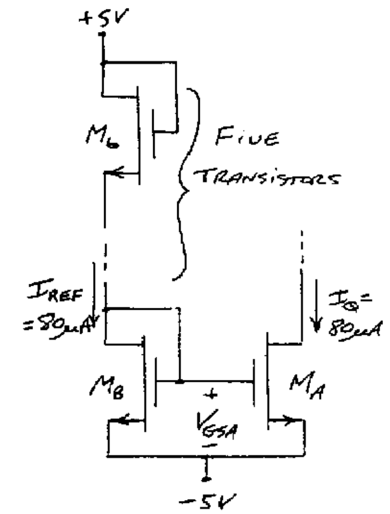
Then

$$\underline{X^2 = 6.56 = \left(\frac{W}{L}\right)}$$

Then

$$\underline{\left(\frac{W}{L}\right)_6 = \left(\frac{W}{L}\right)_5 = (2.5)(6.56) = 16.4}$$

(b) Assume bias voltages are $V^+ = 5V$, $V^- = -5V$



Assume $\left(\frac{W}{L}\right)_A = \left(\frac{W}{L}\right)_B = 6.56$

$$I_Q = 80 = \left(\frac{80}{2}\right)(6.56)(V_{GSA} - 0.5)^2 \Rightarrow$$

$$V_{GSA} = 1.052\,V$$

Need 5 transistors in series

$$V_{GSC} = \frac{10 - 1.052}{5} = 1.79\,V$$

Then

$$I_{REF} = 80 = \left(\frac{80}{2}\right)\left(\frac{W}{L}\right)_C (1.79 - 0.5)^2 \Rightarrow$$

$$\underline{\left(\frac{W}{L}\right)_C = 1.20}$$

(c) $f_{3-dB} = \dfrac{1}{2\pi R_o C}$ where $R_o = R_{o10}\|R_{o12}$

Now

$$R_{o10} = 20.9\sqrt{6.56} = 53.5\ M\Omega$$

$$R_{o12} = 56.3\sqrt{6.56} = 144\ M\Omega$$

Then

$$R_o = 53.5\|144 = 39\ M\Omega$$

$$f_{3-dB} = \frac{1}{2\pi(39x10^6)(3x10^{-12})} = 1.36\ kHz$$

$$GBW = (20{,}000)(1.36x10^3) \Rightarrow GBW = 27.2\ MHz$$

13.34

$$A_d = g_m(M_2)\cdot[r_{o2}(M_2)\|r_{o2}(Q_2)]$$

$$g_m(M_2) = 2\sqrt{\left(\frac{40}{2}\right)(25)(100)} = 447\ \mu A/V$$

$$r_{o2}(M_2) = \frac{1}{\lambda I_{DQ}} = \frac{1}{(0.02)(0.1)} = 500\ k\Omega$$

$$r_{o2}(Q_2) = \frac{V_A}{I_{CQ}} = \frac{120}{0.1} = 1200\ k\Omega$$

Then

$$A_d = 447(0.5\|1.2) \Rightarrow \underline{A_d = 158}$$

13.35

$$A_d = g_m(M_2)\cdot[r_{o2}(M_2)\|r_{o2}(Q_2)]$$

$$g_m(M_2) = 2\sqrt{\left(\frac{80}{2}\right)(25)(100)} = 632\ \mu A/V$$

$$r_{o2}(M_2) = \frac{1}{\lambda I_{DQ}} = \frac{1}{(0.015)(0.1)} = 667\ k\Omega$$

$$r_{o2}(Q_2) = \frac{V_A}{I_{CQ}} = \frac{80}{0.1} = 800\ k\Omega$$

$$A_d = (632)(0.667\|0.80) \Rightarrow \underline{A_d = 230}$$

13.36

$I_{REF} = 200\ \mu A$ $\qquad K_n = K_p = 0.5\ mA/V^2$

$\qquad\qquad\qquad\qquad \lambda_n = \lambda_p = 0.015\ V^{-1}$

$$A_d = g_{m1}(R_{o6}\|R_{o8})$$

where

$$R_{o8} = g_{m8}(r_{o8}r_{o10})$$

$$R_{o6} = g_{m6}(r_{o6})(r_{o4}\|r_{o1})$$

Now

$$g_{m8} = 2\sqrt{K_p I_{D8}} = 2\sqrt{(0.5)(0.1)} = 0.447\ mA/V$$

$$r_{o8} = \frac{1}{\lambda_p I_{D8}} = \frac{1}{(0.015)(0.1)} = 667\ k\Omega$$

$$r_{o10} = \frac{1}{\lambda_p I_{D8}} = 667\ k\Omega$$

$$g_{m6} = \frac{I_{C6}}{V_T} = \frac{0.1}{0.026} = 3.846\ mA/V$$

$$r_{o6} = \frac{V_A}{I_{C6}} = \frac{80}{0.1} = 800\ k\Omega$$

$$r_{o4} = \frac{1}{\lambda_n I_{D4}} = \frac{1}{(0.015)(0.2)} = 333\ k\Omega$$

$$r_{o1} = \frac{1}{\lambda_p I_{D1}} = \frac{1}{(0.015)(0.1)} = 667\ k\Omega$$

$$g_{m1} = 2\sqrt{K_p I_{D1}} = 2\sqrt{(0.5)(0.1)} = 0.447\ mA/V$$

So

$$R_{o8} = (0.447)(667)(667) \Rightarrow 198.9\ M\Omega$$

$$R_{o6} = (3.846)(800)(333\|667) \Rightarrow 683.4\ M\Omega$$

Then

$$A_d = 447(198.9\|683.4) \Rightarrow \underline{A_d = 68{,}865}$$

13.37

Assume biased at $V^+ = 10\ V$, $V^- = -10\ V$

$$P = 3I_{REF}(20) = 10 \Rightarrow I_{REF} = 167\ \mu A$$

$$A_d = g_{m1}(R_{o6}\|R_{o8}) = 25{,}000$$

$$k_n' = 80\ \mu A/V^2,\ k_p' = 35\ \mu A/V^2$$

$$\lambda_n = 0.015\ V^{-1},\ \lambda_p = 0.02\ V^{-1}$$

Assume $\left(\frac{W}{L}\right)_p = 2.2\left(\frac{W}{L}\right)_n$

$$R_{o8} = g_{m8}(r_{o8}r_{o10})$$

$$R_{o6} = g_{m6}(r_{o6})(r_{o4}\|r_{o1})$$

$$r_{o8} = \frac{1}{\lambda_p I_{D8}} = \frac{1}{(0.02)(83.3)} = 0.60\ M\Omega$$

$$r_{o10} = \frac{1}{\lambda_p I_{D8}} = 0.60\ M\Omega$$

$$g_{m8} = 2\sqrt{\left(\frac{k_p'}{2}\right)\left(\frac{W}{L}\right)_8 I_{D8}} = 2\sqrt{\left(\frac{35}{2}\right)(2.2)X^2(83.3)}$$

$$= 113.3X$$

where $X^2 = \left(\frac{W}{L}\right)_n$

$$r_{o6} = \frac{V_A}{I_{C6}} = \frac{80}{83.3} = 0.960\ M\Omega$$

$$r_{o4} = \frac{1}{\lambda_n I_{D4}} = \frac{1}{(0.015)(167)} = 0.40\ M\Omega$$

$$r_{o1} = \frac{1}{\lambda_p I_{D1}} = \frac{1}{(0.02)(83.3)} = 0.60\ M\Omega$$

$$g_{m6} = \frac{I_{C6}}{V_T} = \frac{83.3}{0.026} = 3204\ \mu A/V$$

$$g_{m1} = 2\sqrt{\left(\frac{k_p'}{2}\right)\left(\frac{W}{L}\right)_1 I_{D1}} = 2\sqrt{\left(\frac{35}{2}\right)(2.2)X^2(83.3)}$$

$$= 113.3X$$

Now

$$R_{o6} = (3204)(0.960)[0.40\|0.60] = 738\ M\Omega$$

$$R_{o8} = (113.3X)(0.60)(0.60) = 40.8X\ M\Omega$$

Then

$$A_d = 25{,}000 = (113.3X)[738\|40.8X]$$

$$= (113.3X)\left[\frac{30{,}110X}{738 + 40.8X}\right]$$

which yields $X = 2.48$

or

$$X^2 = 6.16 = \left(\frac{W}{L}\right)_n$$

and

$$\left(\frac{W}{L}\right)_p = (2.2)(6.16) = 12.3$$

13.38

For $v_{cm}(\max)$, assume $V_{CB}(Q_5) = 0$. Then

$$V_S = 15 - 0.6 - 0.6 = 13.8 \text{ V}$$

$$I_{D9} = I_{D10} = \frac{0.236}{2} = 0.118 \text{ mA}$$

Using parameters given in Example 13.11

$$V_{SG} = \sqrt{\frac{I_{D9}}{K_p}} - V_{TP} = \sqrt{\frac{0.118}{0.20}} + 1.4 = 2.17\,V$$

Then

$$v_{cm}(\max) = 13.8 - 2.17 \Rightarrow v_{cm}(\max) = 11.6 \text{ V}$$

For

$v_{cm}(\min)$, assume

$$V_{SD}(M_9) = V_{SD}(sat) = V_{SG} + V_{TP}$$
$$= 2.17 - 1.4 = 0.77 \text{ V}$$

Now

$$V_{D10} = I_{D10}(0.5) + 0.6 + I_{D10}(0.5) - 15$$
$$= 0.118 + 0.6 - 15 \Rightarrow V_{D10} = -14.28 \text{ V}$$

Then

$$v_{cm}(\min) = -14.28 + V_{SD}(\text{sat}) - V_{SG}$$
$$= -14.28 + 0.77 - 2.17 = -15.68 \text{ V}$$

Then, common-mode voltage range

$$\underline{-15.68 \le v_{cm} \le 11.6}$$

Or, assuming the input is limited to ± 15 V, then

$$\underline{-15 \le v_{cm} \le 11.6 \text{ V}}$$

13.39

For $I_1 = I_2 = 300\ \mu$A,

$$V_{SG} = V_{BE} + (0.3)(8) = 0.6 + 2.4 = 3.0 \text{ V}$$

Then

$$I_1 = K_p(V_{SG} + V_{TP})^2$$
$$0.3 = K_p(3 - 1.4)^2$$
$$\Rightarrow \underline{K_p = 0.117\ mA/V^2}$$

13.40

For $V_{CB} = 0$ for both Q_6 and Q_7, then

$$V_S = 0.6 + 0.6 + V_{SG} + (-V_S)$$

So $2V_S = 1.2 + V_{SG}$

Now

$$0.6 + I_2R_1 = V_{SG} = \sqrt{\frac{I_1}{K_p}} + V_{TP} \text{ and } I_1 = I_2$$

Also $I_1 = I_2 = K_p(V_{SG} + V_{TP})^2$ so

$$0.6 + (0.25)(8)(V_{SG} - 1.4)^2 = V_{SG}$$
$$0.6 + 2(V_{SG}^2 - 2.8V_{SG} + 1.96) = V_{SG}$$
$$2V_{SG}^2 - 6.6V_{SG} + 4.52 = 0$$
$$V_{SG} = \frac{6.6 \pm \sqrt{(6.6)^2 - 4(2)(4.52)}}{2(2)} = 2.33 \text{ V}$$

Then $2V_S = 1.2 + 2.33 = 3.53$ and

$$\underline{V_S = 1.765 \text{ V}}$$

13.41

$$I_{C3} = I_{C4} = 300\ \mu\text{A}$$

Using the parameters from Examples 13.12 and 13.13, we have

$$R_{i2} = r_{\pi 13} = \frac{\beta_n V_T}{I_{C13}} = \frac{(200)(0.026)}{0.3} = 17.3 \text{ k}\Omega$$

$$A_d = \sqrt{2K_n I_{Q5}} \cdot (R_{i2}) = \sqrt{2(0.6)(0.3)} \cdot (17.3)$$

or

$$\underline{A_d = 10.38}$$

Now

$$g_{m13} = \frac{I_{C13}}{V_T} = \frac{0.3}{0.026} = 11.5 \text{ mA/V}$$

$$r_{o13} = \frac{V_A}{I_{C13}} = \frac{50}{0.3} = 167 \text{ k}\Omega$$

Then

$$|A_{v2}| = g_{m13} \cdot r_{o13} = (11.5)(167)$$

or

$$\underline{|A_{v2}| = 1917}$$

Overall gain:

$$\underline{|A_v| = (10.38)(1917) = 19,895}$$

13.42

Assuming the resistances looking into Q_4 and into the output stage are very large, we have

$$|A_{v2}| = \frac{\beta R_{O13}}{r_{\pi 13} + (1 + \beta)R_{E13}}$$

where $R_{O13} = r_{o13}[1 + g_{m13}(R_{E13} \| r_{\pi 13})]$

$I_{C13} = 300\ \mu\text{A},\ r_{o13} = \dfrac{50}{0.3} = 167\ \text{k}\Omega$

$g_{m13} = \dfrac{0.3}{0.026} = 11.5\ \text{mA/V}$

$r_{\pi 13} = \dfrac{(200)(0.026)}{0.3} = 17.3\ \text{k}\Omega$

So

$R_{o13} = (167)[1 + (11.5)(1\|17.3)] \Rightarrow 1.98\ \text{M}\Omega$

Then

$$|A_{v2}| = \frac{(200)(1980)}{17.3 + (201)(1)} = 1814$$

Now

$C_i = C_1(1 + |A_{v2}|) = 12[1 + 1814]$

$\Rightarrow C_i = 21,780\ \text{pF}$

$f_{PD} = \dfrac{1}{2\pi R_{eq} C_i}$

$R_{eq} = R_{i2}\|r_{o12}\|r_{o10}$

Neglecting R_3,

$r_{o10} = \dfrac{1}{\lambda I_{D10}} = \dfrac{1}{(0.02)(0.15)} = 333\ \text{k}\Omega$

Neglecting R_5,

$r_{o12} = \dfrac{50}{0.15} = 333\ \text{k}\Omega$

$R_{i2} = r_{\pi 13} + (1+\beta)R_{E13} = 17.3 + (201)(1)$

$= 218\ \text{k}\Omega$

Then

$$f_{PD} = \frac{1}{2\pi[218\|333\|333] \times 10^3 \times (21,780) \times 10^{-12}}$$

or

$\underline{f_{PD} = 77.4\ \text{Hz}}$

Unity-Gain Bandwidth
Gain of first stage:

$A_d = \sqrt{2K_n I_{Q5}} \cdot (R_{i2}\|r_{o12}\|r_{o10})$

$= \sqrt{2(0.6)(0.3)} \cdot (218\|333\|333)$

$= (0.6)(218\|333\|333)$

or $\quad A_d = 56.6$

Overall gain:

$$A_v = (56.6)(1814) = 102,672$$

Then unity-gain bandwidth $= (77.4)(102,672)$

$\Rightarrow \underline{7.95\ \text{MHz}}$

13.43

Since $V_{GS} = 0$ in J_6, $I_{REF} = I_{DSS}$

$\Rightarrow \underline{I_{DSS} = 0.8\ \text{mA}}$

13.44

a. $\quad R_{i2} = r_{\pi 5} + (1+\beta)[r_{\pi 6} + (1+\beta)R_E]$

$r_{\pi 6} = \dfrac{(100)(0.026)}{0.2} = 13\ \text{k}\Omega$

$I_{C5} \cong \dfrac{I_{C6}}{\beta} = \dfrac{200\ \mu\text{A}}{100} = 2\ \mu\text{A}$

So

$$r_{\pi 5} = \frac{(100)(0.026)}{0.002} = 1300\ \text{k}\Omega$$

Then

$R_{i2} = 1300 + (101)[13 + (101)(0.3)]$

or

$\underline{R_{i2} = 5.67\ \text{M}\Omega}$

b. $\quad A_v = g_{m2}(r_{o2}\|r_{o4}\|R_{i2})$

$g_{m2} = \dfrac{2}{V_P} \cdot \sqrt{I_D \cdot I_{DSS}} = \dfrac{2}{3} \cdot \sqrt{(0.1)(0.2)}$

$= 0.0943\ \text{mA/V}$

$r_{o2} = \dfrac{1}{\lambda I_D} = \dfrac{1}{(0.02)(0.1)} = 500\ \text{k}\Omega$

$r_{o4} = \dfrac{V_A}{I_{C4}} = \dfrac{5.0}{0.1} = 500\ \text{k}\Omega$

Then

$A_v = (0.0943)[500\|500\|5670]$

or

$\underline{A_v = 22.6}$

13.45

a. Need $V_{SD}(Q_E) \ge V_{SD}(\text{sat}) = V_P$
For minimum bias ± 3 V

Set $\underline{V_P = 3\ \text{V}}$ and $\underline{V_{ZK} = 3\ \text{V}}$

$I_{REF2} = \dfrac{V_{ZK} - V_{D1}}{R_3}$

so that $R_3 = \dfrac{3 - 0.6}{0.1} \Rightarrow \underline{R_3 = 24\ \text{k}\Omega}$

Set bias in $Q_E = I_{REF2} + I_{Z2} = 0.1 + 0.1 = 0.2$ mA

Therefore,

$\underline{I_{DSS} = 0.2\ \text{mA}}$

b. Neglecting base currents

$$I_{O1} = I_{REF1} = 0.5 \text{ mA} = \frac{12 - 0.6}{R_4}$$

so that

$$\underline{R_4 = 22.8 \text{ k}\Omega}$$

13.46

a. We have

$$g_{m2} = \frac{2}{|V_P|} \cdot \sqrt{I_D \cdot I_{DSS}} = \frac{2}{4} \cdot \sqrt{(0.5)(1)}$$

$$= 0.354 \text{ mA/V}$$

$$r_{o2} = \frac{1}{\lambda I_D} = \frac{1}{(0.02)(0.5)} = 100 \text{ k}\Omega$$

$$r_{o4} = \frac{V_A}{I_D} = \frac{100}{0.5} = 200 \text{ k}\Omega$$

$$g_{m4} = \frac{0.5}{0.026} = 19.23 \text{ mA/V}$$

$$r_{\pi 4} = \frac{(200)(0.026)}{0.5} = 10.4 \text{ k}\Omega$$

So

$$R_{o4} = r_{o4}[1 + g_{m4}(r_{\pi 4} \| R_2)]$$
$$= 200[1 + (19.23)(10.4 \| 0.5)]$$
$$= 2035 \text{ k}\Omega$$

$$|A_d| = g_{m2}(r_{o2} \| R_{o4} \| R_L)$$

For $R_L \to \infty$

$$|A_d| = 0.354(100 \| 2035) = 33.7$$

With these parameter values, gain can never reach 500.

b. Similarly for this part, gain can never reach 700.