EEC 210 | SOLUTION TO HW#8

① Add a dominant pole without changing any of the given poles.

ⓐ The dominant pole will be at a low frequency and will give 90° of phase shift at high frequencies. To obtain a $P_m = 45^\circ$, $|T| = 1$ at 300 KHZ because the pole at 300 KHZ contributes 45° here, and the other poles contribute little phase shift.
Since the GBW is constant after the dominant pole until 300 KHz,
$1 \cdot 300K = 5000\, f_{dom} \longrightarrow f_{dom} = \boxed{60\,HZ}$
Bandwidth with feedback $\simeq \boxed{300\,KHZ}$

ⓑ Because $A_{CL} \simeq 1/f$, the feedback factor required to make $A_{CL} = 20dB = 10$ is $f = 1/10 = -20dB$. Therefore
$1 \cdot 300K = 500\, f_{dom} \longrightarrow \boxed{f_{dom} = 600\,Hz}$
Bandwidth with feedback still $\simeq \boxed{300\,KHZ}$

② ⓐ Move the pole at 300 KHZ to a low-enough frequency. After moving this pole, it will contribute 90° at the unity gain frequency, which must now be 2 MHZ.
$1 \cdot 2Meg = 5000\, f_{dom} \longrightarrow f_{dom} = \boxed{400\,HZ}$
Bandwidth with feedback $\simeq \boxed{2\,MHZ}$

ⓑ $f = 1/10$ as in (1b) above
$1 \cdot 2meg = 500\, f_{dom} \longrightarrow f_{dom} = \boxed{4\,KHZ}$
Bandwidth with feedback still $\simeq \boxed{2\,MHZ}$

③ $L_{eff} = L - 2L_d - X_d = 1 - 2(0.09) - 0.1 = 0.72\,um$
$|I_D| = 200\,uA$ for M8, M5, M7 and M6. $|I_D| = 100\,uA$ for $M_1 - M_4$

$\frac{1}{r_o} = \frac{\partial I_D}{\partial V_{DS}} = \frac{I_D}{L_{eff}} \frac{dx_d}{dV_{DS}}$ From Table 2.4, $\frac{dx_d}{dV_{DS}} = 0.02\,um/V$ (NMOS) or $= 0.04\,um/V$ (PMOS)

$1/r_{o2} = (100u/0.72)(0.04u) = 5.55\,uA/V$ $\quad 1/r_{o4} = (100u/0.72u)(0.02u) = 2.78\,uA/V$

$C_{ox} = \epsilon_{ox}/t_{ox} = 3.9(8.854\times10^{-14})/80\times10^{-8} = 4.32\times10^{-7}\,F/cm^2$

$K_p' = u_p C_{ox} = 150(4.32\times10^{-7}\,F/cm^2) = 64.7\,uA/V^2$

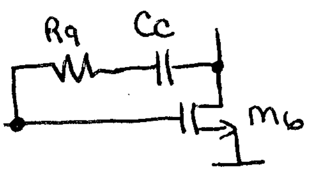
$K_n' = u_n C_{ox} = 450(4.32\times10^{-7}\,F/cm^2) = 194\,uA/V^2$

$g_{m2} = \sqrt{2(64.7)(150/0.72)(100)} = 1.64\,mA/V$

$g_{m6} = \sqrt{2(194)(100/0.72)(200)} = 3.28\,mA/V$

$1/r_{o7} = (200u/0.72u)(0.04u) = 11.1\,uA/V$ $\quad 1/r_{o6} = (200u/0.72u)(0.02u) = 5.55\,uA/V$

$v_o/v_i = g_{m2}(r_{o2}\|r_{o4})\, g_{m6}(r_{o6}\|r_{o7}) = (1.64m/8.33u)(3.28m/16.7u) = \boxed{38700}$



$z = \frac{1}{(1/g_{m6} - R_q)C_c}$ Cancel this zero by moving it to ∞

$R_q = 1/g_{m6} = 305\,\Omega$

$\frac{1}{R_q} = \frac{\partial I_D}{\partial V_{DS}} = k'\left(\frac{W}{L}\right)_q (V_{GSq} - V_{tq} - V_{DSq})$ and $V_{DSq} = 0$
$= k'\left(\frac{W}{L}\right)_q (V_{Gq} - \underbrace{V_{Sq}}_{V_{SS}+V_{GS6}} - V_{tq})$

Assume $\gamma = 0$ $\quad 1/R_q = k'\left(\frac{W}{L}\right)_q (1.5 - V_{GS6} - V_{tq} + 1.5)$

$V_{GS6} = V_{t6} + V_{ov6}$ $\quad V_{ov6} = \sqrt{\frac{2(200)}{194(100/0.72)}} = 0.122\,V$
$= 0.6 + 0.122$
$= 0.722\,V$

$1/305 = 194\left(\frac{W}{L}\right)_q (3 - 0.722 - 0.6)$

$\left(\frac{W}{L}\right)_q = 10.0 = W_q/[1 - 2(0.09)] = W_q/0.82u \rightarrow W_q = \boxed{18.3\,um}$
x_d for $M_q = 0$ (Triode Region)
Use the same drawn length as for M6

(3) continued

The unity-gain frequency is the freq where $|A(\omega)| = \left|\frac{g_{m1}}{j\omega C_c}\right| = 1$

$$f_{unity} = \frac{g_{m1}}{2\pi C_c} = \frac{1.64\times10^{-3} A/V}{2\pi(5\times10^{-12} F)} = \boxed{52.2\ MHz}$$

$$\text{Slew Rate} = \left.\frac{dv_o}{dt}\right|_{max} = \frac{I_{max}}{C_c} = \frac{200\,\mu A}{5\,pF} = \boxed{40\,V/\mu s}$$

(4) From (3), $1/R_9 = k'(W/L)_9(V_{GS9} - V_{t9})$

From KVL, $V_{GS9} = V_{GS11} + V_{GS12} - V_{GS6}$

Since $I_{D12} = I_{D6}$ and since $(W/L)_{12} = (W/L)_6$, $V_{ov12} = V_{ov6}$

Therefore $V_{SB11} = V_{GS12} = V_{t12} + V_{ov12} = V_{SB9} = V_{GS6} = V_{t6} + V_{ov6}$

because $V_{t12} = V_{t6}$ (neither transistor has body effect)

Since $V_{SB11} = V_{SB9}$, $V_{t11} = V_{t9}$ (including body effect)

Also, $V_{ov11} = V_{ov12}$ because $I_{D11} = I_{D12}$ and $(W/L)_{11} = (W/L)_{12}$

Therefore $V_{GS9} = V_{t11} + V_{ov11} + V_{t12} + V_{ov12} - V_{t6} - V_{ov6}$

$= V_{t11} + V_{ov}$ where $V_{ov} = V_{ov6} = V_{ov11} = V_{ov12}$

So $V_{GS9} - V_{t9} = V_{t11} + V_{ov} - V_{t9} = V_{ov}$

Since $V_{GS9} - V_{t9} = V_{GS6} - V_{t6}$ and since $\frac{1}{R_9}$ should $= g_{m6}$ to cancel the RHP zero,

$1/R_9 = k'(W/L)_9(V_{GS9} - V_{t9}) = g_{m6} = k'(W/L)_6(V_{GS6} - V_{t6})$

$(W/L)_9 = (W/L)_6 = 100/1$

(5) To obtain 45° phase margin, set 2nd pole = unity gain frequency

$$|P_2| = \frac{g_{m6} C_c}{C_L C_1 + C_c C_L + C_1 C_c} = \frac{g_{m2}}{C_c} = \frac{1.64\,mA/V}{5\,pF} = 328\,\text{meg}\,\frac{rad}{s}$$

C_1 is dominated by the gate of M_6

minimum estimate for $C_1 = C_{gs6}(i) + C_{gs6}(ol)$

$= \frac{2}{3}(100)(0.72)(4.3) + 0.35(100) = 241\,fF$

Maximum estimate for $C_1 = C_{gs6}(i) + C_{gs6}(ol) + C_{gs9}(i) + C_{gs9}(ol) + C_{gd2}(ol) + C_{gd4}(ol)$

$= \frac{2}{3}(100)(0.72)(4.3) + 0.35(100) + \underbrace{\tfrac{1}{2}(100)(0.82)}_{M_9 \text{ is in the triode region}} + 0.35(100) + 0.35(150) + 0.35(50) = 387\,fF$

$$328\,\text{meg}\,\frac{rad}{s} = \frac{3.28\,m\,(5p)}{C_L C_1 + C_L(5p) + C_1(5p)}$$

Case 1 (min C_1)

$C_L(241f) + C_L(5p) + 241f(5p) = 5\times10^{-23}$

$C_L = 9.3\,pF$

Case 2 (max C_1)

$C_L(387f) + C_L(5p) + 387f(5p) = 5\times10^{-23}$

$C_L = 8.9\,pF$

Therefore, C_L should be less than about $\boxed{8.9\,pF}$