10.11 Based on 10.11 but more of a discussion than an exact solution to that problem. (1)

	PMOS	NMOS
Table 2.1	$\mu_p = 100\ cm^2/Vs$	$\mu_n = 350\ cm^2/Vs$
	$t_{ox} = 9 \cdot 10^{-9}\ m = 90\ \text{Å}$	$t_{ox} = 90\ \text{Å}$

$C_{ox} = 6.9\ fF/\mu m^2$ @ $t_{ox} = 50\ \text{Å}$ (p. 14)

$\Rightarrow C_{ox} = 6.9\ fF/\mu m \cdot \frac{50\text{Å}}{90\text{Å}} = 3.83\ fF/\mu m^2$

	PMOS	NMOS
	$\mu_p C_{ox} = 3.83 \cdot 10^{-5}\ F/m^2$	$\mu_n C_{ox} = 1.34 \cdot 10^{-4}\ F/m^2$
Table 2.1	$V_{THp} = -0.8\ V$	$V_{THn} = 0.7\ V$
	$\lambda_p = 0.2$	$\lambda_n = 0.1$
	$L_{Dp} = 0.09\ \mu m$	$L_{Dn} = 0.08\ \mu m$
	$L_{eff} = L - 2L_D = 0.5 - 2 \cdot 0.09 = 0.32 \mu m$	$L_{eff} = L - 2L_D = 0.5 - 2 \cdot 0.08 = 0.34\ \mu m$

Bias voltages V_{b1} and V_{b2}:

$$|V_{GS3}| = |V_{THp}| + \sqrt{\frac{|I_{D3}|}{\frac{1}{2}\mu_p C_{ox} \cdot \frac{W}{L_{eff}}}} = 0.8 + \sqrt{\frac{125\mu}{\frac{1}{2} \cdot 3.83 \cdot 10^{-5} \cdot \frac{50\mu}{0.32\mu}}} = 1.00\ V$$

$$V_{b1} = V_{DD} - |V_{GS3}| = 3.0 - 1.00 = 2.00\ V$$

$$V_{GS7} = V_{THn} + \sqrt{\frac{I_{D7}}{\frac{1}{2}\mu_n C_{ox} \cdot \frac{W}{L_{eff}}}} = 0.7 + \sqrt{\frac{1m}{\frac{1}{2} \cdot 1.34 \cdot 10^{-4} \cdot \frac{50\mu}{0.34\mu}}} = 1.02\ V$$

$$V_{b2} = V_{GS7} = 1.02\ V$$

$$|V_{GS6}| = |V_{TH6}| + \sqrt{\frac{I_{D6}}{\frac{1}{2}\mu_p C_{ox} \frac{W}{L_{eff}}}} = 0.8 + \sqrt{\frac{1m}{\frac{1}{2} \cdot 3.83 \cdot 10^{-5} \cdot \frac{60\mu}{0.32\mu}}} = 1.33\ V$$

$$V_X = V_Y = V_{DD} - |V_{GS6}| = 3 - 1.33 = 1.67\ V$$

Checking bias with simulation.

Adjusting bias to get all transistors into saturation region and continue with calculations using simulated values

Output resistance

$r_{o1} = r_{o2} = \frac{1}{\lambda_n I_D} = \frac{1}{0,1 \cdot 125\mu} = 80\ k\Omega$ 87.7 kΩ from simulation

$r_{o3} = r_{o4} = \frac{1}{\lambda_p |I_D|} = \frac{1}{0,2 \cdot 125\mu} = 40\ k\Omega$ 50.3 kΩ from simulation

$r_{o7} = r_{o8} = \frac{1}{\lambda_n I_D} = \frac{1}{0,1 \cdot 1m} = 10\ k\Omega$ 11.2 kΩ from simulation

$r_{o5} = r_{o6} = \frac{1}{\lambda_p |I_D|} = \frac{1}{0.2 \cdot 1m} = 5\ k\Omega$ 5,7 kΩ from simulation

Transconductance

$g_{m1} = g_{m2} = \sqrt{2\mu_n C_{ox} \cdot \frac{W}{L_{eff}} \cdot I_D} = \sqrt{2 \cdot 1,34 \cdot 10^{-4} \cdot \frac{50\mu}{0,34\mu} \cdot 125\mu} = 2,22\ mA/V$
(2,33m in sim)

$g_{m5} = g_{m6} = \sqrt{2\mu_p C_{ox} \frac{W}{L_{eff}} |I_D|} = \sqrt{2 \cdot 3,83 \cdot 10^{-5} \cdot \frac{60\mu}{0,32\mu} \cdot 1m} = 3,79\ mA/V$
(4,30m in sim)

λ-effect has not been included in calculations.
That's why simulated values are different from calculated.

Gain

$A_{v1} = g_{m1} \cdot (r_{o1} // r_{o3}) = 2,33\ m \cdot (87,7k // 50,3k) = 74,5$

$A_{v2} = g_{m5} \cdot (r_{o5} // r_{o7}) = 4,30\ m \cdot (5,7k // 11,2k) = 16,2$

$A_{v1} \cdot A_{v2} = 1210 = 61,7\ dB$

1212 in simulation

Capacitances

Assuming $E = 1.5\,\mu m$

$A_D = A_S = W \cdot E = 50\mu \cdot 1.5\mu = 75p$ for all except M_5 M_6

$60\mu \cdot 1.5\mu = 90p$ for M_5 M_6

$P_S = P_D = 2(W+E) = 2 \cdot (50\mu + 1.5\mu) = 103\mu$ for all except M_5 M_6

$2 \cdot (60\mu + 1.5\mu) = 123\mu$ for M_5 M_6

Table 2.1:

PMOS

$CGDO = 0.3 \cdot 10^{-9}$ F/m

$CGSO = 0.3\ 10^{-4}$ F/m

$CJ = 0.94 \cdot 10^{-3}$ F/m²

$CJSW = 0.32 \cdot 10^{-11}$ F/m

NMOS

$CGDO = 0.4 \cdot 10^{-9}$ F/m

$CGSO = 0.4 \cdot 10^{-9}$ F/m

$CJ = 0.56 \cdot 10^{-3}$ F/m²

$CJSW = 0.35 \cdot 10^{-11}$ F/m

M_5, M_6: $C_{gs} = \frac{2}{3} W \cdot L_{eff} \cdot C_{ox} + W \cdot C_{ov} =$

$= \frac{2}{3} \cdot 60\mu m \cdot 0.32\mu m \cdot 3.83 fF/\mu m^2 + 60\mu m \cdot 0.3 \cdot 10^{-9}$ F/m $=$

$= 49 fF + 18 fF = 67 fF$

$C_{gd} = W \cdot C_{ov} = 60\mu m \cdot 0.3 \cdot 10^{-9}$ F/m $= 18 fF$

C_{db} is capacitance for reverse biased junction

$C_j = \frac{C_{j0}}{\left(1 + \frac{V_R}{\phi_B}\right)^m}$ $\phi_B = PB = 0.9$ V (NMOS and PMOS)

$m = MJ$ or $MJSW$ $MJ = 0.5$ PMOS, $MJSW = 0.3$ PMOS

$C_{db} = AD \cdot \frac{CJ}{\left(1 + \frac{|V_{DS}|}{PB}\right)^{MJ}} + PD \cdot \frac{CJSW}{\left(1 + \frac{|V_{DS}|}{PB}\right)^{MJSW}} =$

$= 90p \cdot \frac{0.94 \cdot 10^{-3}}{\left(1 + \frac{1.04}{0.9}\right)^{0.5}} + 123\mu \cdot \frac{0.32 \cdot 10^{-11}}{\left(1 + \frac{1.04}{0.9}\right)^{0.3}} =$

$= 57.6 fF + 0.3 fF = 57.9 fF$

In agreement with simulation

M_7, M_8:

$$C_{gs} = \frac{2}{3} W \cdot L_{eff} \cdot C_{ox} + W \cdot C_{ov} =$$

$$= \frac{2}{3} \cdot 50\mu \cdot 0{,}34\mu \cdot 3.83 fF/\mu m^2 + 50\mu \cdot 0.4 \cdot 10^{-9} F =$$

$$= 43{,}4 fF + 20 fF = 63{,}4 fF$$

$$C_{gd} = W \cdot C_{ov} = 50\mu \cdot 0.4 \cdot 10^{-9} F = 20 fF$$

NMOS

MJ= 0.45

MJSW= 0,2

$$C_{db} = A_D \cdot \frac{C_j}{\left(1 + \frac{V_{DS}}{\phi_B}\right)^{m_j}} + P_D \cdot \frac{C_{jsw}}{\left(1 + \frac{V_{DS}}{\phi_B}\right)^{m_{jsw}}} =$$

$$= 75p \cdot \frac{0{,}56 \cdot 10^{-3}}{\left(1 + \frac{1{,}96}{0{,}9}\right)^{0{,}45}} + 103\mu \cdot \frac{0{,}35 \cdot 10^{-11}}{\left(1 + \frac{1{,}96}{0{,}9}\right)^{0.2}} =$$

$$= 25 fF + 0{,}3 fF = 25{,}3 fF$$

In agreement with simulation.

M_3, M_4:

$$C_{gs} = \frac{2}{3} W \cdot L_{eff} \cdot C_{ox} + W \cdot C_{ov} =$$

$$= \frac{2}{3} \cdot 50\mu \cdot 0{,}32\mu \cdot 3{,}83 fF/\mu m^2 + 50\mu \cdot 0.3 \cdot 10^{-9} F =$$

$$= 40{,}9 fF + 15 fF$$

$$C_{gd} = W \cdot C_{ov} = 50\mu \cdot 0{,}3 \cdot 10^{-9} F = 15 fF$$

PMOS

Mj = 0.5

M_{jsw}= 0.3

$$C_{db} = A_D \cdot \frac{C_j}{\left(1 + \frac{|V_{DS}|}{\phi_B}\right)^{m_j}} + P_D \cdot \frac{C_{jsw}}{\left(1 + \frac{|V_{DS}|}{\phi_B}\right)^{m_{jsw}}} =$$

$$= 75p \cdot \frac{0{,}94 \cdot 10^{-3}}{\left(1 + \frac{1{,}29}{0{,}9}\right)^{0.5}} + 103\mu \cdot \frac{0{,}32 \cdot 10^{-11}}{\left(1 + \frac{1{,}29}{0{,}9}\right)^{0.3}} =$$

$$= 45{,}2 fF + 0{,}25 fF = 45{,}4 fF$$

M_1, M_2:

$$C_{gs} = 43{,}4 fF + 20 fF = 63{,}4 fF \quad (= M_7\ M_8)$$

$$C_{gd} = 20 fF$$

$$C_{db} = 75p \cdot \frac{0{,}56 \cdot 10^{-3}}{\left(1 + \frac{1{.}01}{0{,}9}\right)^{0{,}45}} + 103\mu \cdot \frac{0{.}35 \cdot 10^{-11}}{\left(1 + \frac{1{.}01}{0{,}9}\right)^{0.2}} =$$

$$= 29{,}9 fF + 0{,}31 fF = 30{,}2 fF$$

Associate poles with nodes

Two nodes X, Y and Out1, Out2

Y: $C_Y = C_{gd4} + C_{db4} + C_{gd2} + C_{db2} + C_{gs6} + C_{gd}(1 + |A_{v2}|) =$

$= 15 + 45{,}4 + 20 + 30{,}2 + 20(1 + 16.2) = 455\,fF$

$R_Y = r_{o2} \parallel r_{o4} = 87{,}7k \parallel 50.3k = 32\,k\Omega$

$$f_{pY} = \frac{1}{2\pi R_Y C_Y} = \frac{1}{2\pi \cdot 32k \cdot 455f} = 10.9\ MHz$$

Out: $C_{out} = C_L + C_{db6} + C_{gd6}\left(1 + \frac{1}{|A_{v2}|}\right) + C_{db8} + C_{gd8} =$

$C_L = 1pF$ $\quad = 1000 + 57{,}9 + 18\left(1 + \frac{1}{16.2}\right) + 25.3 + 20 = 1122\,fF$

$R_{out} = r_{o6} \parallel r_{o8} = 5.7k \parallel 11.2k = 3{,}8\,k\Omega$

$$f_{pOUT} = \frac{1}{2\pi R_{out} C_{out}} = \frac{1}{2\pi \cdot 3.8k \cdot 1122f} = 37{,}6\ MHz$$

Two poles at 10.9 MHz and 37.6 MHz

Right half plane zero

$$\omega_z = \frac{g_{m6}}{C_{GD6}}$$

$$f_{z2} = \frac{g_{m6}}{2\pi C_{GD6}} = \frac{4.30 \cdot 10^{-3}}{2\pi \cdot 18 \cdot 10^{-15}} = 38\ GHz$$ in second stage

There is also a zero in first stage

$$f_{z1} = \frac{g_{m2}}{2\pi C_{GD2}} = \frac{2{,}33 \cdot 10^{-3}}{2\pi \cdot 20 \cdot 10^{-15}} = 18.5\ GHz$$

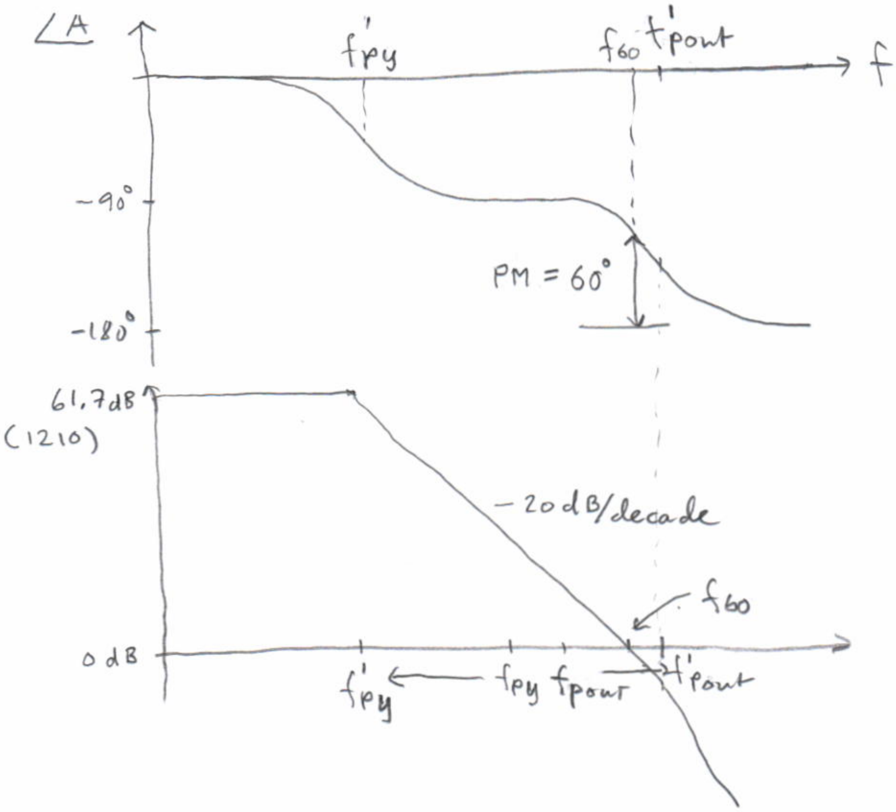
Next step is to do a miller compensation for 60° phase margin

Study loop gain βA

Unity gain feedback $\beta = 1 \Rightarrow \beta A = A$

Miller compensation will split the poles

After compensation $f_{p1} \to f'_{p1}$ $f_{p2} \to f'_{p2}$



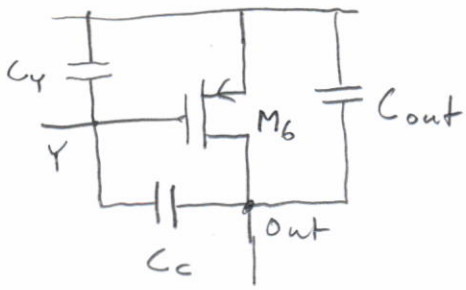
Phase: $-90° - \arctan \frac{f_{60}}{f'_{pout}} = -120°$ ⟵ PM = 60°

$$\arctan \frac{f_{60}}{f'_{pout}} = 30°$$

$$f_{60} = \tan 30° \cdot f'_{pout}$$

Magnitude: Gain · frequency = constant in −1 slope (−20dB/dec)

$$1212 \cdot f'_{py} = 1 \cdot f_{60}$$



After compensation

Because of the pole split f_{p2} moves to higher frequency. Large C_c can be viewed as short circuit at 2nd pole. Node resistance at output node $= \frac{1}{g_{m6}}$ and C_{out} is parallell to C_Y

Dominant pole:

$$f'_{pY} = \frac{1}{2\pi R_Y \cdot [C_Y + (1 + A_{v2}) C_c]}$$

Second pole:

$$f'_{pOUT} = \frac{g_{m6}}{C_Y + C_{OUT}} = \frac{4.30\,m}{455f + 1122f} = 2{,}73\ GHz$$

$$f_{60} = f'_{pOUT} \cdot \tan 30^\circ = 2{,}73 \cdot 0{,}577 = 1{,}57\ GHz$$

$$f'_{pY} = \frac{f_{60}}{1212} = 1.30\ MHz$$

$$C_Y + (1 + A_{v2}) C_c = \frac{1}{2\pi R_Y f'_{pY}}$$

$$C_c = \left[\frac{1}{2\pi R_Y f'_{pY}} - C_Y\right] \cdot \frac{1}{1 + A_{v2}} =$$

$$= \left[\frac{1}{2\pi\, 32k \cdot 1.30M} - 455f\right] \frac{1}{1 + 16.2} = 196\ fF$$

Move the zero to infinity

$$R_Z = \frac{1}{g_{m6}} = \frac{1}{4.30m} = 233\,\Omega$$

Placing the zero atop second pole

$$R_Z = \frac{C_{OUT} + C_Y + C_C}{g_{m6} \cdot C_C} = \frac{1122f + 455f + 196f}{4.30m \cdot 196f} =$$

$$= 2.1\,k\Omega$$

From simulations there seems to be a zero in first stage that makes it hard to get enough phase margin.

It is not a good idea to miller compensate that stage because it will move pole associated to node Y (dominating pole) to higher frequency.

One way is to move the dominating pole to lower frequency, but it will also lower the bandwith. From simulation I can see that I have to lower the magnitude curve 10,7 dB. ⇒ Lower dominating pole to $\frac{1.30\,MHz}{3{,}43} =$ $= 379\,kHz$ $\quad -10{,}7dB = \frac{1}{3{,}43}$

$$C_C = \left[\frac{1}{2\pi\, 32k \cdot 379k} - 455f\right] \frac{1}{1 + 16.2} = 7.36\,fF$$

Simulation shows $PM = 49°$ and dominating pole at 374 kHz

Placing the zero atop second pole

$$R_Z = \frac{C_{out} + C_Y + C_C}{g_{m6} \cdot C_C} = \frac{1122f + 455f + 736f}{4.3m \cdot 736f} = 731\,\Omega$$