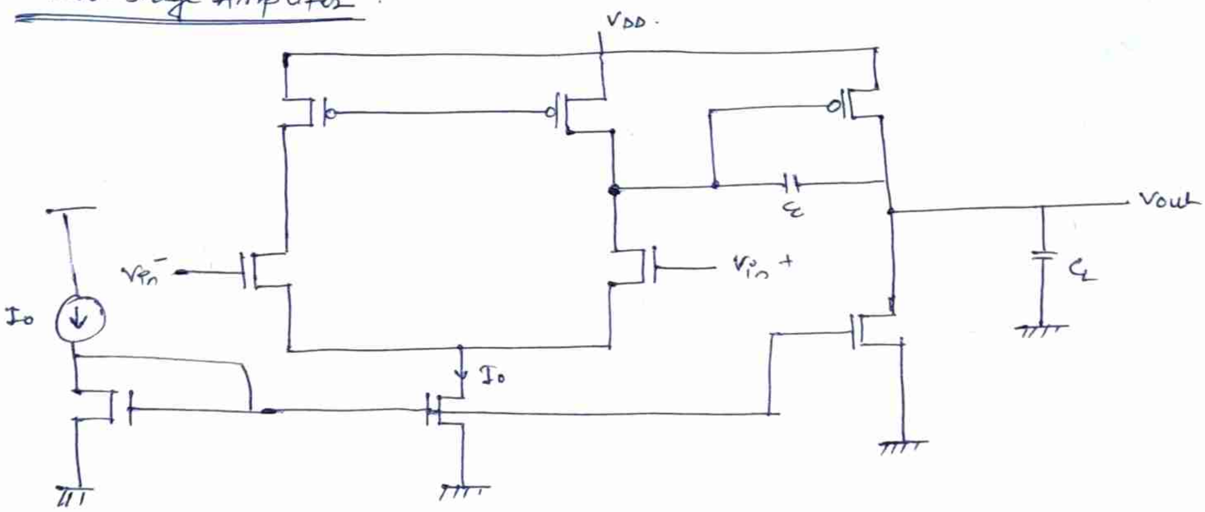
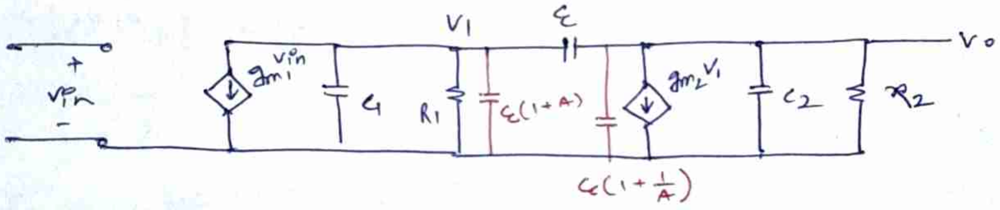
Design of Two stage Op-Amp.

Two-stage Amplifier.



phase margin
slew Rate
swing limit



$P_1 = ?$
$P_2 = ?$
$GBW = ?$
phasemargin = ?

we can't apply
miller theorem
bcz. ① pole splitting
② zero

$$\frac{V_o}{V_{in}} = \frac{V_o}{V_1} \times \frac{V_1}{V_{in}}$$

$$\frac{V_1}{1/sC_1} + \frac{V_1}{R_1} + g_{m1} V_{in} + \frac{V_1 - V_o}{1/sC_c} = 0$$

$$V_1\left(sC_1 + \frac{1}{R_1} + sC_c\right) + g_{m1} V_{in} - V_o s C_c = 0$$

$$V_1 = \frac{V_o \cdot sC_c R_1 - g_{m1} R_1 V_{in}}{1 + sR_1(C_1 + C_c)} \quad \text{— ①}$$

$$\frac{V_o}{1/sC_2} + \frac{V_o}{R_2} + g_{m2}V_1 + \frac{V_o - V_1}{1/sC_c} = 0$$

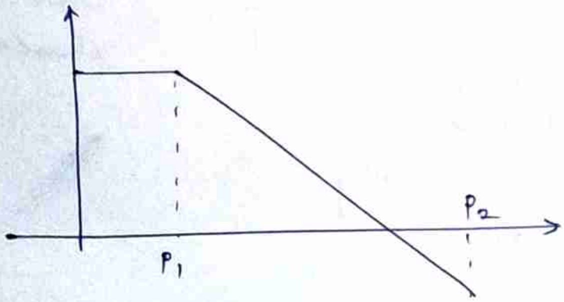
$$V_o\left[s(C_2+C_c)+\frac{1}{R_2}\right] = V_1(sC_c - g_{m2})$$

$$V_o\left[s(C_2+C_c)+\frac{1}{R_2}\right] = \frac{(V_o\, sC_cR_1 - g_{m1}R_1V_{in})(sC_c-g_{m2})}{1+s(C_1+C_c)R_1}$$

$$V_o\left[s(C_2+C_c)R_2+1\right]\left[1+s(C_1+C_c)R_1\right] = (V_o\cdot sC_cR_1 - g_{m1}R_1V_{in})(sC_c-g_{m2})$$

$$\frac{V_o}{V_{in}} = \frac{g_{m1}R_1\; g_{m2}R_2\left(1-\frac{sC_c}{g_{m2}}\right)}{s^2\left[R_1R_2(C_1C_2+C_1C_c+C_2C_c)\right]+s\left[R_2(C_c+C_2)\cancel{C}+R_1(C_c+C_1)+C_cg_{m2}R_1R_2\right]+1}$$

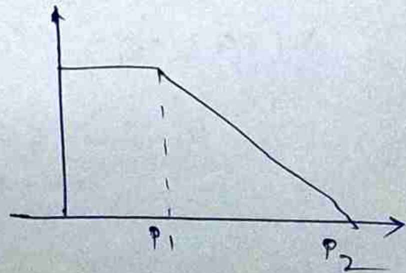
$$\frac{V_o}{V_{in}} = \frac{g_{m1}\, g_{m2}\, R_1R_2\left(1-\frac{sC_c}{g_{m2}}\right)}{s^2\left[R_1R_2(C_1C_2+C_1C_c+C_2C_c)\right]+s\left[R_2(C_c+C_2)+R_1(C_c+C_1)+C_cg_{m2}R_1R_2\right]+1}$$



for DC $\Rightarrow j\omega = 0$

$$\frac{V_o}{V_{in}} = \frac{A_{DC}\left(1-\frac{s}{Z}\right)}{\left(1+\frac{s}{P_1}\right)\left(1+s/P_2\right)}$$ std eqn for 2-pole system.

$$= \frac{A_{DC}\left(1-\frac{s}{Z}\right)}{1+s\left(\frac{1}{P_1}+\frac{1}{P_2}\right)+s^2\left(\frac{1}{P_1P_2}\right)}$$



$$s\left(\frac{1}{P_1}+\frac{1}{P_2}\right) \approx \frac{s}{P_1}$$

$\frac{1}{P_1}$ = coefficient of 's'

$$s^2 = \frac{1}{P_1P_2}$$

$$P_1 \simeq \frac{1}{R_2(C_c + C_2) + R_1(C_c + C_1) + g_{m2} R_2 R_1 C_c}$$

$$\boxed{P_1 \approx \frac{1}{g_{m2} R_2 R_1 C_c}}$$ 1st pole

$$P_1 P_2 = \frac{1}{R_1 R_2 (C_1 C_2 + C_1 C_c + C_2 C_c)}$$

$$P_2 = \frac{g_{m2} \cancel{R_1 R_2} C_c}{\cancel{R_1 R_2} [C_1 C_2 + C_1 C_c + C_2 C_c]} = \frac{g_{m2} C_c}{C_1 C_2 + C_1 C_c + C_2 C_c} \approx \frac{g_{m2} C_c}{C_c C_2}$$

$$\boxed{P_2 = \frac{g_{m2} \cancel{C_c}}{\cancel{C_c} C_2}}$$ 2nd pole.

$$\boxed{\begin{aligned} Z &= \frac{g_{m2}}{C_c} \\ P_1 &= \frac{1}{g_{m2} R_1 R_2 C_c} \\ P_2 &= \frac{g_{m2} \cancel{C_c}}{C_2 \cancel{C_c}} \end{aligned}}$$

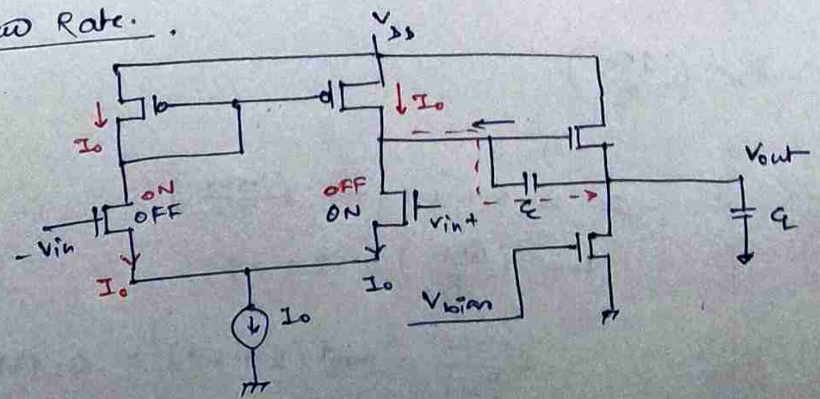
A_{DC} = DC gain = $g_{m1} R_1 \cdot g_{m2} R_2$

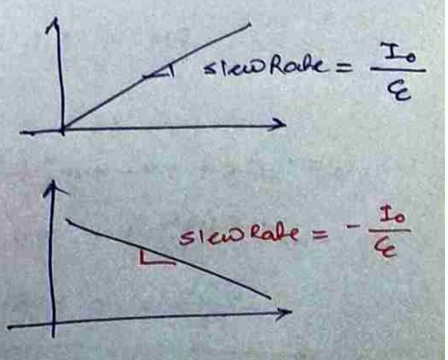
gain bandwidth product $\Rightarrow$ GBW = DC gain $\times P_1$

$$= \frac{g_{m1} g_{m2} R_1 R_2}{g_{m2} R_1 R_2 C_c}$$

$$\boxed{GBW = \frac{g_{m1}}{C_c}}$$

slew Rate.

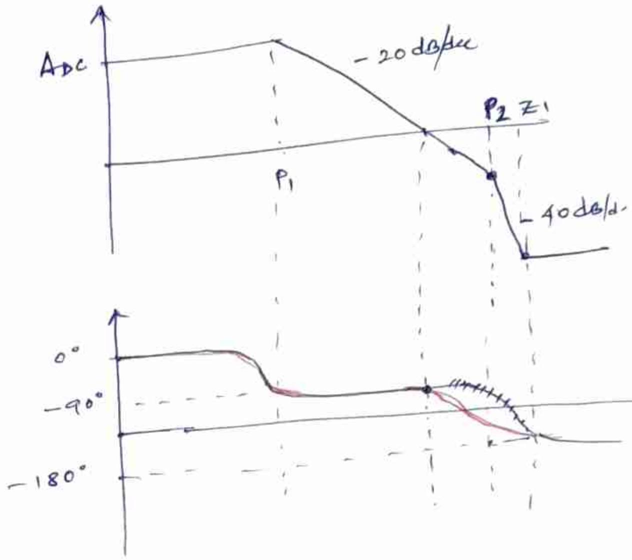




Phase Margin.

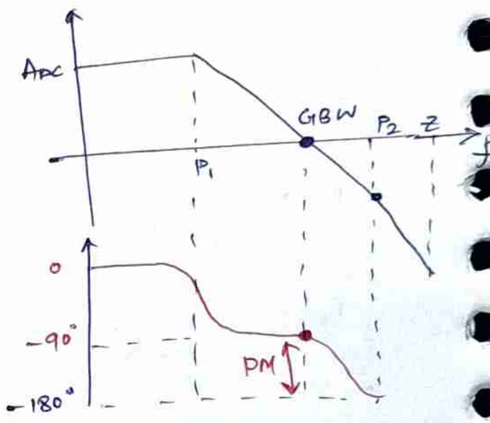
$$\boxed{z \geq 10\ G.BW} \quad \text{—— ①}$$

$$GBW = \frac{g_{m1}}{C_c}$$



Angle of transfer function

$$\angle \frac{V_o}{V_{in}} = -\tan^{-1}\left(\frac{\omega}{z}\right) - \tan^{-1}\left(\frac{\omega}{P_1}\right) - \tan^{-1}\left(\frac{\omega}{P_2}\right)$$



$$\angle \frac{V_o}{V_{in}} = -\tan^{-1}\left(\frac{\omega}{z}\right) - \tan^{-1}\left(\frac{\omega}{P_1}\right) - \tan^{-1}\left(\frac{\omega}{P_2}\right)$$

$$= -\tan^{-1}\left(\frac{GBW}{z}\right) - \tan^{-1}\left(\frac{GBW}{P_1}\right) - \tan^{-1}\left(\frac{GBW}{P_2}\right)$$

$$= -\tan^{-1}\left(\frac{GBW}{10 \cdot GBW}\right) - \tan^{-1}\left(\frac{g_{m1} g_{m2} R_1 R_2 \cancel{C_c}}{\cancel{C_c}}\right) - \tan^{-1}\left(\frac{g_{m1}}{C_c}\frac{C_2}{g_{m2}}\right)$$

$$= -\tan^{-1}\left(\frac{1}{10}\right) - \tan^{-1}\left(g_{m1} g_{m2} R_1 R_2\right) - \tan^{-1}\left(\frac{g_{m1} C_2}{C_c\, g_{m2}}\right)$$

$$\angle \frac{V_o}{V_{in}} = -\tan^{-1}\left(\frac{1}{10}\right) - \tan^{-1}\left(A_{DC}\right) - \tan^{-1}\left(\frac{GBW}{P_2}\right)$$

$$-180° + PM = -5.71 - 90 - \tan^{-1}\left(\frac{GBW}{P_2}\right)$$

$$PM = 84.29 - \tan^{-1}\left(\frac{GBW}{P_2}\right)$$

PM = 45°

$$45° = 84.29 - \tan^{-1}\left(\frac{GBW}{P_2}\right)$$

$$\tan^{-1}\left(\frac{GBW}{P_2}\right) = 39.29$$

$$\frac{GBW}{P_2} = 0.8181$$

$$\boxed{P_2 \geq 1.22\ GBW}$$

PM = 60°

$$60° = 84.29 - \tan^{-1}\left(\frac{GBW}{P_2}\right)$$

$$\tan^{-1}\left(\frac{GBW}{P_2}\right) = 24.29$$

$$\frac{GBW}{P_2} = \tan^{-1}(24.29) = 0.4513$$

$$P_2 = \frac{GBW}{0.4513} \Rightarrow \boxed{P_2 = 2.2GBW}$$

$P_2 \approx 2.2\ GBW \Rightarrow \boxed{P_2 \geq 2.2\ GBW}$ @ $60°$ PM

$P_2 = 1.22\ GBW \Rightarrow \boxed{P_2 \geq 1.22\ GBW}$ @ $45°$ PM

$P_2 = \frac{g_{m2}}{C_2} \geq 2.2\ GBW$

$$\frac{g_{m2}}{C_2} \geq 2.2 \cdot \frac{g_{m1}}{C_c}$$

$$\frac{g_{m2}}{C_L} \geq 2.2 \times \frac{g_{m1}}{C_c}$$

$$\frac{10 \cdot \cancel{g_{m1}}}{C_L} \geq 2.2 \cdot \frac{\cancel{g_{m1}}}{C_c}$$

$$\boxed{C_c \geq 0.22\ C_L} \quad @ \quad PM = 60°$$

$Z = 10 \cdot GBW$

$$\frac{g_{m2}}{C_c} = 10 \cdot \frac{g_{m1}}{C_c}$$

$$\boxed{g_{m2} = 10 \cdot g_{m1}}$$

Specification:

DC gain = 1000 = 60 dB

GBW = 30 MHz.

PM $\geq 60°$

Slew Rate = 20 V/μsec.

ICMR(+) = 1.6 V

ICMR(−) = 0.8 V

$C_L = 2PF$

Power $\leq 300\mu W$

$V_{DD} = 1.8V$

process = 180 nm.

$L_{min} = 180nm$

$L \geq 2 \cdot L_{min}$

$L = 500nm$

Specification

$V_{DD} = 1.8\,V$

DC gain = 1000 = 60 dB

GBW = 30 MHz

PM $\geq 60°$

slew Rate = 20 V/μsec.

ICMR (+) = 1.6 V

ICMR (−) = 0.8 V

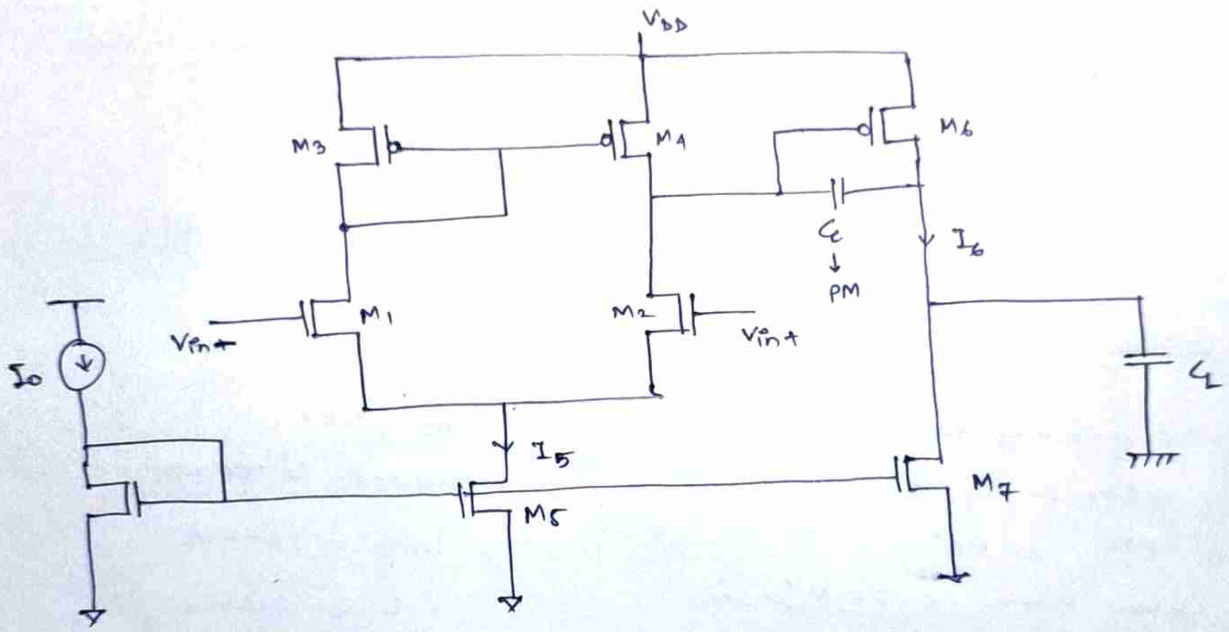
$C_L = 2\,pF$

Power $\leq$ 300 μwatt.

process = 180nm

Lmin = 180 nm.

L = 500nm ⇒ L ≥ 2.Lmin



M3 & M4 → max ICMR (ICMR+)

M1 & M2 → GBW

I_5 → slew Rate.

M5 → min ICMR (ICMR−)

① L = 500nm

② To have PM = 60° $C_c \geq 0.22\,C_L$ $C_L = 2\,pF$

$C_c \geq 0.22 \times 2\,pF$

$C_c \geq 0.44\,pF$

$\boxed{C_c \geq 400\,fF}$

for Design. we use.

$\boxed{C_c = 800\,fF}$

② SR / I_5

$$\text{Slew Rate} = SR = \frac{I_5}{C_c}$$

$$I_5 = SR \cdot C_c$$

$$= \frac{20\,V}{\mu sec} \times 800\,fF$$

$$I_5 = 16\,\mu A$$

$$\boxed{I_5 = 20\,\mu A}$$ ⇒ used in design.

③ M_1 & M_2

$$g_{m1} = GBW \times C_c \times 2\pi$$

$$= 30\,MHz \times 800f \times 2\pi$$

$$= 150.79\,\mu$$

$$\boxed{g_{m1} = 160\,\mu}$$ → used in design.

~~ID eq~~ $$\left(\frac{W}{L}\right) = \frac{g_m^2}{\mu_n C_{ox} \times 2 I_D}$$

$$I_D = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)(V_{GS} - V_T)^2$$

$$g_m = \frac{\partial I_D}{\partial V_{GS}} = \frac{\mu_n C_{ox}(W/L)}{2} \cdot 2(V_{GS} - V_T)$$

$$g_m = \mu_n C_{ox}\left(\frac{W}{L}\right) \cdot (V_{GS} - V_T)$$

$$g_m^2 = \left[\mu_n C_{ox}\left(\frac{W}{L}\right)\right]^2 \frac{(V_{GS} - V_T)^2}{2} \times 2$$

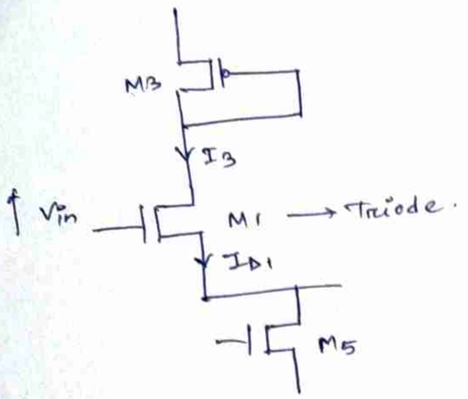
$$g_m^2 = 2 I_D\, \mu_n C_{ox}\left(\frac{W}{L}\right)$$

$$\frac{W}{L} = \frac{g_m^2}{\mu_n C_{ox}\, 2 I_D}.$$ $$2 I_D = I_5$$

$$\left(\frac{W}{L}\right)_1 = \left(\frac{W}{L}\right)_2 = \frac{g_{m1}^2}{\mu_n C_{ox}\, I_5} = \frac{(160\mu)^2}{300 \times 20} = 4.266$$

$$\boxed{\left(\frac{W}{L}\right)_1 = \left(\frac{W}{L}\right)_2 = 5\,\mu}$$

4) M3 & M4



for M_1 to be in saturation:

$$\Rightarrow V_d > V_g - V_{t1}$$

$$V_g < V_{D1} + V_{t1}$$

$$V_{in} < V_{D1} + V_{t1}$$

$$V_{in\,max} = V_{D1} + V_{t1} \quad \text{— (1).}$$

$$\Rightarrow V_{D1} = V_{DD} - V_{sg3}$$

$$V_{D1} = V_{DD} - \left[\sqrt{\frac{2I_3}{\beta}} + |V_{t3}|\right]$$

$$\Rightarrow I_3 = \frac{1}{2}\mu_p C_{ox}\left(\frac{W}{L}\right)_3 (V_{gs} - V_t)^2$$

$$I_3 = \frac{\beta}{2}(V_{gs} - V_t)^2$$

$$V_{gs} = \sqrt{\frac{2I_3}{\beta}} + |V_{t3}|$$

$$\Rightarrow V_{in\,max} \leq \underbrace{V_{D1} + V_{t1}}_{min}$$

Calculated previously.

$$\boxed{\begin{aligned} \mu_p C_{ox} &= 60\mu \\ \mu_n C_{ox} &= 300\mu \end{aligned}}$$

$$ICMR+ \leq V_{D1\,min} + V_{t1\,min}$$

$$ICMR+ \leq \left[V_{DD} - \left\{\sqrt{\frac{2I_3}{\beta}} + |V_{t3}|\right\}\right]_{min} + V_{t1\,min}$$

$$ICMR^+ \leq V_{DD} - \sqrt{\frac{2I_{D3}}{\beta_3}} - |V_{t3}|_{max} + V_{t1\,min}$$

$$\frac{2I_3}{\beta_3} = \left(V_{DD} - ICMR_{max} - |V_{t3}|_{max} + V_{t1\,min}\right)^2$$

$$\frac{2I_{D3}}{\mu_p C_{ox}\left(\frac{W}{L}\right)_3} = V_{DD} - ICMR+ - |V_{t3}|_{max} + V_{t1\,min}$$

$$\left(\frac{W_1}{L}\right)_3 = \frac{2I_{D3}}{\mu_p C_{ox}\left[V_{DD} - ICMR^+ - V_{t3\,max} + V_{t1\,min}\right]^2}$$

$V_{DD} = 1.8$

$I_{D3} = \frac{I_{D5}}{2} = 10\mu$

$\mu_p C_{ox} = 60\mu$

$ICMR+ = 1.6\ V$

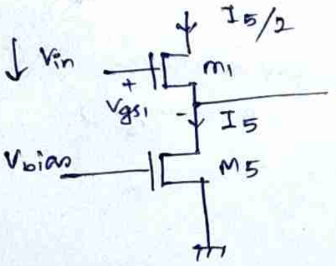
Simulation value. $\begin{cases} V_{t3\,max} = 0.51\ V \\ V_{t1\,min} = 0.47\ V \end{cases}$

$$\left(\frac{W}{L}\right)_{3,4} = \frac{2 \times 10\mu}{60\mu\left[1.8 - 1.6 - 0.51 + 0.47\right]^2}$$

$$= 13.02\ \mu$$

$$\boxed{\left(\frac{W}{L}\right)_3 = \left(\frac{W}{L}\right)_4 = 14\mu}$$

Design of M5



$2I_1 = I_5$

M5 to be in saturation.

$V_{D5} > V_g - V_t$

M5 goes into triode region.

V_{Dsat} required voltage M5 to goes into saturation.

$$V_{in\,(min)} \geq V_{gs1} + V_{Dsat5}$$

$$ICMR_{min} \geq V_{gs1\,max} + V_{Dsat}$$

$$ICMR- \geq \left[\sqrt{\frac{2I_{D1}}{\beta_1}} + V_{t1}\right]_{max} + V_{Dsat}$$

$$ICMR- \geq \sqrt{\frac{2I_{D1}}{\beta_1}} + V_{t1max} + V_{Dsat}$$

$$V_{Dsat} \geq ICMR- - \sqrt{\frac{2I_{D1}}{\beta_1}} - V_{t1\,max}$$

$V_{t1\,max} = 0.59\ V$ } Simulation Result.

$$V_{Dsat} \geq 0.8 - \sqrt{\frac{2 \times 10\mu}{300\mu \times 5}} - V_{t1\,max}$$

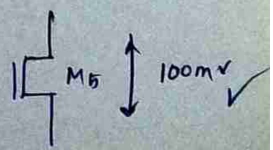
$$V_{Dsat} = 0.8 - 0.1154 - 0.59V$$

$$= 94.6\ mV$$

If $\left(\frac{W}{L}\right)_5 = 6$

$$V_{Dsat} = 0.8 - \sqrt{\frac{2 \times 10\mu}{300\mu \times 6}} - 0.59$$

$$= 105\ mV$$



$$I_{D5} = \frac{\mu_n C_{ox} \left(\frac{W}{L}\right)_5 (V_{Dsat})^2}{2}.$$

$$\left(\frac{W}{L}\right)_5 = \frac{2 I_{D5}}{\mu_n C_{ox} \ (V_{Dsat})^2} = \frac{2 \times 20\mu}{300 \times (105\ mV)^2} = 12.09$$

$$\boxed{\left(\frac{W}{L}\right)_5 = 12\mu} \qquad \boxed{\left(\frac{W}{L}\right)_1 = \left(\frac{W}{L}\right)_2 = 6\mu}$$

↓ modified value.

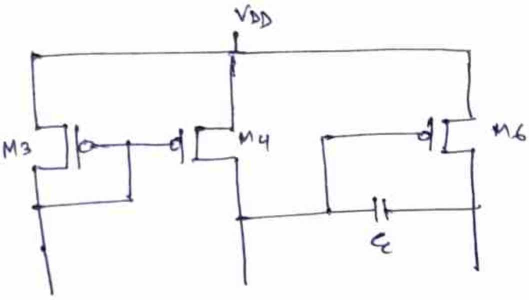
Design of M6 :

for 60° PM

$$g_{m6} \geq 10 \cdot g_{m1}$$

$$g_{m6} \geq 10 \times 160\mu$$

$$g_{m6\,min} = 1600\mu$$



$V_{DS3} = V_{DS4} = V_{DS6}$ (Consider proper mirroring.)

$$V_{gs3} = V_{gs4} = V_{gs6}$$

$$I_D = \mu_p C_{ox} \left(\frac{W}{L}\right) \cdot \frac{[V_{gs} - V_T]^2}{2}$$

$$\frac{\left(\frac{W}{L}\right)_6}{\left(\frac{W}{L}\right)_4} = \frac{I_6}{I_4} \qquad \frac{\left(\frac{W}{L}\right)_6}{\left(\frac{W}{L}\right)_4} = \frac{g_{m6}}{g_{m4}}$$

$$\left(\frac{W}{L}\right)_4 = 14$$

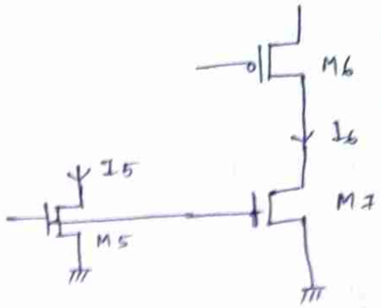
$$g_{m4} = \sqrt{\mu_p C_{ox} \left(\frac{W}{L}\right)_4 2 I_D}$$

$$g_{m4} = \sqrt{60 \times 14 \times 2 \times 10} = 129.61\ \mu$$

$$\left(\frac{W}{L}\right)_6 = \frac{g_{m6}}{g_{m4}} \left(\frac{W}{L}\right)_4 = \frac{1600}{129.61} \times 14$$

$$\left(\frac{W}{L}\right)_6 = 172.82 \qquad \boxed{\left(\frac{W}{L}\right)_6 = 174}$$ used in sim.

I_7



$$\frac{I_6}{I_4} = \frac{(W/L)_6}{(W/L)_4}$$

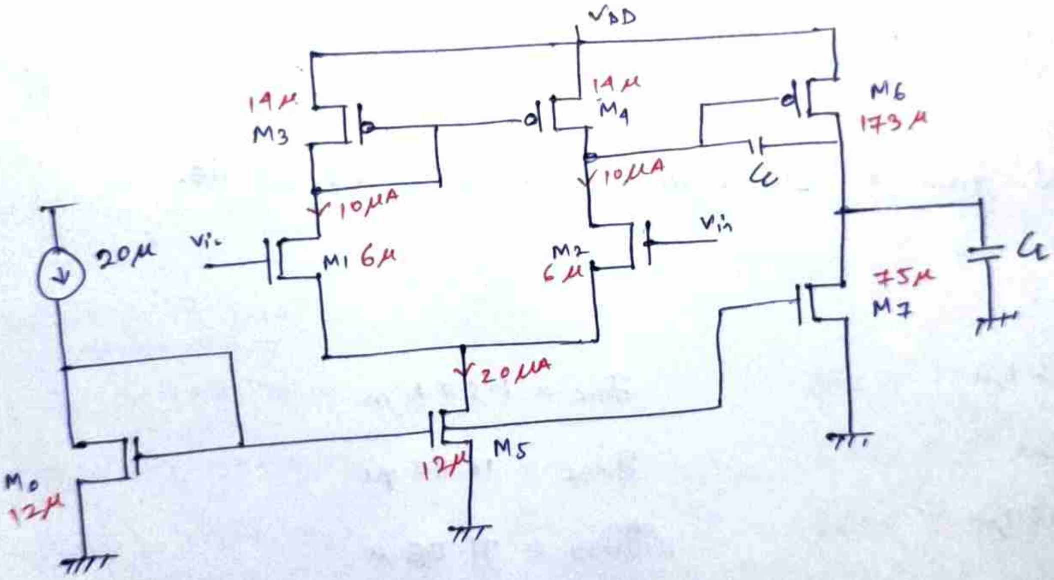
$$I_6 = \frac{174}{14} \times 10 = 124.28\ \mu A$$

$$\boxed{I_6 = 125\ \mu A}$$

$$\frac{I_7}{I_5} = \frac{(W/L)_7}{(W/L)_5}$$

$$\left(\frac{W}{L}\right)_7 = \frac{I_7}{I_5}\left(\frac{W}{L}\right)_5 = \frac{125}{20} \times 12 = 75$$

$$\boxed{\left(\frac{W}{L}\right)_7 = 75\ \mu}$$ used in design.



$I_5 = 20\mu$

$C_c = 800\ fF$

$I_6 = I_7 = 125\ \mu A.$

$M_1, M_2 = 6 \longrightarrow \frac{3\mu}{500n}$

$M_3\ M_4 = 14 \longrightarrow \frac{7\mu}{500n}$

$M_5 = 12 \longrightarrow \frac{6\mu}{500n}$

$M_6 = 174 \longrightarrow \frac{87\mu}{500n}$

$M_7 = 75 \longrightarrow \frac{37.5\mu}{500n}$

Ac analysis

~~$W_7 = 28.5\mu$~~

freq sweep 100 Hz → 100 MHz.

ICMR (−) = 0.8V

$g_{m1} = 145\,\mu$

$g_{ds1} = 838.7n$

$g_{ds4} = 969\,n$

gain for 1st stage.

$$A_v = \frac{g_{m1}}{g_{ds1} + g_{ds4}}$$

$$= \frac{145}{0.8387 + 0.969} = 80.24$$

$A_v(dB) = 20\log(80.24) = 38.08\ dB$

$g_{m6} = 1.423\ m$

$g_{ds6} = 9.386\mu$

$g_{ds7} = 30.839\mu$

gain for 2nd stage.

$$A_v = \frac{1423}{9.386 + 30.84}$$

$$= 35.38$$

$A_v(dB) = 20\log(35.38)$

$= 30.97\ dB$

$\boxed{\text{total gain} = 69.056\ dB.}$

ICMR (+) = 1.6V

$g_{m1} = 154.72\mu$

$g_{ds1} = 1.7027\mu$

$g_{ds4} = 1.0468\mu$

gain on 1st stage

gain = 56.46

gain $A_v(dB) = 20\log(56.46)$

$A_v = dB = 35.03\ dB.$

$g_{m6} = 1.4648\ m$

$g_{ds6} = 10.605\mu$

$g_{ds7} = 11.33\mu$

gain on 2nd stage.

$$\text{gain } A_v = \frac{1.4648m}{10.605\mu + 11.33\mu}$$

$A_v = 66.72$

$A_v(dB) = 20\log(66.72)$

$A_v = 36.48\ dB$

$\boxed{\text{total gain} = 71.51\ dB}$

from simulation.

$V_{CM} = 1.6\,V$

gain $A_v(dB) = 71.45$ dB (Achived)

$f_{03dB} = 24.43$ MHz. = GBW (Not Achived).

PM = 63.72° (Achived)

Target to achive GBW = 30 MHz.

$C_c \geq 400fF$ @ICMR = 1.6v

Now set $\boxed{C_c = 600fF}$

gain $A_v(dB) = 71.45$ dB (Achived)

GBW = 30.8 MHz. (Achive)

PM = 57.23°

$C_c \downarrow$ GBW $\uparrow$

@ ICMR = 0.8v

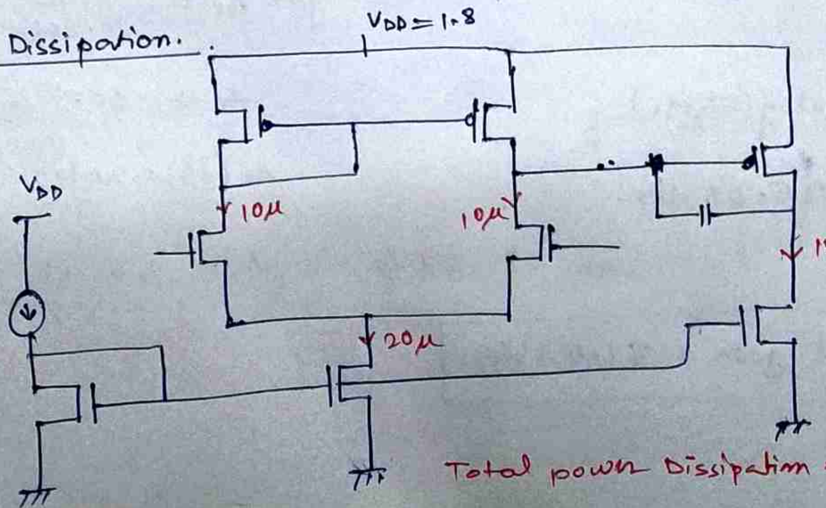
$C_c = 600fF$

gain (dB) = 69

GBW = 30.53 MHz.

PM = 56.91°

power Dissipation.



Total power Dissipation = 1.8 × (125µ × 20µ)
= 261 µW.