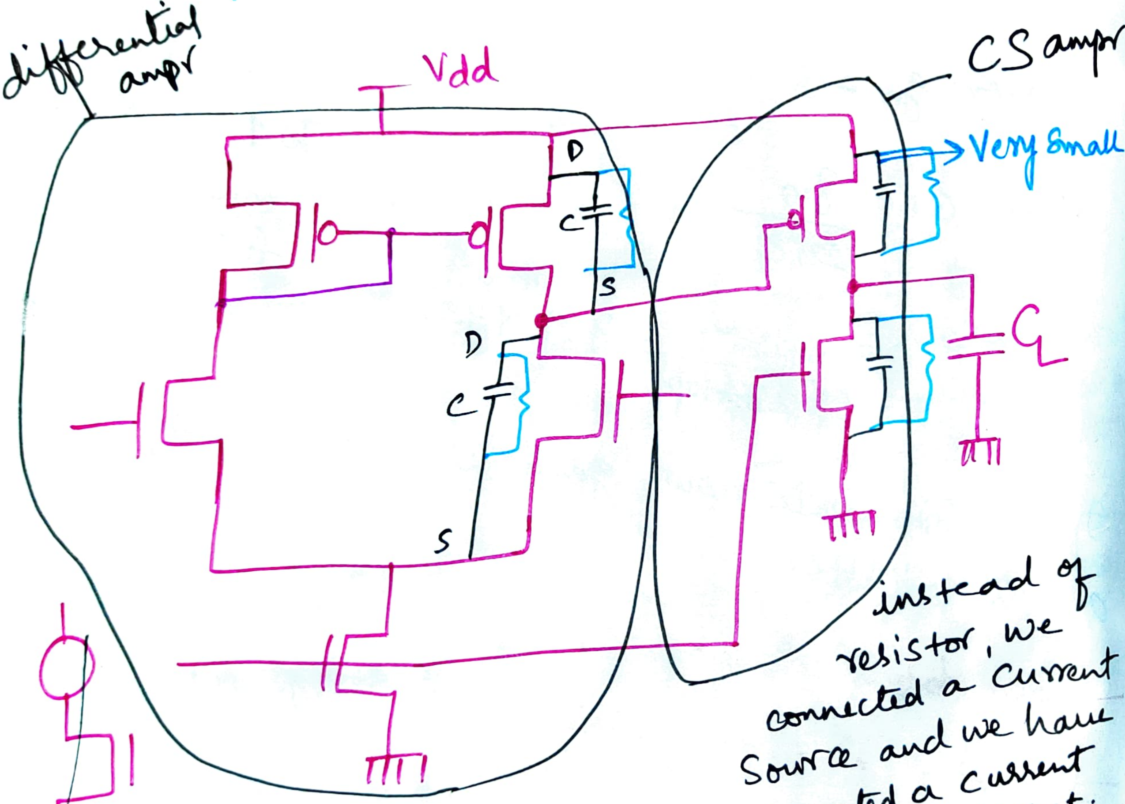
Two Stage op amp

A single stage opamp does not provide much gain, We need two stage op-amp

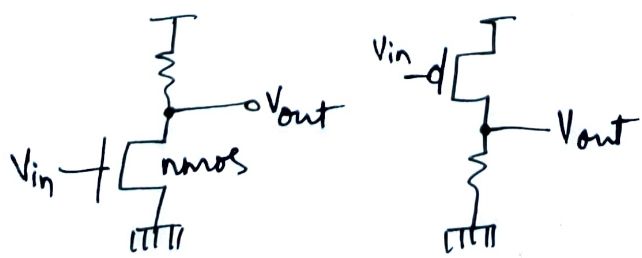
diff ampr

Gain Stage → simplest one is common source.



instead of resistor, we connected a current source and we have implemented a current source using Mosfet.

- CS can be either with pmos or nmos ampr



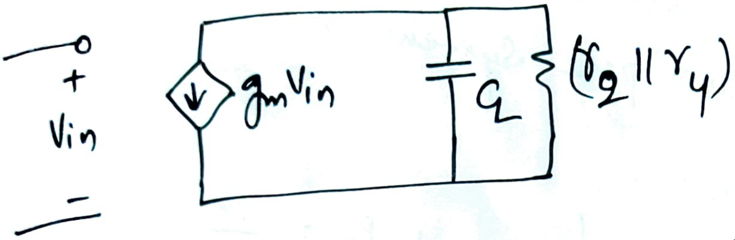
With nmos, the swing will be limited

good swing will be obtained, if we connect this.

In single stage op amp, we were not worried about stability, phase Margin because it is a single pole System

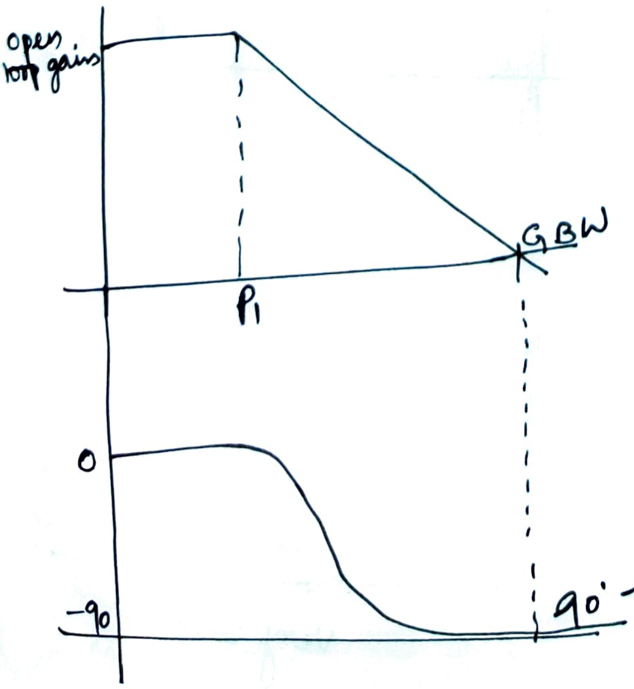
diff amp

— Small Signal model of diff amp

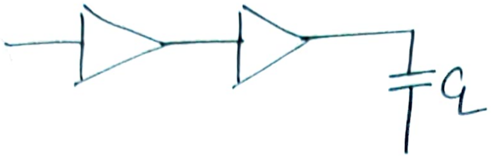


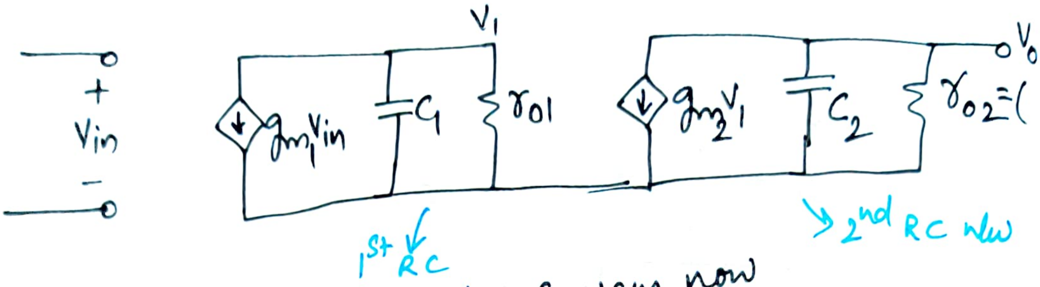
But in 2 Stage op amp, we are Connecting C_L at output of CS ampr. So, the Small Signal model is no longer C_L for 2 Stage op-amp but it is C_1 (Say)
The value of C_1 is very less as most of them are parasitics and gate cap.

for single stage op-amp



↳ Safe as long as single op-amp is considered.



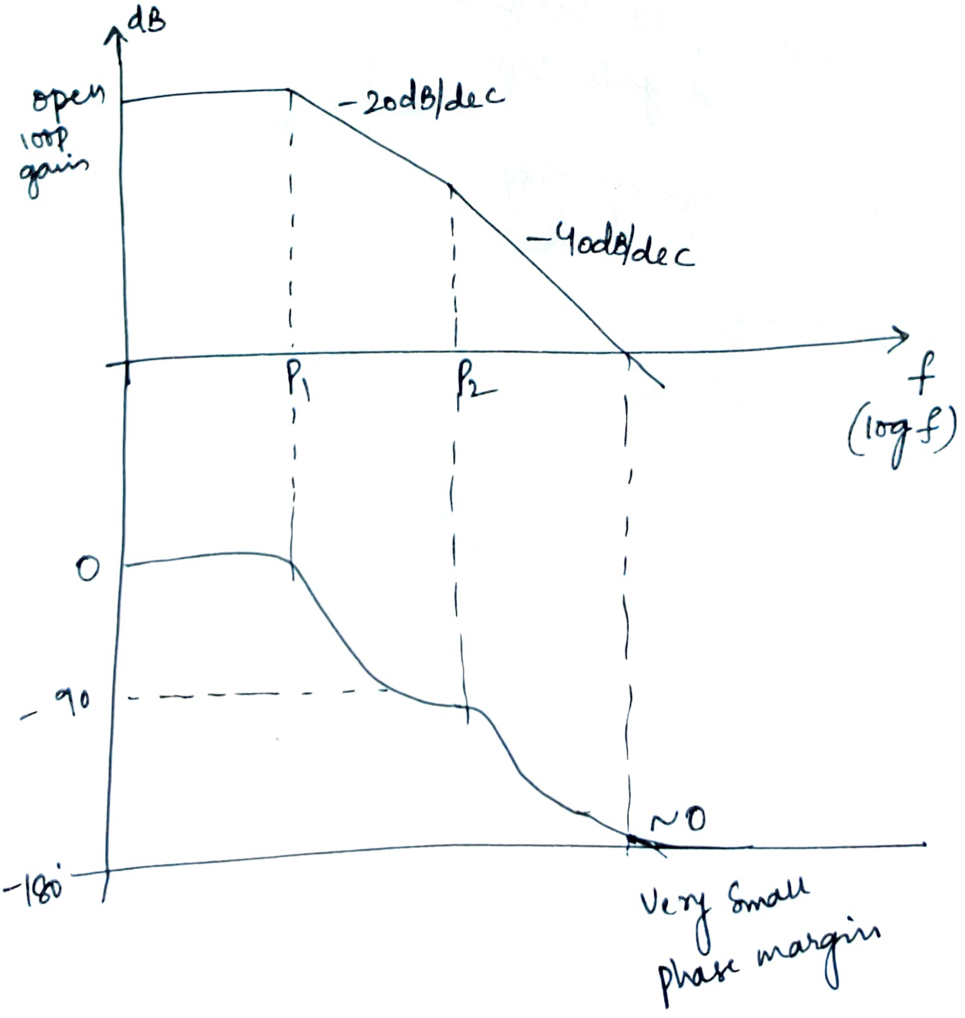


This is a two pole System now

Roughly poles are

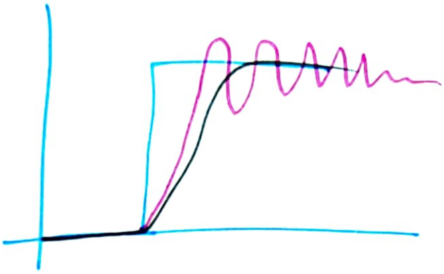
$$P_1 = \frac{1}{r_{01} C_1} \; ; \; P_2 = \frac{1}{r_{02} C_2}$$

Plotting Bode plot of this (for two pole System)



Initialy for single pole system, the phase Margin was good but now it is very small.

What is the problem if the phase margin is very small



if phase margin is good, we get good curve.

if P.M is small, we get ringing curves, which is not required.

To remove ringing and to get smooth curve, we need P.M, which should be minimum 45° (45°)

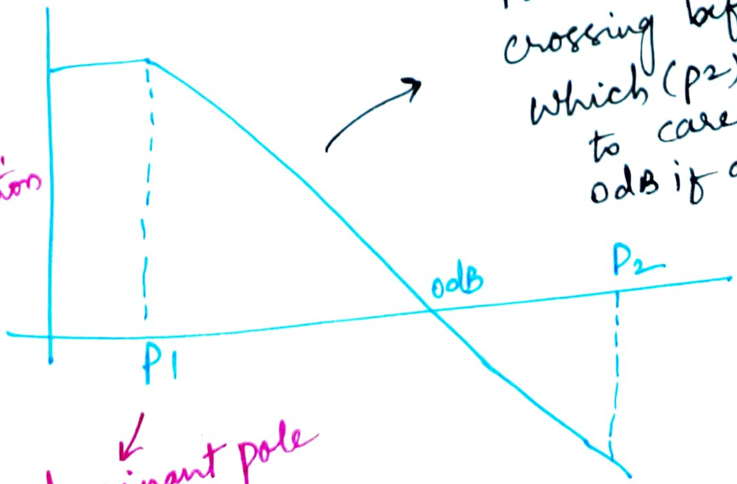
If 60° P.M ⇒ very good.

- But here P.M is 0°.

We will apply dominant pole concept, and we move P_1 to left; such that the system looks like single pole system.

i.e if P_1 is moved left then 0 dB crosses the line before P_2.

This process is called compensation



here we have two poles but 0 dB is crossing before P_2 which (P_2) no need to care. i.e after 0dB if a pole comes there will be no effect

dominant pole

We can move P1 or P2, but if we move P2 which dependant on load capacitance becomes a problem, so P2 cannot be moved.

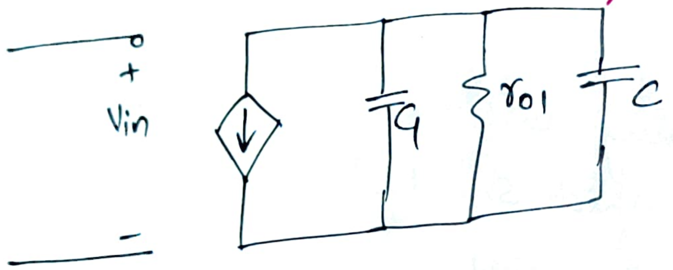
$$P_1 = \frac{1}{r_{o1} C_1}$$

↳ if we ↑ the value of $C_1 \Rightarrow r_{o1} C_1 \uparrow \Rightarrow \frac{1}{r_{o1}}$

i.e P_1 is less ⇒ it can be moved left.

increase of C_1 is done by adding 'c'

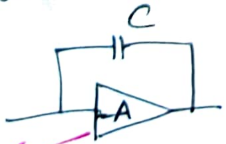
d



$$P_1 = \frac{1}{r_{o1} C_1} \sim \frac{1}{r_1 (C_1 + C)}$$

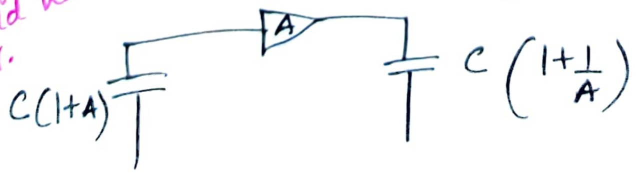
to move the pole more towards left, the 'C' should be big. To avoid that big 'C' value, we can use miller effect.

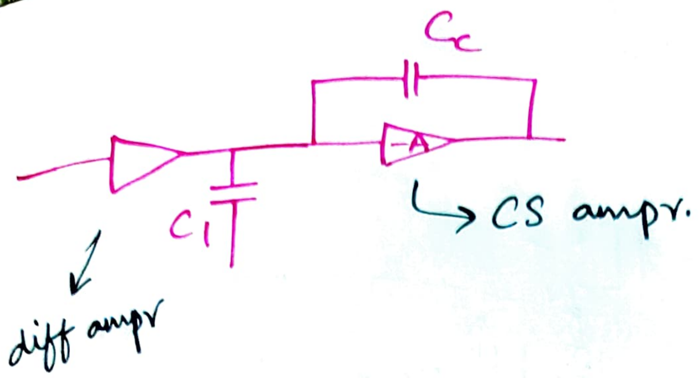
Miller Effect

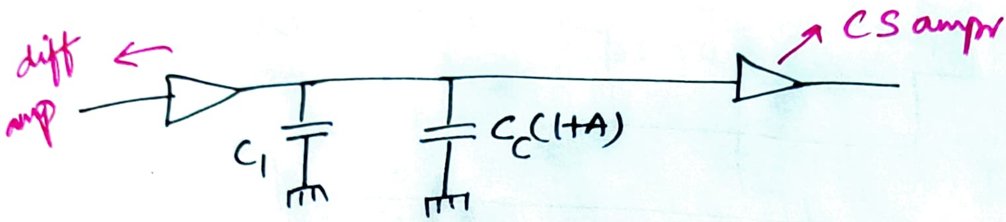


To implement miller effect, we should have an ampr.

big 'c' value can be avoided because, $(1+A)$ is getting for $c \Rightarrow$ 'c' value increases.

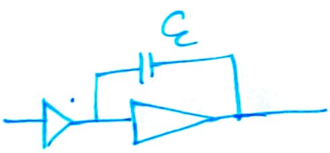


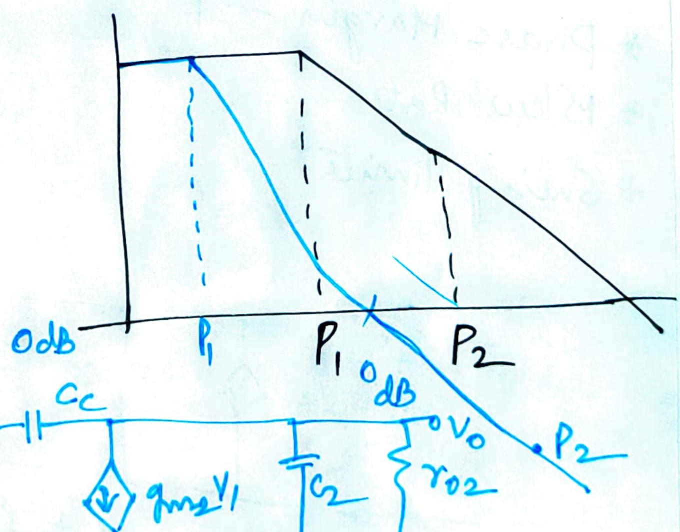


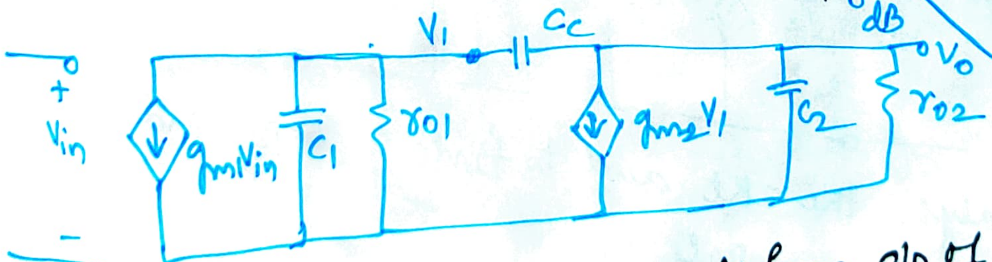


$$P_1 = \frac{1}{r_1\left[C_1 + C_c(1+A)\right]}$$

The circuit is now.

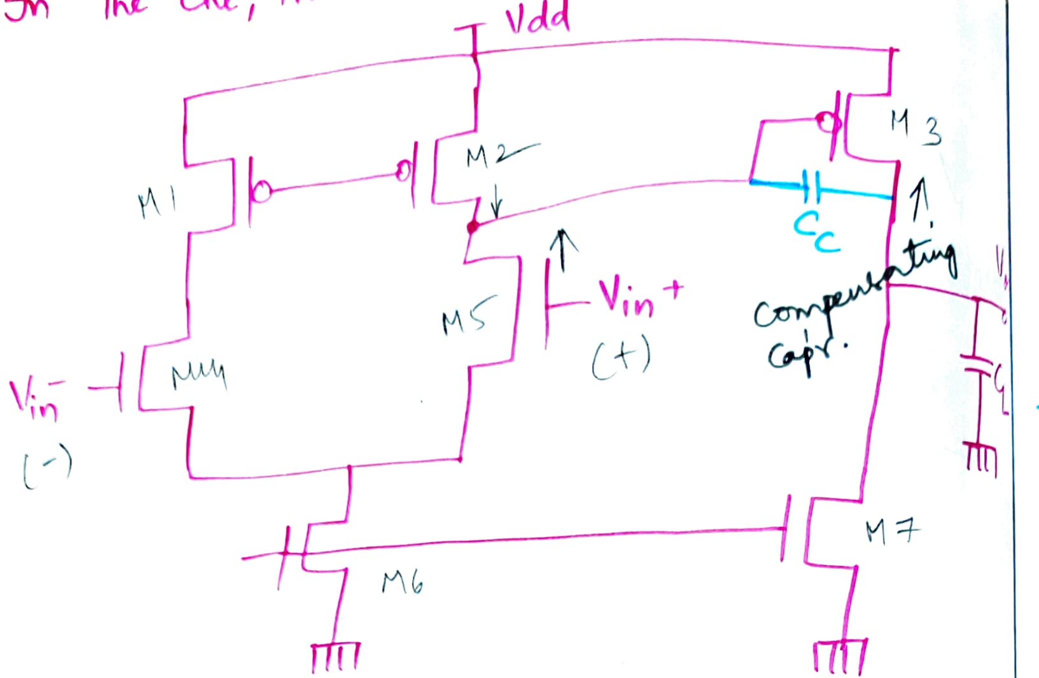






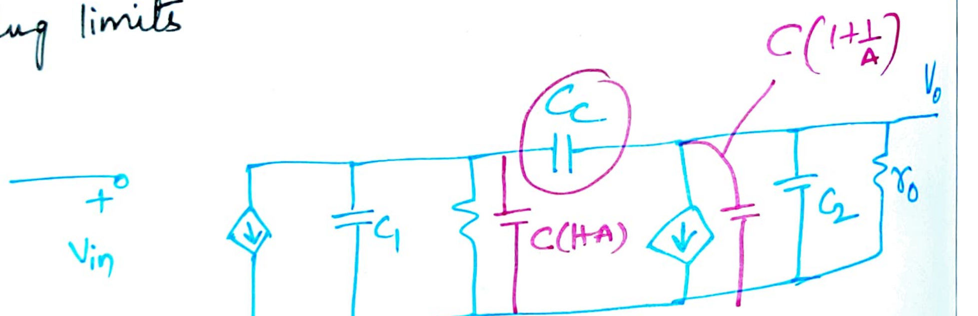
C_c is present from o/p of 1^{st} stage to o/p of 2^{nd} stage.

In the ckt, the two-Stage op-amp is



Let us See the terms

* Phase Margin — poles, Zeros, GBW etc
* Slew Rate
* Swing limits



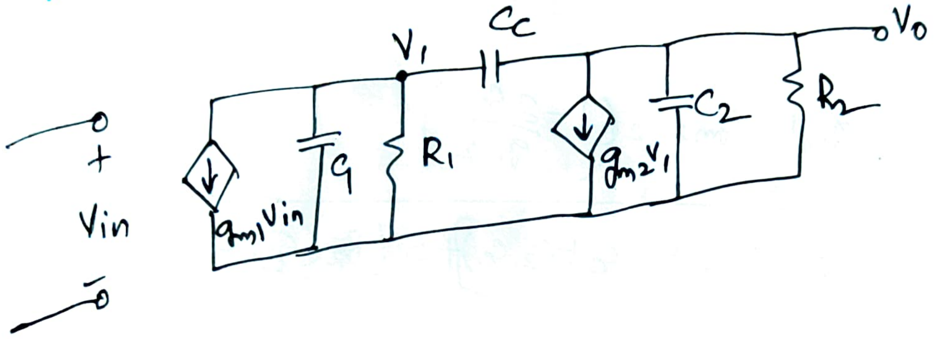
Analyse the ckt and to find
pole P_1
P_2
GBW
PM.

To find P_1, P_2,
GBW, PM
find Transfer fn

This is miller theorem, but we cannot do this b'coz of two reasons
1) Pole Splitting 2) Zero

At high frequency, this capacitance may be short and the signal may flow from $\xrightarrow[C_c]{\dashv\vdash}$, but if we are splitting C_c in two, then the flow may be interrupted $\longrightarrow$ which is zero effect.

– So solve the above small signal model, manually without splitting.



To find

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

Node eqn at V_1,

$$\frac{V_1}{\frac{1}{SC_1}} + \frac{V_1}{R_1} + g_{m1}V_{in} + \frac{V_1 - V_o}{\frac{1}{SC_c}} = 0.$$

$$V_1\left(SC_1 + \frac{1}{R_1} + SC_c\right) + g_{m1}V_{in} - V_o S C_c = 0.$$

$$\boxed{V_1 = \frac{V_o \cdot SC_cR_1 - g_{m1} \cdot R_1 V_{in}}{1 + SR_1(C_1 + C_c)}} \quad -(1)$$

Node eqn at V_o,

$$\frac{V_o}{\frac{1}{SC_2}} + \frac{V_o}{R_2} + g_{m2}V_1 + \frac{V_o - V_1}{\frac{1}{SC_c}} = 0$$

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

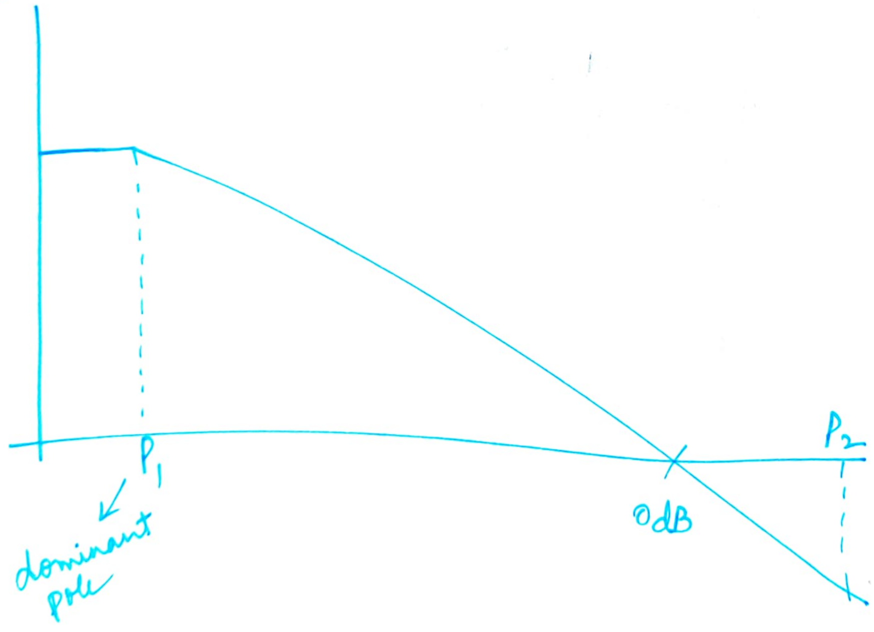
Substitute (1) here.

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

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

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

Bode plot



at lower frequencies, what is significant is P1.
we have to make few assumptions like
DC ⇒ jw i.e S = 0
if we put S=0, we get DC gain

at lower frequencies, the coefficient of S is dominant for two pole system, the standard transfer function is

$$\frac{V_o}{V_{in}} = \frac{\overset{\text{DC gain of op-amp}}{A_{DC}}\left(1-\frac{s}{z}\right)}{\left(1+\frac{s}{P_1}\right)\left(1+\frac{s}{P_2}\right)}$$

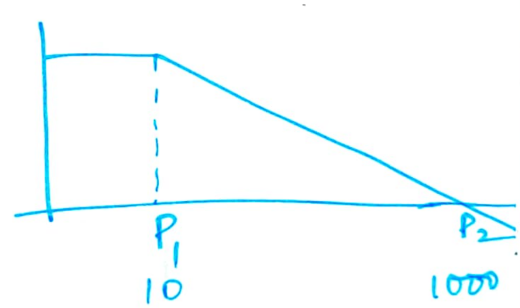
from the obtained $\frac{V_o}{V_{in}}$, we need to find Z_1, P_1, P_2 by assumptions.

$\rightarrow$ Resemblance

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

From $\frac{V_o}{V_{in}}$ of opamp, it is required to find Z_1, P_1, P_2, A_{DC}. which is difficult as the eqn is longer.

$$s \text{ term} = \frac{1}{P_1}+\frac{1}{P_2} \approx \frac{1}{P_1}$$



as it is far from P_1

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

$$\text{'s' term} = \frac{1}{P_1}$$

$\frac{1}{P_1} \rightarrow$ coeff. of 's'

$$\frac{1}{P_1}+\underbrace{\frac{1}{P_2}}_{\text{This can be neglected}}$$

$$\approx \frac{1}{P_1}$$

$$\frac{1}{10}+\frac{1}{1000}$$

$$0.1 + 1m$$

$$100m + 1m$$

dominating

$$P_1 \approx \frac{1}{R_2(C_C+C_2)+R_1(C_C+C_1)+C_C\underbrace{g_{m2}R_2}_{\text{gain of single stage op-amp}}R_1}$$

R_1 is also large

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

To find P_2:

$$\text{Coeff of } s^2 = \frac{1}{P_1 P_2}$$

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

$$P_2 = \frac{1}{\cancel{R_1} R_2 (C_1 C_2 + C_1 C_c + C_2 C_c)} \cdot g_{m2} \cancel{R_1} R_2 C_c$$

$$P_2 = \frac{g_{m2} C_c}{\underbrace{C_1 C_2}_{\text{gate cap'ce \& parasitic cap'ce}} + \underbrace{C_1 C_c}_{\text{Effective cap'ce can be neglected}} + C_2 C_c} \approx \frac{g_{m2} \cancel{C_c}}{C_2 \cancel{C_c}}$$

big

load cap'ce.

$$\boxed{P_2 \approx \frac{g_{m2}}{C_2}}$$

Zero

on comparison,

$$\boxed{Z = \frac{g_{m2}}{C_c}}$$

DC gain

↳ when all 'S' terms are zero, what is remaining is DC gain.

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

$$z = \frac{g_{m2}}{C_C}$$

$$P_1 = \frac{1}{g_{m2} R_1 R_2 C_C}$$

$$P_2 = \frac{g_{m2}}{C_2}$$

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

Gain Bandwidth product

$$GBW = DC\,gain * P_1$$

$$= g_{m1} \cancel{R_1} * \cancel{g_{m2}} \cancel{R_2} * \frac{1}{\cancel{g_{m2}} \cancel{R_1} \cancel{R_2} C_C}$$

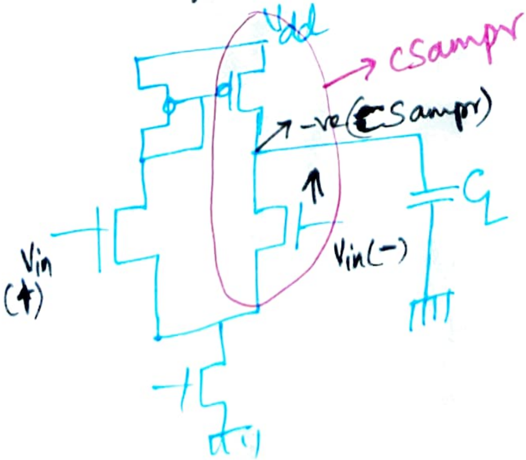
$$\boxed{GBW = \frac{g_{m1}}{C_C}}$$

unity gain BW

Slew Rate :

S.R is different for 2 Stage than single stage

→ CS ampr ⇒ Inverter (∵ 180° phase shift)



Slew rate is the rate of change of voltage i.e how quickly the voltage changes.

What are the limiting factors

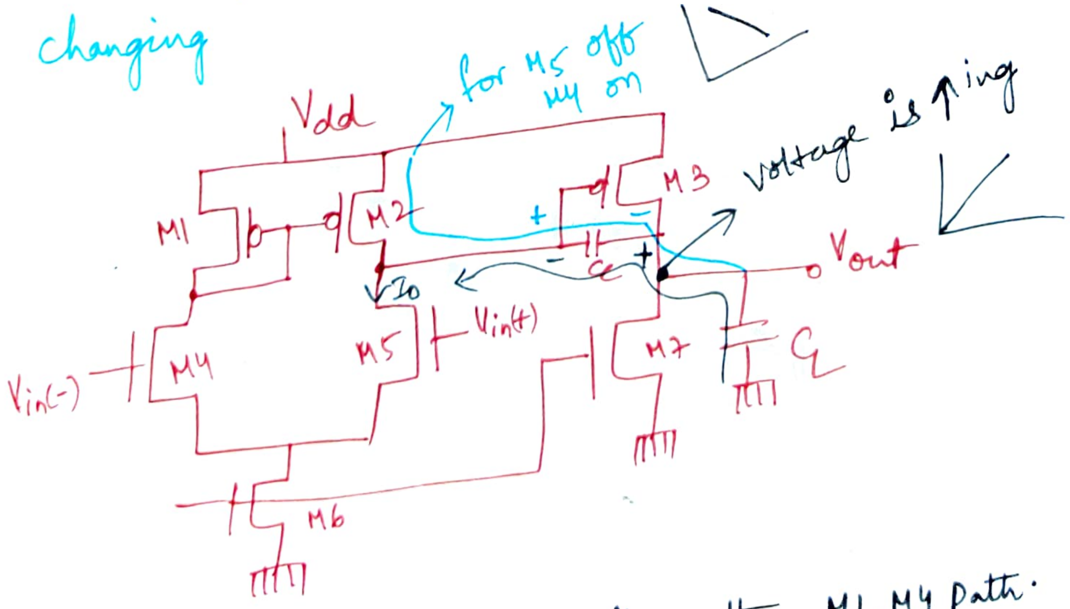
Suppose if input at Vin(-) is going up and i/p at Vin(+) is going down, how quickly the Vol. changing
increasing/peak value

max Vin(-) can go till the mosfet is completely turned on and Vin(+) Mosfet is completely turned off. Then the 'I_o' completely flows thru tail nmos. and this is coming from 'C_L' and all
(I_o)

Other transistors are off.

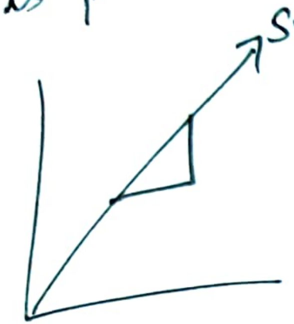
for 2 Stage slew rate

when Vin of M_5 is ↑ing, how quickly M_4 i/p is changing



When M4 is off, no current flows thru M1, M4 path. As M2 is current mirror of M1, 'I_o' does not flow thru M2 also. (M2 OFF). All the 'I_o' flows thru M5 Mosfet, Which is coming from C_L thru C_c

Voltage at V_{out} is linearly ↑ing b'coz of ε which is present and controlling the current



$$\boxed{S.R = \frac{I_0}{C_c}}$$ → due to I_0 & ε the Voltage is changing,

- If M5 is off, M4 is on, then current flows thru M1, M4 path, ∵ M1 is conducts, M2 also conducts and reaches that current to V_{out} thru ε.

Here also I_0 & ε are responsible for S.R

Phase Margin

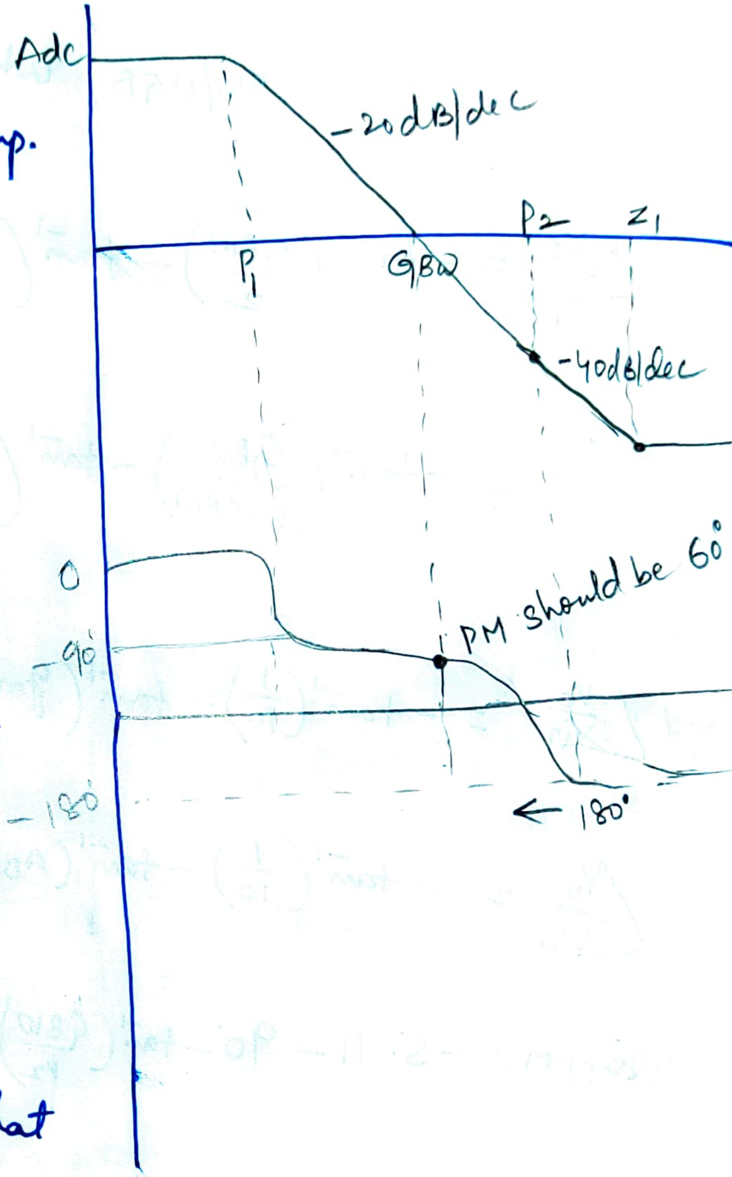
- The PM has to be like this for 2-stage opamp.

- If P_2 ~~180°~~ is moving left, PM decreases. We should see P_2 is away from GBW

- Zero (Z_1) comes after long freq of GBW product

Generally, we assume

$$Z \geq 10\,GBW$$



We have to find out what condition gives 60° phase margin

W.K.T from part 3,

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

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

PM should be 60° at GBW.

When f is at GBW/UGB, what is PM is our interest

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

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

$$\angle\frac{V_o}{V_{in}} = -\tan^{-1}\left(\frac{1}{10}\right) - \tan^{-1}\left(g_{m1} g_{m2} R_1 R_2\right) - \tan^{-1}\left(\frac{g_{m1} C_2}{C_c \cdot g_{m2}}\right)$$

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

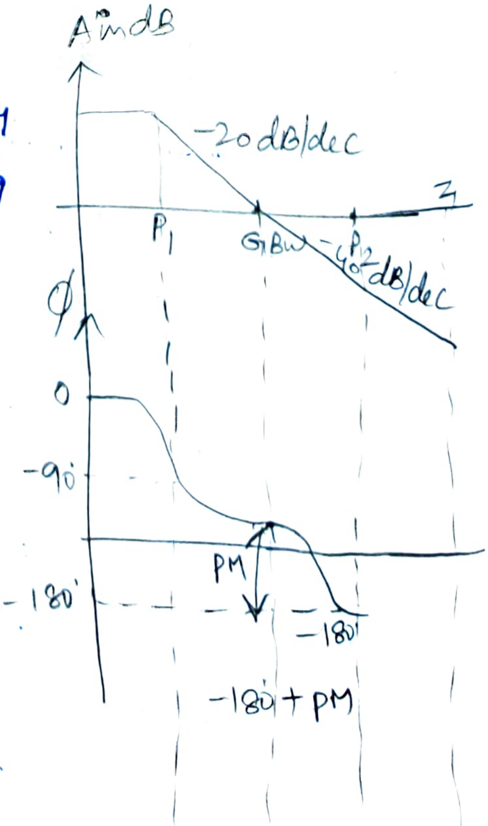
$-180^\circ + PM = -5.71 - 90^\circ - \tan^{-1}\left(\frac{GBW}{P_2}\right)$ (All values are substituted from previous parts)

if $A_{DC} = 100 \Rightarrow \tan^{-1}(100) = 89.4$

1000 $= 89.94$

10000 89.99

(≈ 90)



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

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

Let us calculate for $PM = 60^\circ$ &

$PM = 45^\circ$

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

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

$$\frac{GBW}{P_2} = \tan(24.29)$$

$$\frac{GBW}{P_2} = 0.4513$$

$$P_2 = \frac{GBW}{0.4513}$$

$$P_2 = 2.2\, GBW$$

If we want PM to be $> 60^\circ$ then $\boxed{P_2 \geq 2.2 GBW}$

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

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

$$\frac{GBW}{P_2} = \tan(39.29)$$

$$= 0.8181$$

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

$$P_2 = 1.22\, GBW$$

$\therefore$ If we want PM to be $> 45^\circ$ then P_2 should be $\geq 1.22 GBW$

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

Let us consider $P_2 \geq 2.2 GBW$

WKT P_2, GBW

$$\frac{g_{m2}}{C_2} \geq 2.2 \frac{g_{m1}}{C_c} \quad — (A)$$

$C_2 = C_L$
$\downarrow$
because c_2 is o/p of 2nd stage $\Rightarrow$ load cap.

We assumed $Z = 10 \cdot GBW$

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

$$g_{m2} = 10 \cdot g_{m1} \quad — (B)$$

Substitute B in A

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

$$\frac{10}{C_L} \geq \frac{2.2}{C_C}$$

$$C_C \geq \frac{2.2}{10} C_L$$

$$\boxed{C_C \geq 0.22 C_L}$$

In the circuit, to get PM as 60°, we should make sure that $C_C \geq 0.22 C_L$.

Design of two stage opamp

Specifications

DC gain = 1000 ⇒ 20 log 1000 = 60 dB

GBW = 30 MHz

PM ≥ 60°

Slew rate = 20 V/μsec

ICMR (+) = 1.6 V

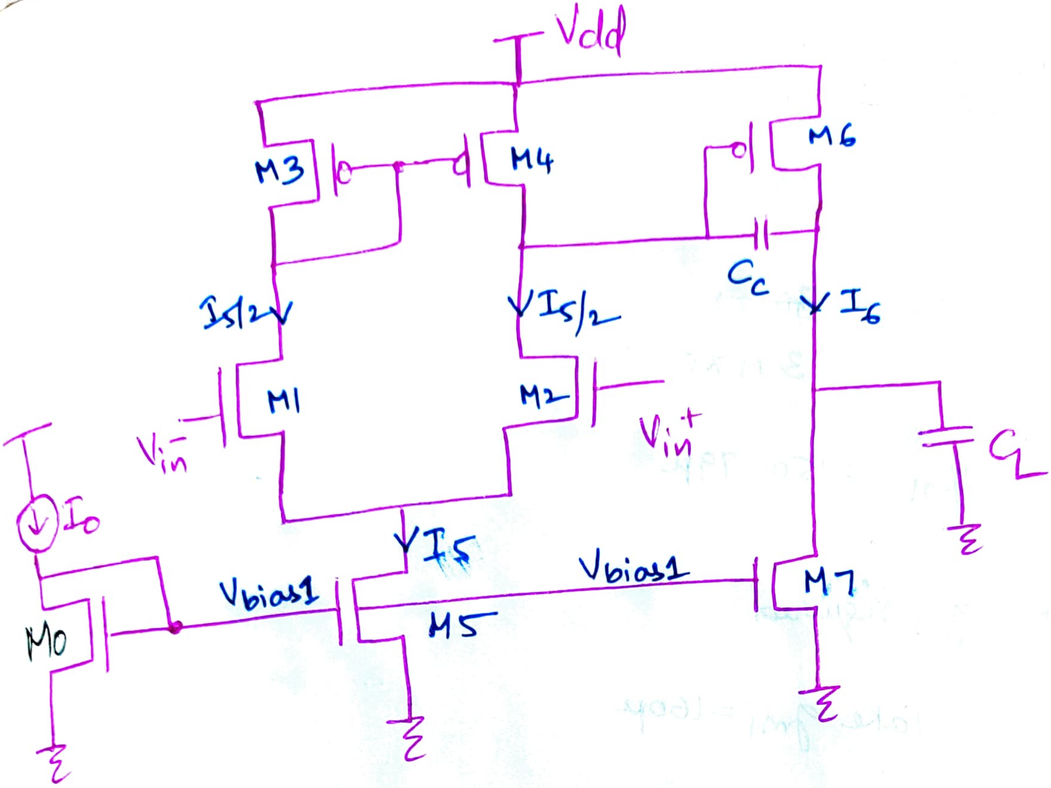
ICMR (−) = 0.8

C_L = 2 pF

Power dissipation ≤ 300 μW

V_{dd} = 1.8 V

Process = 28 nm



M3, M4 — ICMR(+) I_5 - Slew rate

M1, M2 — GBW C_c - P.M

M5 — ICMR(−)

M6 — Gain & M3, M4 design

① L = 500nm C_L = 2pf (given)

② $C_c \geq 0.22 C_L$

$C_c \geq 0.22 \times 2p$

$C_c \geq 0.44pF$

$\geq 440fF$

we take $C_c = 800fF$ in ckt

③ $SR = \frac{I_5}{C_c}$

$I_5 = SR * C_c$

$= \frac{20\mu}{\mu s} \times 800fF \Rightarrow 16\mu A$

$I_5 = 20\mu A.$

Design of M1, M2

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

$$g_{m1} = \cancel{GB\omega \times}$$
$$30M \times 800f \times 2\pi$$

$$g_{m1} = 150.79\mu$$

Min g_{m1} required

Take $g_{m1} = 160\mu$

W.K.T

$$\boxed{\begin{aligned} I_D &= \mu_n C_{ox} \frac{W}{2L} (V_{gs} - V_t)^2 \\ g_m &= \frac{\partial I_D}{\partial V_{gs}} = \frac{\mu_n C_{ox}}{2}\left(\frac{W}{L}\right) 2(V_{gs} - V_t) \\ g_m &= \mu_n C_{ox}\left(\frac{W}{L}\right)(V_{gs} - V_t) \end{aligned}}$$

$$g_{m1} = \sqrt{2 I_D \mu_n C_{ox}\left(\frac{W}{L}\right)}$$

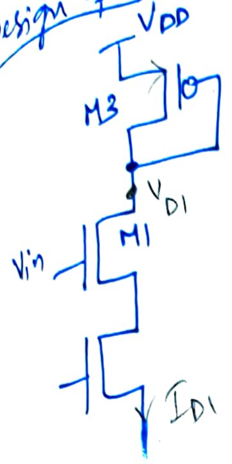
$$\left(\frac{W}{L}\right)_1 = \frac{g_{m1}^2}{\mu_n C_{ox} (2 I_{D1})} = \frac{g_{m1}^2}{\mu_n C_{ox} (I_S)}$$

$\frac{I_S}{2} = I_{D1}$

$I_S = 2I_{D1}$

$$\left(\frac{W}{L}\right)_1 = \frac{(160\mu)^2}{300 \times 20} = 4.26$$

Design of M3, M4



- M3 will be always in S.R because it is diode connected
- If Vin is ↑ed, M1 may enter in to linear region.

To have M1 in S.R,

$$V_{D1} > V_{g1} - V_{t1}$$

$$V_{g1} < V_{D1} + V_{t1}$$

$$V_{in} \leq V_{D1} + V_{t1}$$

$$V_{in\,max} \leq V_{D1} + V_{t1}$$

$$V_{DD} - V_{SG3} - V_{D1} = 0$$

$$V_{D1} = V_{DD} - V_{SG3}$$

W.k.T

$$V_{gs} = \sqrt{\frac{2 I_D}{\beta}} + |V_t| \quad (\because \text{from } I_D \text{ eqn in S.R})$$

$$V_{gs} = \sqrt{\frac{2 I_{D3}}{\beta_P}} + |V_{tp}|$$

$$V_{D1} = V_{DD} - \left[\sqrt{\frac{2 I_{D3}}{\beta_P}} + |V_{t3}|\right]$$

$$V_{in\,max} \leq V_{D1} + V_{t1}$$

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

$$ICMR(+) \leq V_{DD} - \left[\sqrt{\frac{2 I_{D3}}{\beta_{P3}}} + |V_{t3}|\right] + V_{t1}$$

$$V_{DD} - \sqrt{\frac{2 I_{D3}}{\beta_{P3}}} - |V_{t3}| + V_{t1}$$

$$\boxed{\beta = \mu_n C_{ox} \frac{W}{L}}$$

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

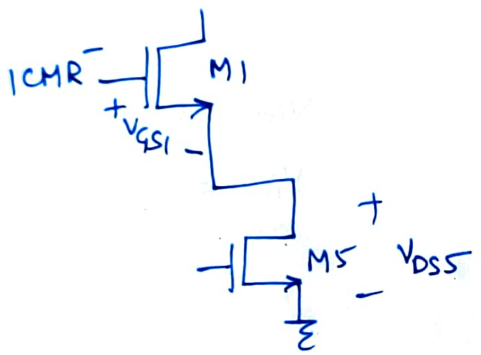
$$V_{t3\,max} = 0.51$$

$$V_{t1\,min} = 0.47$$

$$\left(\frac{W}{L}\right)_{3,4} = 13.02$$

use $\left(\frac{W}{L}\right)_{3,4} = 14$

Design of M5:



$$ICMR^- - V_{GS1} - V_{DS5} = 0$$

$$ICMR^- = V_{GS1} + V_{DS5}$$

$$V_{GS1} = V_t + \sqrt{\frac{2I_D}{\mu_n C_{ox}\left(\frac{W}{L}\right)_1}}$$

$$V_{GS1} = 0.47 + \sqrt{\frac{2(10\mu)}{300\mu \times 4.26}}$$

$$V_{GS1} = 0.59V \approx 0.6V$$

$$V_{DS} = 105mV$$

$$I_{ds5} = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)_5 (V_{ds5})^2$$

$$\left(\frac{W}{L}\right)_5 = 12.$$

Design of M6

for 60° P.M

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

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

$\geq 1600\mu$

$V_{DS_{m3}} = V_{DS_{m4}} \approx V_{DS_{m6}}$

$V_{GS_{m3}} = V_{GS_{m4}} = V_{GS_{m6}}$ (from mirroring)

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

W.K.

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

$g_{m6} = 1600\mu$

$\Downarrow$

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

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

$$= \sqrt{60\mu \times \cancel{\left(\frac{W}{L}\right)} 14 \times 2(10\mu)}$$

$g_{m4} = 129.61\mu$

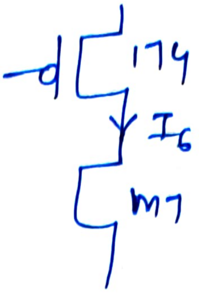
$$\left(\frac{W}{L}\right)_6 = \frac{1600\mu}{129.6\mu} \times 14$$

$$\left(\frac{W}{L}\right)_6 = 172.82.$$

$$\approx 173.$$

Design of M7

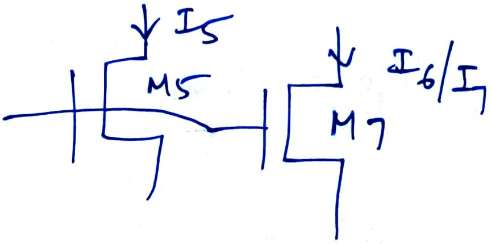
$$\frac{I_6}{I_4} = \frac{(W/L)_6}{(W/L)_4}$$



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

$$I_6 = 124.28\mu \approx 125\mu A. = I_7.$$

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



$$\left(\frac{W}{L}\right)_7 = \frac{125\mu}{20\mu} \times 12$$

$$\left(\frac{W}{L}\right)_7 = 75.$$

$I_5 = 20\mu$

$(W/L)_{3,5}$ $c_c = 800fF$

$\left(\frac{W}{L}\right)$ of $M_1, M_2 = 6 \rightarrow \frac{3\mu}{500n}$

$\left(\frac{W}{L}\right)_{0,2}$ $M_3, M_4 = 14 \rightarrow \frac{7\mu}{500n}$

$(W/L)_6$ $M_5 = 12 \rightarrow \frac{6\mu}{500n}$

$(W/L)_7$ $M_6 = 174 \rightarrow \frac{87\mu}{500n}$

The W/L denoted in black are instance numbers in tool

(W/L) $M4$

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

$I_6, I_7 = 125\mu.$