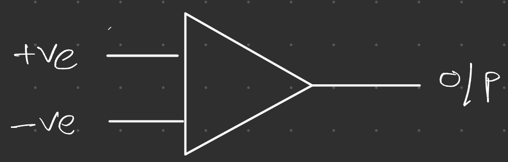
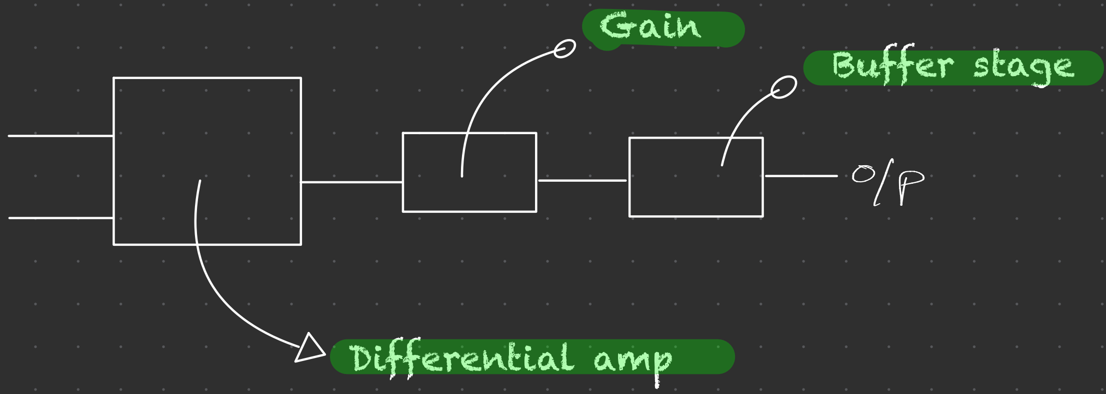
Two stage op-amp.

Design of two stage op-amp

Op-amp design





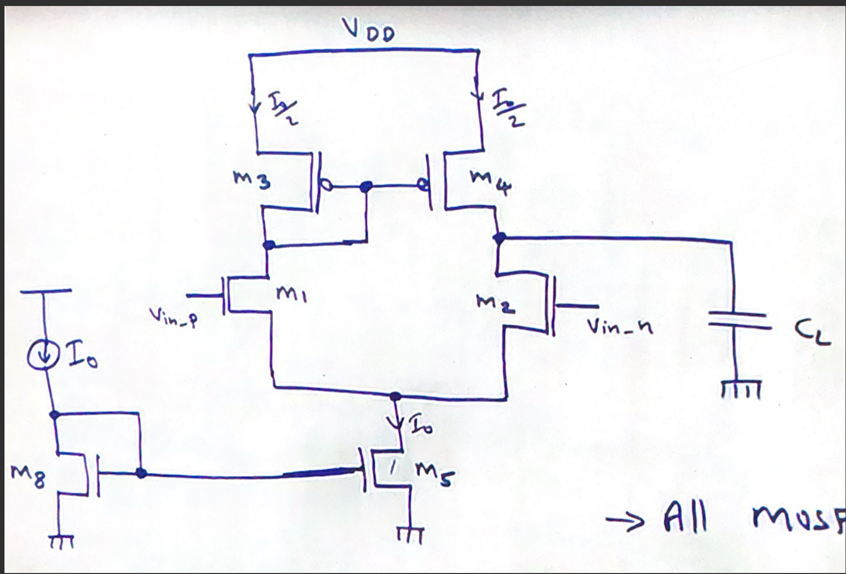
Specification

UMC 180 nm process
VDD = 1'8V
Av = 100 40 dB

Cl= 10 pf
ICMR += 1.6V
ICMR -= 0'8V
SR = 5v/usee
Power < 3 mw

Gain b.w = 5GHz

Differential amplifier part



$m_3 = m_4$
$m_1 = m_2$

$\boxed{\text{We need to find } W/L}$

⊙ Steps to follow:

UMC 180 nm process
VDD = 1'8V
Av = 100 40 dB

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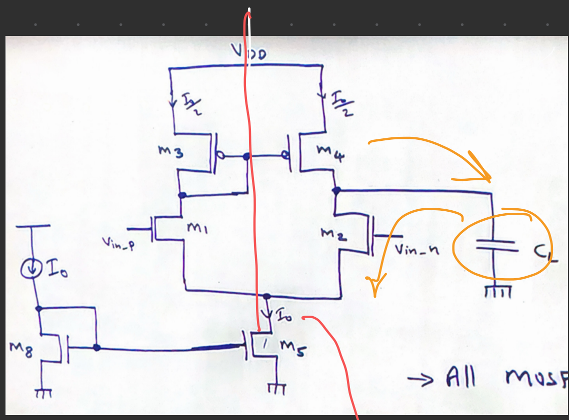
ICMR += 1.6V
ICMR -= 0'8V
SR = 5v/usee
Power < 3 mw
Gain b.w =5 MHz

1. All MOSFET should be in "Saturation Region"
2. $I_o \longrightarrow$ Slew Rate
3. $M_3, M_4 \longrightarrow$ ICMR + (max)
4. $M_1, M_2 \longrightarrow$ Gain × B.W
5. $M_8 \longrightarrow I_o$ & M_5

(i) Finding Io From Slew Rate :

Slew rate : max change of o/p voltage

UMC 180 nm process
VDD = 1'8V
Av = 100 40 dB
Cl= 10 pf
ICMR += 1.6V
ICMR -= 0'8V
SR = 5v/usec
Power < 3 mw
Gain b.w =5 MHz



→ charging of C_L is through M_4, discharging through M_2

$Q = CV$

$$\frac{dq}{dt} = I = C \cdot \frac{dv}{dt}$$

$$\frac{dv}{dt} = I/C$$

$I_o = 50\,\mu A$

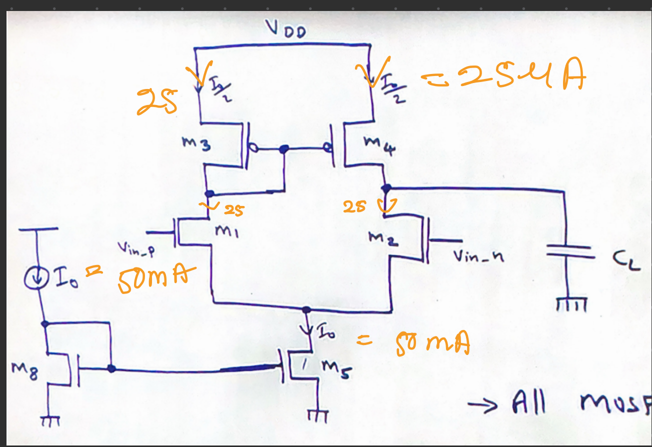
$$\boxed{\text{Slew rate} = \frac{I}{C}}$$

$$\boxed{I_o = SR \times C_L}$$

$$I_o = 5 \times 10^{6} \times 10 \times 10^{-12}$$

$$= 50 \times 10^{-6}$$

$$\boxed{I_o = 50\,\mu A}$$

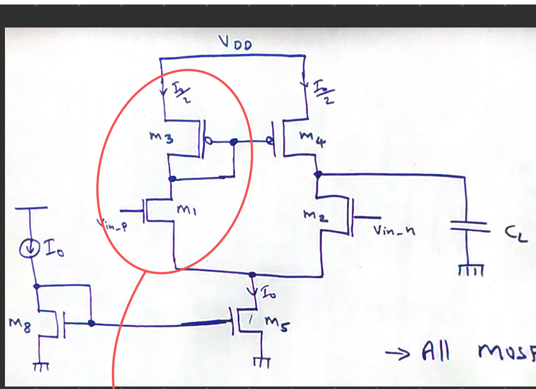


② M_3, M_4 From ICMR (+ve):

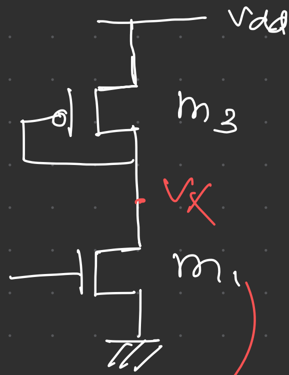
$$\boxed{m_3 = m_4}$$

UMC 180 nm process
VDD = 1.8V
Av = 100 40 dB

Cl = 10 pf
ICMR + = 1.6V
ICMR − = 0.8V
SR = 5v/usec
Power < 3 mw
Gain b.w = 5 MHz



① What should be the maximum value of Vin, to keep M_1 in "Saturation".



$$V_D \geq V_G - V_t$$

$$V_x \geq \underbrace{\text{ICMR (+ve)}}_{(max) \to V_{in}} - V_t$$

$$\boxed{V_x \geq 1.6 - 0.45} \simeq \boxed{1.15\,v}$$

$$\boxed{V_{DS} \geq V_{GS} - V_t}$$

$$\boxed{V_x \simeq 1.2 > 1.15}$$

$$V_{DS}\big|_{m3} = V_{dd} - V_x \left[\begin{array}{l}\text{diode} \\ \text{Connected}\end{array}\right.$$

$$= 1.8 - 1.2 = \underline{\underline{0.6}}$$

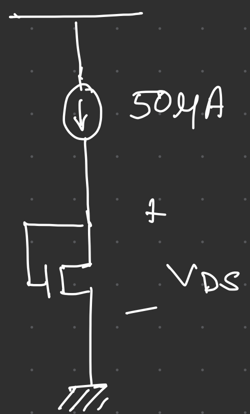
$V_{DS} = 0.6V$

$I_o = \frac{50}{2} = 25\mu A$

$$\boxed{M_3, M_4}$$

① Finding $\mu_n C_{ox}$ & $\mu_p C_{ox}$ Using Cadence:

(i)

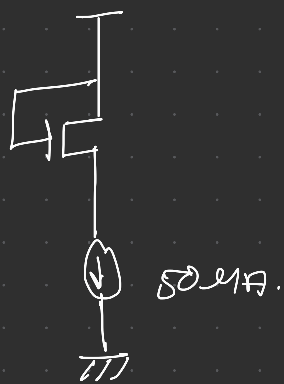


$\beta_{eff} = \mu_p C_{ox} \left(\frac{W}{L}\right)_{eff} \simeq 60\mu$

10 ≈ (approx)

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

Vdd = 2V



$V_{tp} = 0.5V$

$V_{tn} = 0.4V$

Find $\left(\frac{W}{L}\right)_{m_3} = \quad I_3 = \frac{\mu_p C_{ox}\left(\frac{W}{L}\right)}{2} [V_{GS} - V_t]^2$

or $25\mu A = \frac{60\mu}{2} \left(\frac{W}{L}\right) [0.6 - 0.5]^2$ PMOS

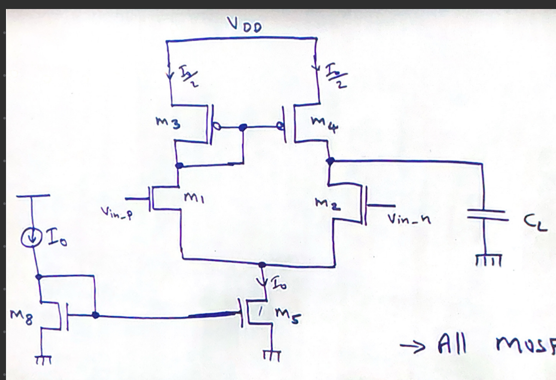
$\left(\frac{W}{L}\right) = 83.33 \simeq 84$

$$\boxed{\left(\frac{W}{L}\right)_{m3, m4} = 84}$$

m3, m4 are

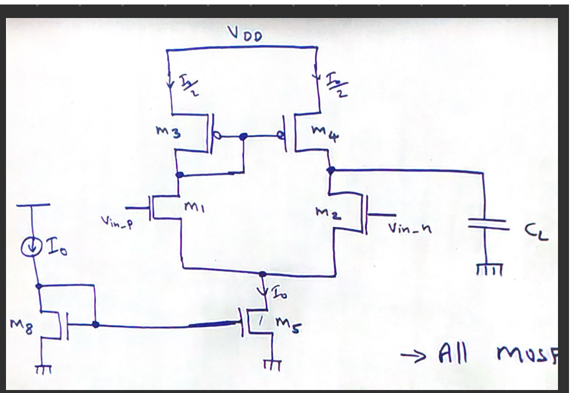
Symmetrical also

p-mos



⊙ Find M_1 & M_2 :

From Gain Bandwidth parameter.



+ ——

Vin

− ——

$$\therefore \frac{V_o}{r_{o4} \parallel r_{o2}} + \frac{V_o}{1/sC_2} + g_m v_{in} = 0$$

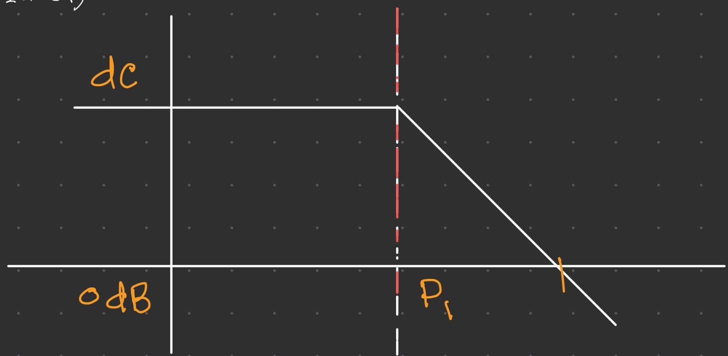
$$\# \quad \frac{V_o}{V_{in}} = \frac{-g_m (r_{o2} \parallel r_{o4})}{1 + sC_L (r_{o2} \parallel r_{o4})}$$

Single pole System :

dc gain

$= g_m (r_{o2} \parallel r_{o4})$

$$\boxed{P_1 = \frac{-1}{(r_{o4} \parallel r_{o2}) C_L}}$$



$$\therefore \boxed{\text{Gain Bandwidth} = \frac{g_m}{s C_L}}$$

$$G.BW = \frac{g_{m\,1\,or\,2}}{2\pi \; C_L}$$

$$g_{m\,1,2} = 2\pi \times C_L \times GB = 2\pi \times 10pF \times 5MHz$$

$$\boxed{g_{m1,2} = 314.16\mu S}$$

Finding $\left(\frac{W}{L}\right)$ of m_1, m_2:

$$I_D = \frac{\mu_n C_{ox} W/L}{2} \left[V_{GS} - V_T\right]^2$$

$$\boxed{\frac{\partial I}{\partial V_{GS}} = g_m = \mu_n C_{ox} \frac{W}{L} \left[V_{GS} - V_T\right]}$$

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

$$= 2 I_D \mu_n C_{ox} \frac{W}{L}$$

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

$\therefore$ $\frac{W}{L}$ of $m_1 = m_2 \cong 6.57$

$$\boxed{\left(\frac{W}{L}\right)_{m_1, m_2} \simeq 7}$$

⊙ Finding M_5 from minimum ICMR (-ve):

give → ICMR (-ve) ≃

ICMR minimum = 0.8V

UMC 180 nm process
VDD = 1.8V
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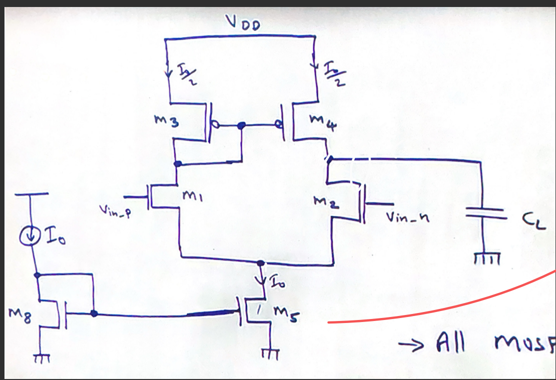
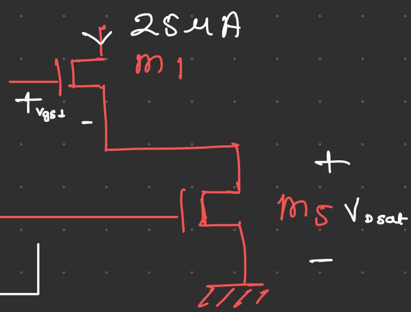
CL = 10 pf
ICMR + = 1.6V
ICMR - = 0.8V
SR = 5V/usec
Power < 3 mw
Gain b.w = 5 MHz



V_{in} (min) = 0.8



$$V_{in} > V_{gs1} + V_{Dsat}$$

$$0.8 > V_{gs1} + V_{Dsat}$$

$V_{gs} = ?$

$$I_o = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}[V_{gs} - V_t]^2$$

$$= 25\mu = \frac{300\mu}{2}(7)[V_{gs} - 0.45]^2$$

$V_{gs} = 0.6$

$$0.8 > 0.6 + V_{Dsat}$$

$$\therefore \boxed{V_{Dsat} \leq 0.2}$$

$$I_{D5} = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(0.2)^2$$

Current Mirror

$$\therefore \left(\frac{W}{L}\right)_5 = 8.33 \simeq 9 = \left(\frac{W}{L}\right)_8$$

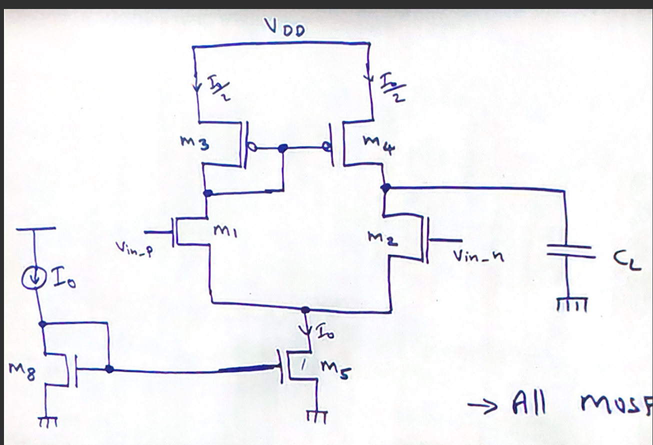
$\odot$ ALL (W/L)

(i) $(W/L)_{1,2} = 7$

(ii) $(W/L)_{3,4} = 84$

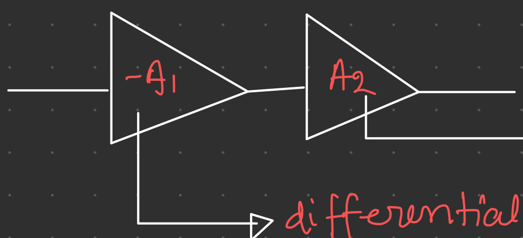
(iii) $(W/L)_{5,8} = 9$

So, $(W/L)_5 = (W/L)_8$



\# Differential op-amp could not generate that much gain.

Design of two-stage op-amp.



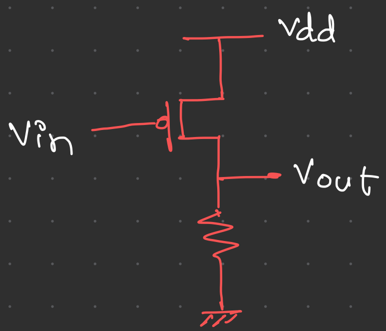
Common Source Amplifier

differential Amplifier

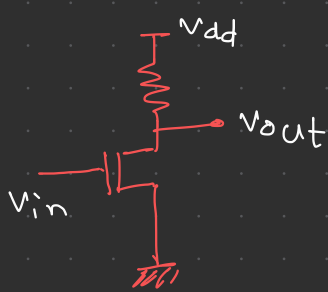
Differential Amplifier + Common Source Amplifier

(i) Using n-MOS

(ii) Using P-MOS

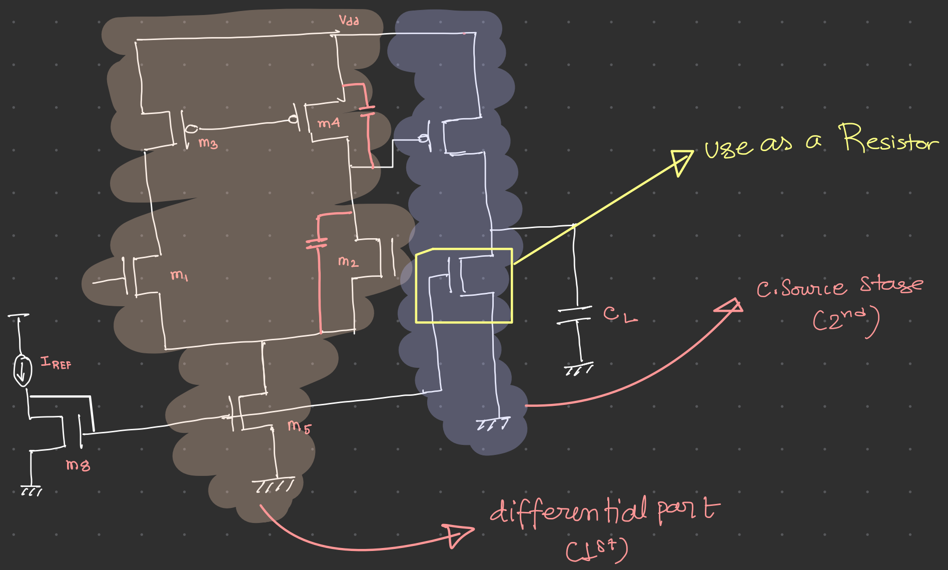


(Recomended)

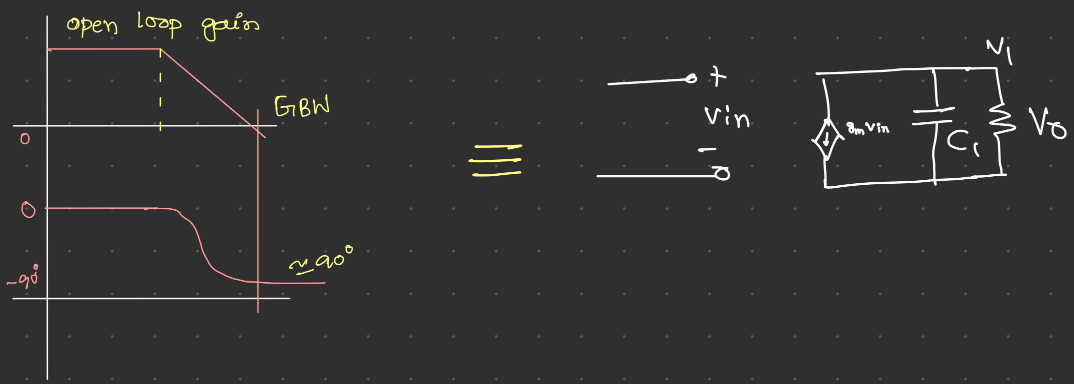


Not Recomended
swing will be limited

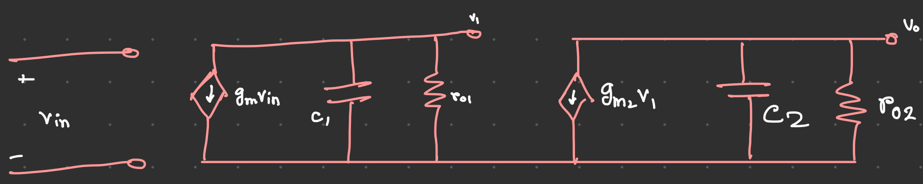
Both Together:

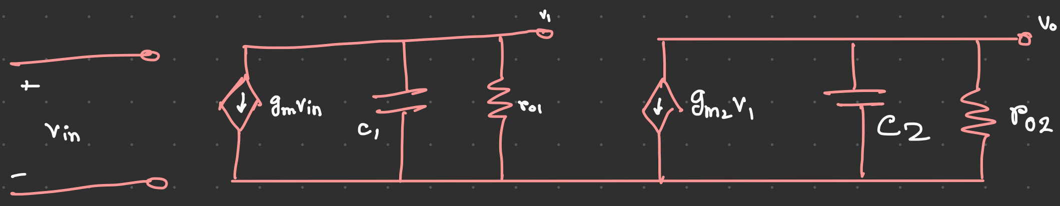


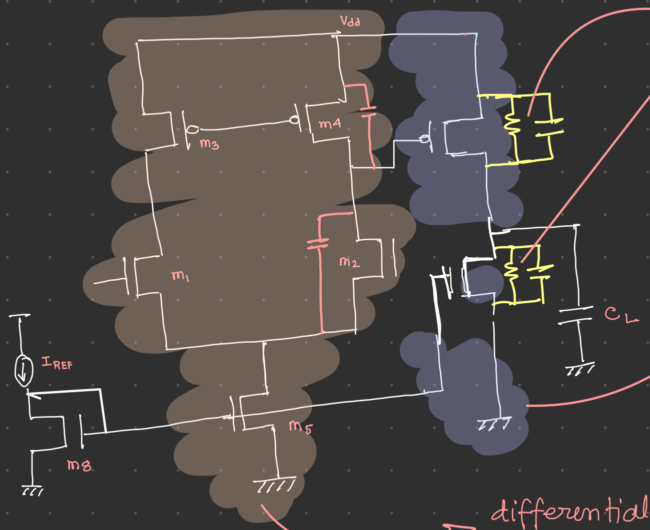
Recall 1st stage:



⊙ Two stage part:







Parallel of two resistor $\simeq r_{02}$

C.Source Stage (2nd)

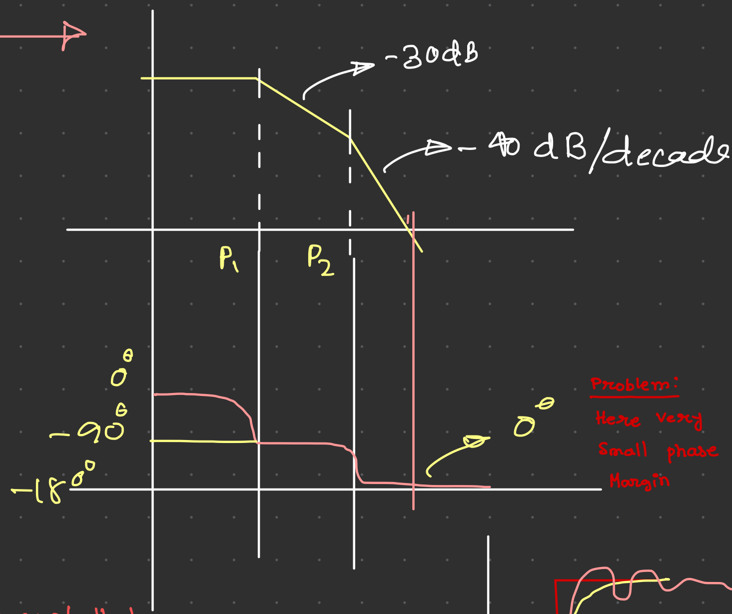
differential part (1st)

Two pole system:

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

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

$$P_2 = \frac{1}{r_{o2} C_2}$$



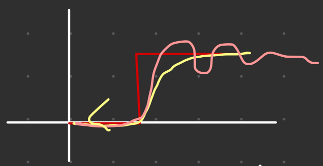
Problem:
Here very small phase Margin

By using Dominant Pole Concept

Solution

Try to shift P_1 pole left side such that P_2 comes after crossing 0dB / gain 1.

→ Compensation



low phase Margin

High phase Margin

minimum phase Margin = 45° or 60° (good)

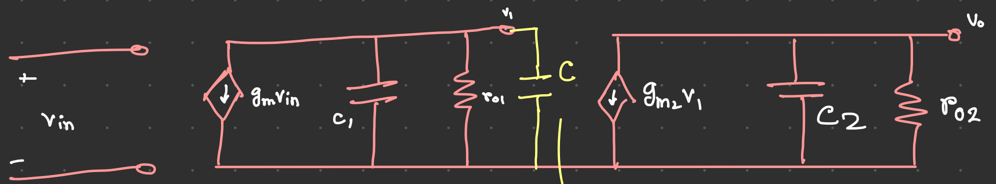
$$P_1 = \frac{1}{r_{o1} C_1}$$

We try to increase the value of C_1 So we can shift the pole towards left.

$$P_2 = \frac{1}{r_{o2} C_2}$$

C_2 Consists of load capacitance

So, we don't have That much Control in C_2

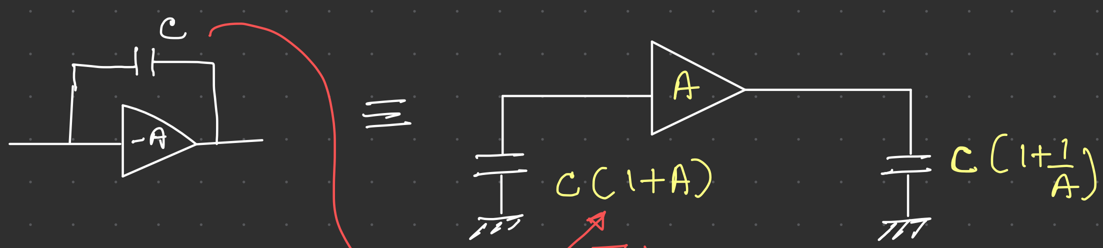


additional capacitance → parallel with C_1

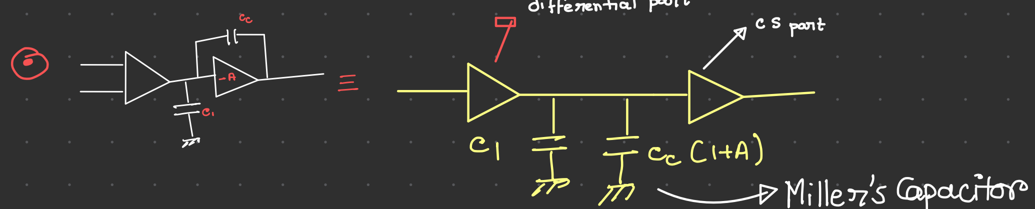
$(C+C_1)$

So, $P_1 = \dfrac{1}{r_{o1}(C_1+C)}$ → 'C' should be big enough

Miller Effect:



This way we can make a large capacitor.



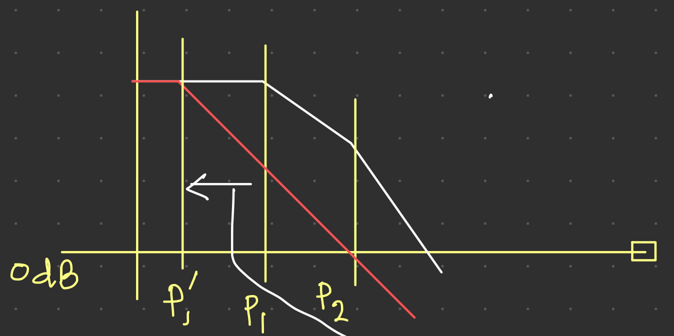
$$\boxed{P_1 = \frac{1}{r_{o1}\left[(C_1 + C_c(1+A)\right]}}$$

pole left shift

Initial Pole: ——

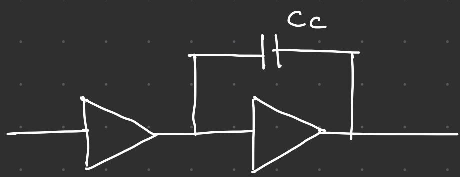
After adding capacitor: ——

$$P_1' = \frac{1}{r_{o1}\left[C_1 + C_c(1+A)\right]}$$



left shift of pole 'p'

$C_c \longrightarrow$ Compensated Capacitance



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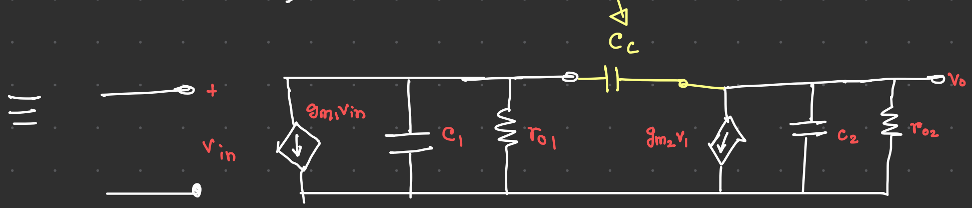
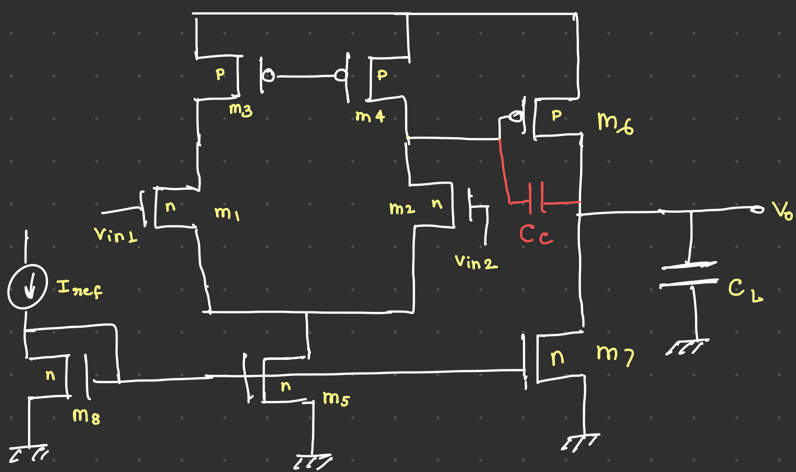


Two Stage Op-Amp

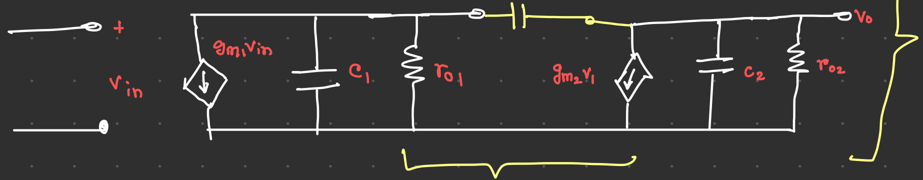


Design of Two Stage OP-Amp:

→ Key points: Phase margins → Pole, Zero, G.B.W.

Slew rate

Swing Limits

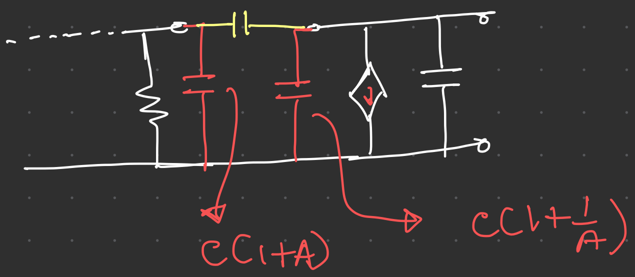


Need to find P_1, P_2, G.B.W

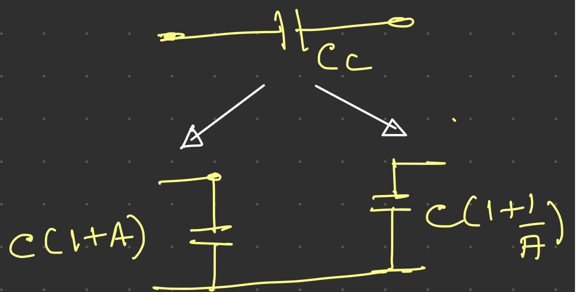
We can not use Miller Theorem to find Transfer function

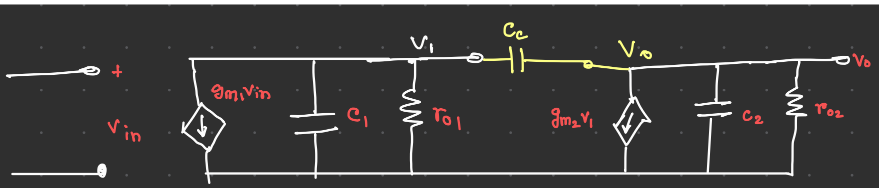
Because:

① pole splitting
② Zero.



in high Frequency Cc got short ckt. But if we apply Miller's Theorem Then that will not happen in high frequency due to the divide in capacitances.





Aim to find $\frac{V_o}{V_{in}} = \underbrace{\frac{V_1}{V_{in}}}_{1^{st}\ \text{stage}} \times \underbrace{\frac{V_o}{V_1}}_{\text{second stage}}$

KCL @ node V_1,

$$\frac{V_1}{r_{o1}} + \frac{V_1}{1/sC_1} + g_{m1}V_{in} + \frac{V_1 - V_o}{1/sC_c} = 0$$

$$sC_1V_1 + \frac{V_1}{r_{o1}} + g_{m1}V_{in} + (V_1 - V_o)sC_c = 0$$

$$\boxed{V_1 = \frac{V_o\, sC_c r_{o1} - g_{m1} r_{o1} V_{in}}{1 + s r_{o1}(C_1 + C_c)}} \quad (1)$$

KCL @ V_o,

$$\frac{V_o - V_1}{1/sC_c} + g_{m2}V_1 + \frac{V_o}{1/sC_2} + \frac{V_o}{r_{o2}} = 0$$

$$sC_c(V_o - V_1) + g_{m2}V_1 + sC_2V_o + \frac{V_o}{r_{o2}} = 0$$

$$V_o\left[sC_c + sC_2 + \frac{1}{r_{o2}}\right] = V_1\left[sC_c - g_{m2}\right]$$

$$\rightarrow V_o\left[s(C_2 + C_c) + r_{o2}\right]$$

$$= \frac{V_o\, sC_c r_{o1} - g_{m1} r_{o1} V_{in}}{1 + s r_{o1}(C_1 + C_c)}\left[sC_c - g_{m2}\right]$$

"Transfer function of Two Stage Op-Amp:

$$\boxed{\frac{V_o}{V_{in}} = \frac{g_{m1} r_{o1} g_{m2} r_{o2}\left(1 - \frac{sC_c}{g_{m2}}\right)}{s^2\left[r_{o1}r_{o2}(C_1C_2 + C_1C_c + C_2C_c)\right] + s\left[r_{o2}(C_c + C_2) + R_1(C_c + C_1) + C_c g_{m2} r_{o1} r_{o2}\right] + 1}}$$

$\rightarrow$ (i)

$$\frac{V_o}{V_{in}} = \frac{g_{m1} r_{o1}\, g_{m2} r_{o2} \left(1 - \frac{sC_c}{g_{m2}}\right)}{s^2 \left[r_{o1} r_{o2} (C_1 C_2 + C_1 C_c + C_2 C_c)\right] + s\left[r_{o2}(C_c + C_2) + R_1 (C_c + C_1) + C_c g_{m2} r_{o1} r_{o2}\right] + 1}$$

Standard Transfer function for two pole system:

$$\frac{V_o}{V_{in}} = \frac{A_{DC}\left(1 - \frac{s}{z}\right)}{\left(1 + \frac{s}{P_1}\right)\left(1 + \frac{s}{P_2}\right)}$$

1 zero

Two pole

We need to find z, P_1, P_2 and put in the equation

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

Considering $\boxed{P_1 << P_2}$ $\frac{1}{P_1} + \frac{1}{P_2} \simeq \frac{1}{P_1}$ $\rightarrow s\frac{1}{P_1}$

co-efficient of 's' is $\frac{1}{P_1}$

$$\frac{1}{P_1} = r_{o2}(C_c + C_2) + r_{o1}(C_c + C_1) + \left[C_c \underbrace{g_m r_{o1} r_{o2}}_{\text{gain of one stage}}\right]$$

Comparatively larger than other

$$\boxed{P_1 \simeq \frac{1}{g_{m2} r_2 r_1 C_c}}$$

Co-efficient of s^2 is $\frac{1}{P_1 P_2}$

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

$$P_2 = \frac{g_{m2} \cancel{R_2} \cancel{R_1} C_c}{\cancel{R_1 R_2}[\underbrace{C_1 C_2 + C_1 C_c}_{\text{small}} + \underbrace{C_2 C_c}_{\text{big}}]}$$

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

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

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

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

DC gain $\longrightarrow$ $s = 0$ at equation (i)

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

$R_1 = r_{o1}$
$R_2 = r_{o2}$

Gain Bandwidth Calculation:

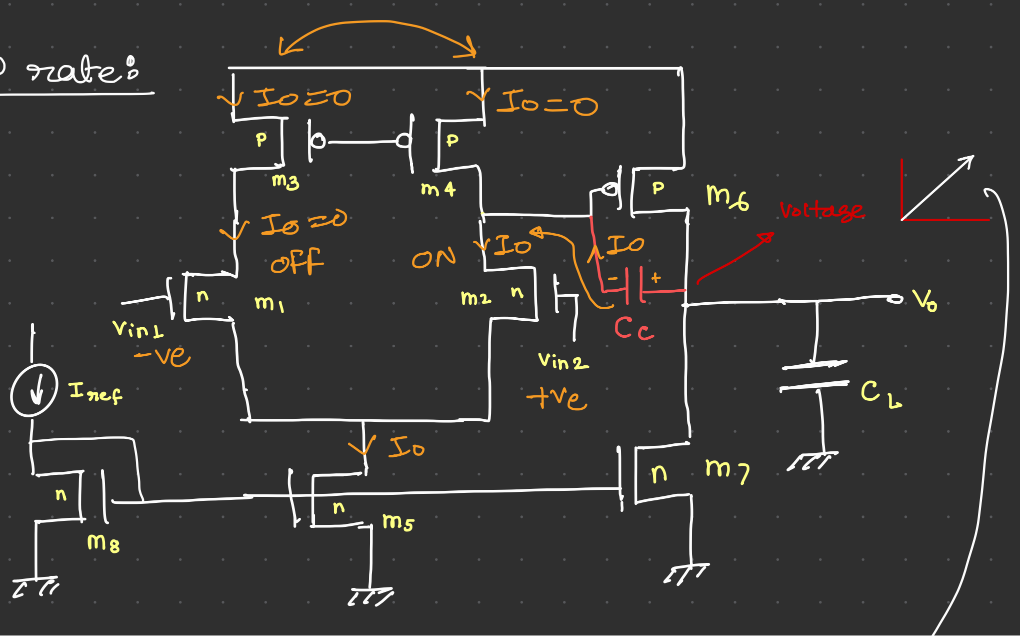
$= \text{DC gain} \times P_1$

$= \frac{g_{m1} \cancel{R_1} \cancel{g_{m2}} \cancel{R_2} \times 1}{\cancel{g_{m2}} \cancel{R_1} \cancel{R_2} C_c}$

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

Current Mirror

Slew rate:



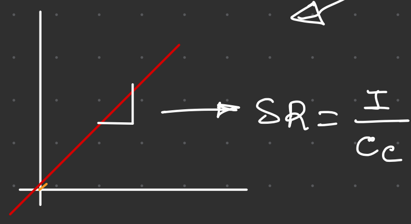
Case I: m_1 is off so

m_2 is ON

m_1 has no current so

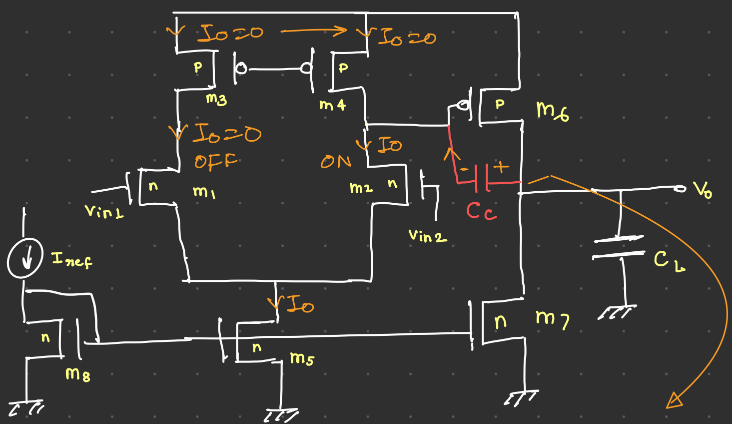
m_3 has no current so

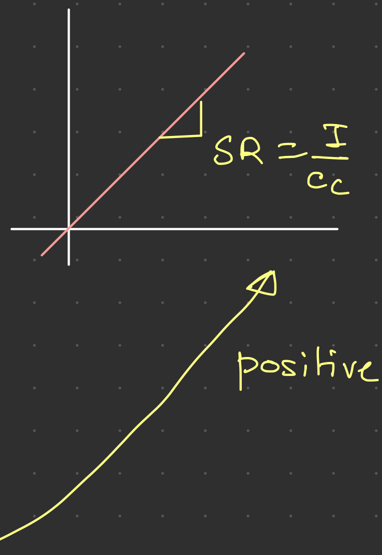
m_4 has no current



→ So, The current flowing through m_5 is flow from m_2 and coming from C_c $\overset{-\ \ +}{—||—}$

The Voltage at that point is like a straight line passing through origin and the slope is the Slew Rate $= \frac{I}{C_c}$



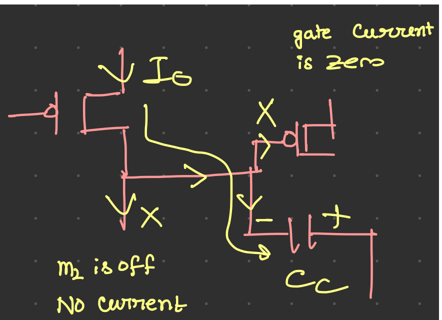


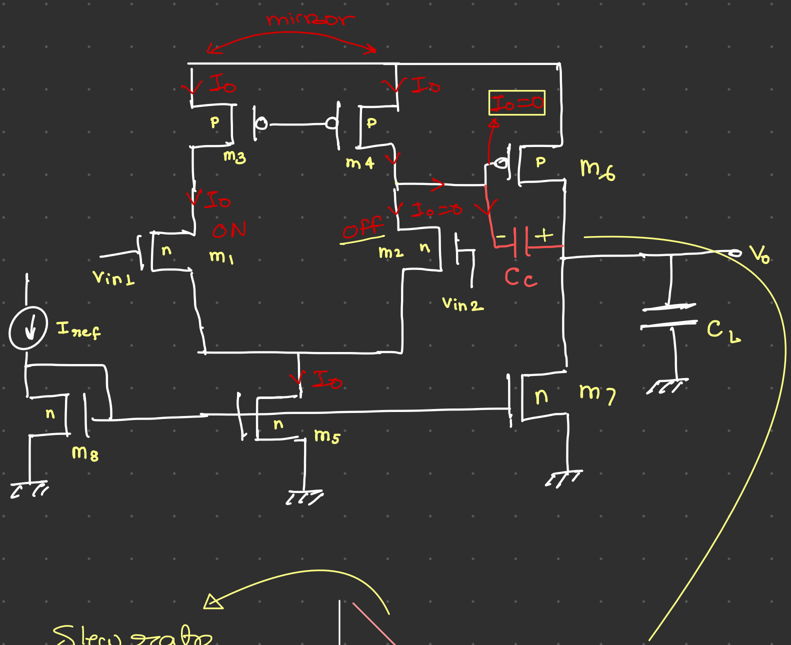
Case-I

So, voltage is Increasing

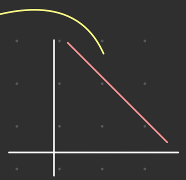
case II: m_1 is ON ⟶ m_2 is off

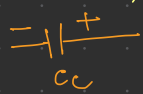
I_o is flowing through m_5, m_1, m_3 and so m_4 due to mirroring And then it has no way but to flow through the capacitor C_c





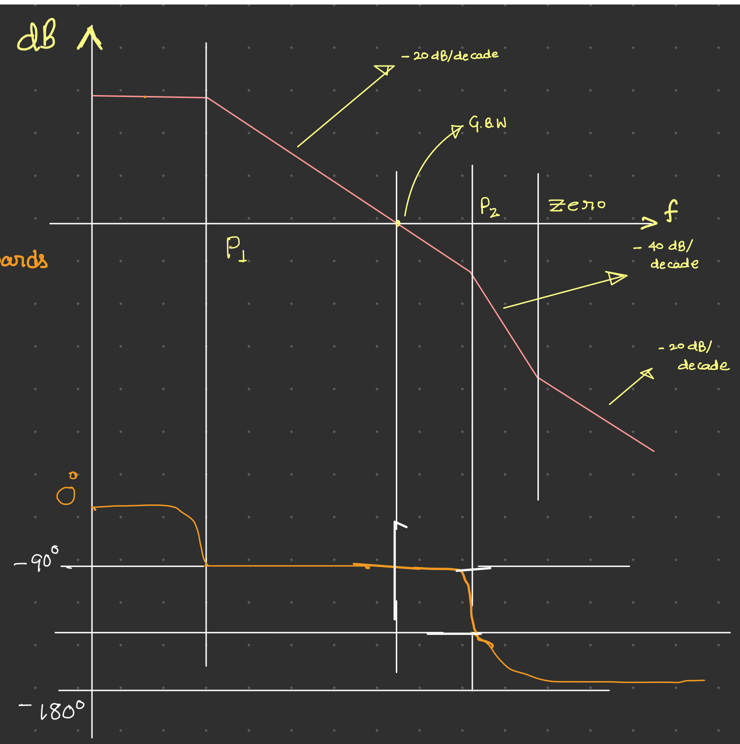
Slew rate is $\frac{I_o}{C_c}$





Phase Margin :

To get a good Phase Margin P_2 should be far from G.B.W Point [Try to shift P_2 towards Right]



$$\boxed{Zero \geq 10\, GBW}$$

$$\frac{V_o}{V_{in}} = \frac{A_{DC}\left(1 - \frac{s}{z}\right)}{\left(1+\frac{s}{P_1}\right)\left(1+\frac{s}{P_2}\right)}$$

Angle of Tranfer function!

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

$$\boxed{P_1 \approx \frac{1}{g_{m_2} R_2 R_1 C_c}}$$

$$\boxed{P_2 = \frac{g_{m_2}}{C_2}}$$

$$\boxed{Z = \frac{g_{m_2}}{C_c}}$$

$$\boxed{A_{DC} = g_{m_1} R_1\, g_{m_2} R_2}$$

A phase margin of 60° is preferable and requires at least 45° of phase Margin.

So, we need to find the relation to get that much p.M.

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

This angle should give at least 60° or 45° of P.M.

We are calculating the P.M at $\boxed{f = G.B.W}$

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

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

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

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

$$\boxed{Z = 10\, GBW}$$

$$\boxed{G.BW = \frac{g_{m1}}{C_c}}$$

$$\angle \frac{V_o}{V_{in}} \Big|_{\omega = GBW}$$

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

$$= -\tan^{-1}\left(\frac{1}{10}\right) - \tan^{-1}\left[\frac{g_{m1}}{\cancel{C_c}} \times g_{m2} r_2 r_1 \cancel{C_c}\right] - \tan^{-1} \frac{GBW}{P_2}$$

$$= -\tan^{-1} \frac{1}{10} - \tan^{-1}\left[\underbrace{g_{m1} g_{m2} r_2 r_1}_{\text{DC gain } A_{DC}}\right] - \tan^{-1} \frac{GBW}{P_2}$$

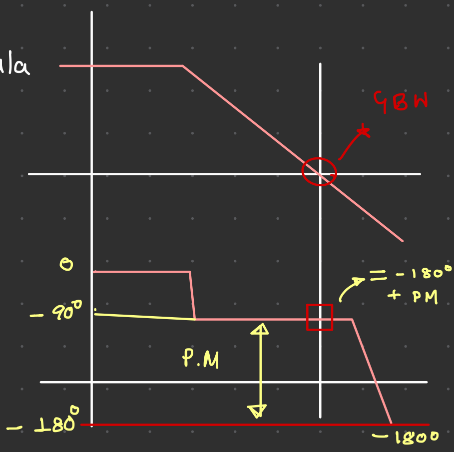
$\rightarrow$ Higher Value

$\tan^{-1}$ (Big Value) $\simeq 90$

$\downarrow$ DC gain

$$-180^\circ + PM = -5.71 - 90 - \tan^{-1}\frac{GBW}{P_2}$$

$$\boxed{PM = 84.29 - \tan^{-1}\left[\frac{GBW}{P_2}\right]} \longrightarrow \text{general Formula}$$



Case I

for $PM = 60^\circ$

$$60 = 84.29 - \tan^{-1}\frac{GBW}{P_2}$$

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

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

$$\boxed{P_2 \geq 2.2\, GBW}$$

Case II

for $PM = 45^\circ$

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

All Parameters Together:

$\boxed{P_1 = \frac{1}{g_{m2} r_1 r_2 C_c}}$ $\boxed{P_2 = \frac{g_{m2}}{C_2}}$ $\boxed{A_{dc} = g_{m1} r_1 \, g_{m2} r_2}$ $\boxed{P_2 \geq 2.2\, GBW}$ → For 60° phase Margin

$\boxed{Z = \frac{g_{m2}}{C_c}}$ $\boxed{Z = 10\, GBW}$ $\boxed{GBW = \frac{g_{m1}}{C_c}}$

Calculations:

$$Z = \frac{g_{m2}}{C_c} = 10\, GBW$$

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

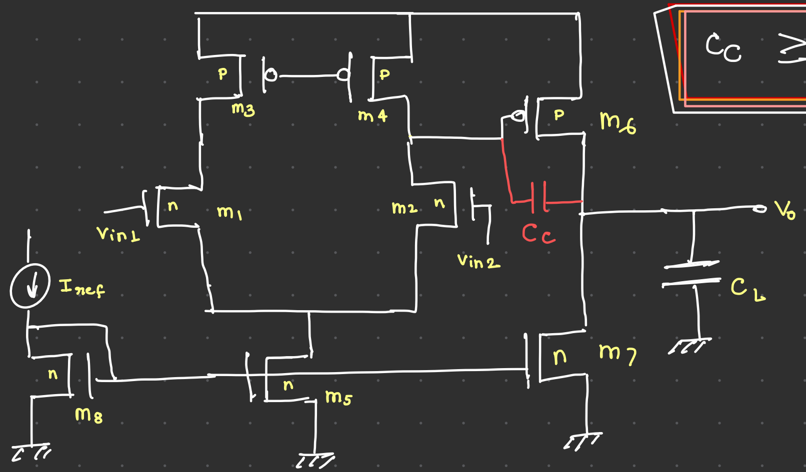
$$\Rightarrow \boxed{g_{m2} = 10\, g_{m1}}$$

$$P_2 \geq 2.2\, GBW$$

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

$$\frac{10\, g_{m1}}{C_2} \geq 2.2 \frac{g_{m1}}{C_c}$$

$$\boxed{C_c \geq 0.22\, C_2}$$



Here, C_c is the Compensation Capacitance and $\boxed{C_2 = C_L}$

C_2 = equal capacitance of 2nd Stage which is C_L here, so, $\boxed{C_2 = C_L}$

C_c should be 0.22 times of C_2, g_{m2} should be 10 times g_{m1}, zero should be 10 times GBW to make phase margin 60° which is desirable

Assumptions taken: $Z = 10\, GBW$, $\tan^{-1}(\text{large}) = 90$

$\frac{1}{P_1} + \frac{1}{P_2} \simeq \frac{1}{P_1}$ $\boxed{P_2 >> P_1}$ $C_2 C_c >> C_1 C_c, C_1 C_2$

⊙ Design Specification: [Process : 180 nm]

DC gain : 1000 = 60 dB	Slew rate: 20 V/μsec
GBW : 30 MHz	ICMR (+) : 1.6 V
P.M : ≥ 60°	ICMR (-) : 0.8 V
Power : 300 μW	C_L : 2 pF
	Vdd : 1.8 V

→ $L_{min} = 180\ nm$ $\quad L \geq 2L_{min}$

$\boxed{L = 500\ nm}$

① All MOSFET should be in "Saturation Region"

② I_0 → Slew Rate

③ M_3, M_4 → ICMR + (max)

④ M_1, M_2 → Gain × B.W

⑤ M_8 → I_0 & M_5

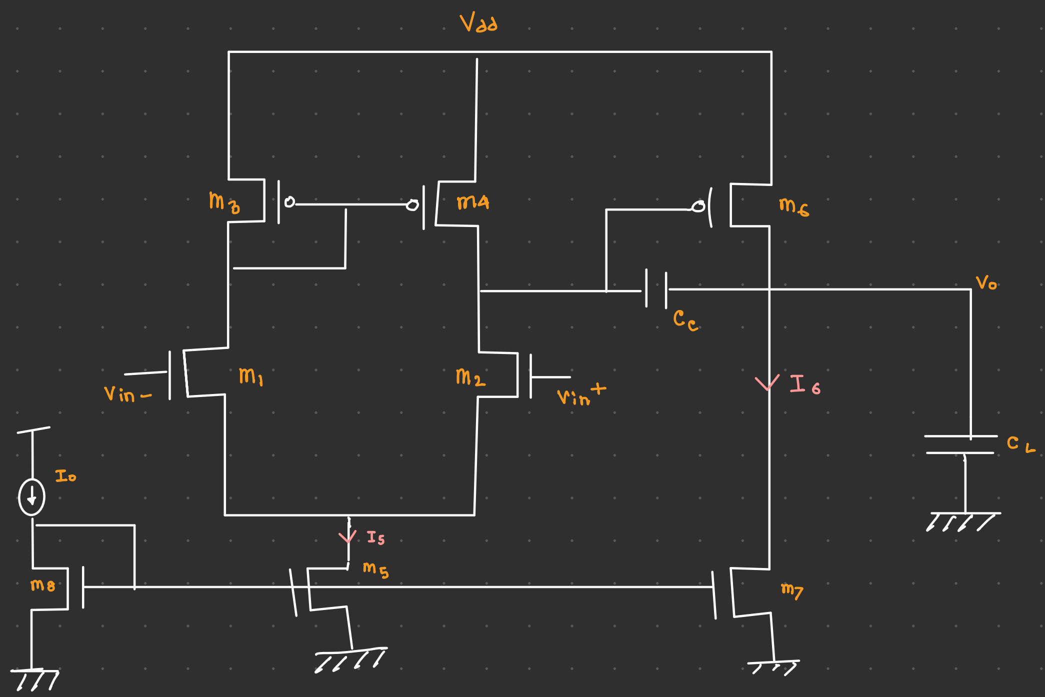


Fig: Two Stage Op-Amp

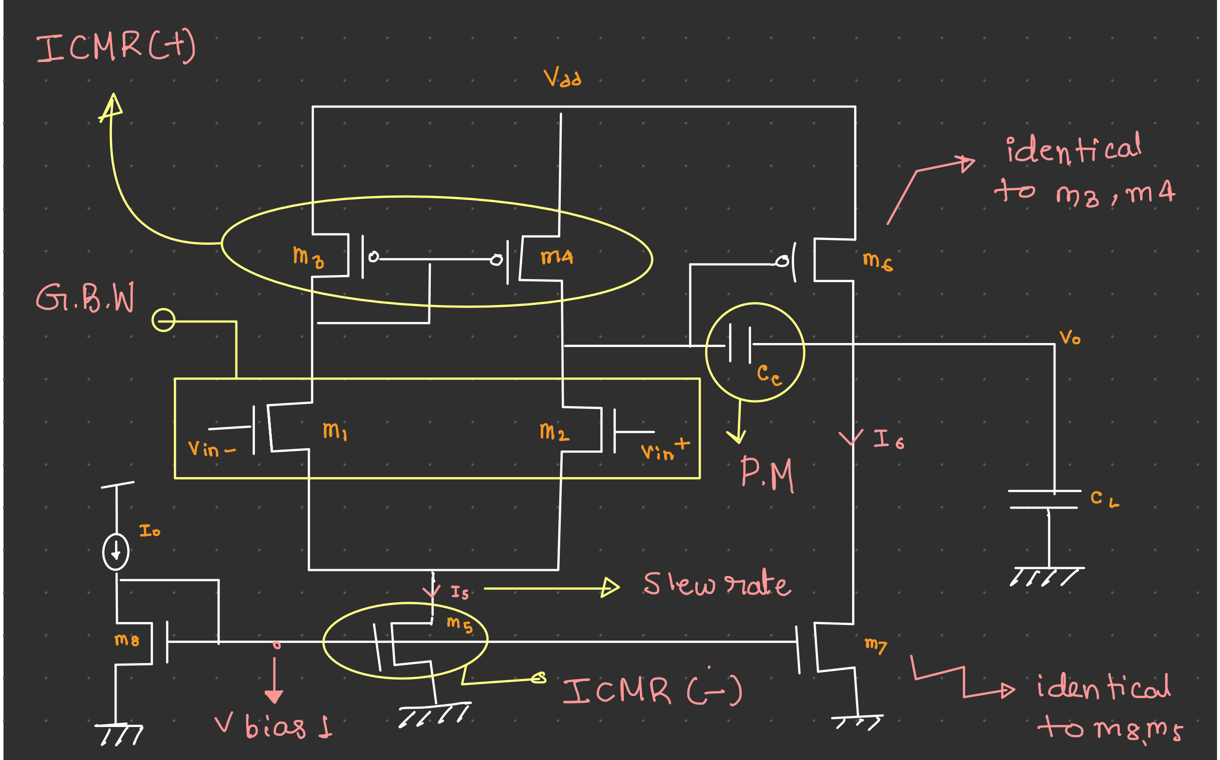


Fig: Two Stage Op-Amp

Given: ① Channel length $\boxed{L = 500\ nm}$

② To get PM of $60^\circ \longrightarrow C_c \geq 0.22\, C_L$

$C_c \geq 0.22 \times 2pF$

Condition for 60° phase margin $\boxed{C \geq 440\ fF}$

For simulation Purpose we choose

$\boxed{C = 800\ fF}$ ← Assume

③ $\text{Slew rate} = \dfrac{I_5}{C_c}$

$I_5 = \text{Slew rate} \times C_c$

$= \dfrac{20\,V}{\mu s} \times 800\,fF$

$\boxed{I_5 = 16\,\mu A} \longrightarrow \boxed{I_5 = 20\,\mu A}$

Assume

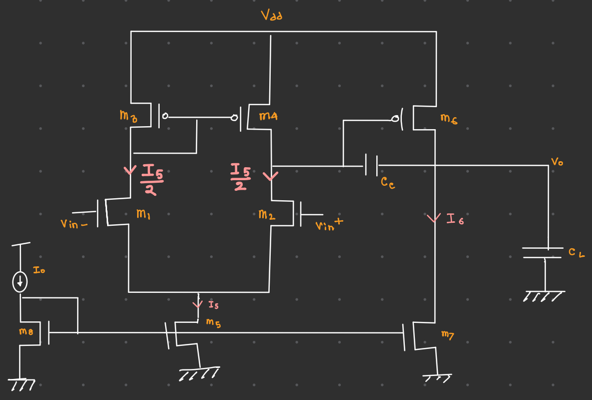
④ $\boxed{m_1, m_2 \quad \text{From G.B.W}}$

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

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

$\boxed{g_{m1} = 150.79\,\mu S \simeq 160\,\mu S}$

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



For, m_1, m_2

$$\frac{I_S}{2} = I_D\,(m_1, m_2)$$

$$\boxed{2 I_D = I_S}$$

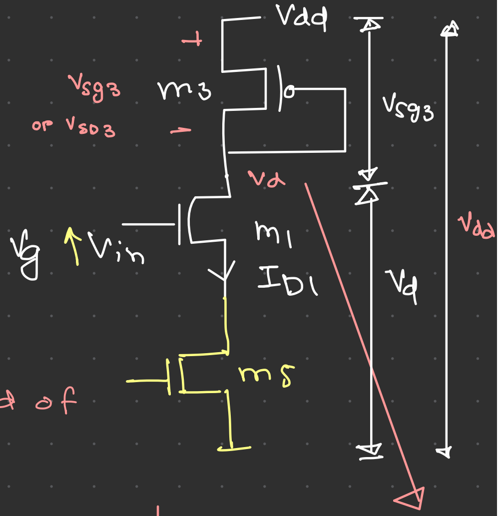
$$\boxed{\frac{W}{L} = \frac{g_m^2}{\mu_n C_{ox} \times I_S}}$$

$$\mu_n C_{ox} = 300\mu$$

$$\frac{W}{L} = \frac{160^2}{300 \times 20} \simeq 4.266$$

$$\boxed{\left[\frac{W}{L}\right]_{m_1, m_2} = 5}$$

Design of m_3, m_4: m_3, m_4 are identical



- m_3 is in Saturation for all time because it is diode connected.
- So if Vin goes high m_1 will go in Triode Region.
- So, m_1 to be in saturation

$V_{DS} > V_{GS} - V_t$ $\quad$ $V_{t1} \longrightarrow$ Threshold of m_1

$V_D > V_G - V_{t1}$

$\boxed{V_g < V_D + V_{t1}} \equiv V_{in} < V_{D1} + V_{t1}$

$\therefore \boxed{V_{in}(max) = V_{D1} + V_{t1}}$ — (I)

$V_d = V_{dd} - V_{sg3}$ — (II)

$I_3 = \mu_n C_{ox} \frac{W}{2L} (V_{gs} - V_t)^2$

$I_3 = \frac{\beta}{2} [V_{gs} - V_t]^2$

$\boxed{V_{gs} = \sqrt{\frac{2 I_3}{\beta}} + |V_t|_3}$ — (III)

From (II) $V_d = V_{dd} - \left[\sqrt{\frac{2 I_3}{\beta}} + |V_{t3}|\right]$ — (IV)

$\longrightarrow$ From (I) $V_{in(max)} \leq V_{D1} + V_{t1}$

To make Vin max less than equal to RHS, RHS should be minimum.

$\therefore \quad V_{in}(max) \leq [V_{D1} + V_{t1}]_{min}$

$V_{in}(max) \le (V_{D1} + V_{t1})_{min}$

$$\boxed{\text{or, } ICMR(+) \le V_{dd} - \underbrace{\left[\sqrt{\frac{2I_{D3}}{\beta}} + |V_{t3}|\right]}_{min} + V_{t1(min)}}$$

$$ICMR(+) \le V_{dd} - \sqrt{\frac{2I_{D3}}{\beta}} - \underline{|V_{t3}|_{max}} + V_{t1}(min)$$

Because if V_{t3} in max then only the whole quantity goes minimum

$$ICMR(+) \le V_{dd} - \sqrt{\frac{2I_{d3}}{\beta_3}} - |V_{t3}|^{max} + |V_{t1}|^{min}$$

We know, $\mu_n C_{ox} = 300\mu$

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

$$\beta_3 = \mu_p C_{ox}\left(\frac{W}{L}\right)$$

putting the value of β_3 and find $\left(\frac{W}{L}\right)$

$$ICMR(+) \le V_{dd} - \sqrt{\frac{2I_{D3}}{\mu_n C_{ox}\left(\frac{W}{L}\right)_3}} - |V_{t3}|_{max} + |V_{t1}|_{min}$$

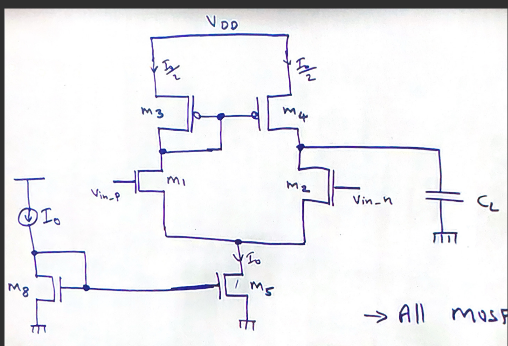
$$\text{or } \sqrt{\frac{2I_{D3}}{\mu_p C_{ox}\left(\frac{W}{L}\right)_3}} \le V_{dd} - ICMR(+) - |V_{t3}|_{max} + |V_{t1}|_{min}$$

$$\text{or, } \frac{2I_{D3}}{\mu_p C_{ox}\left(\frac{W}{L}\right)_3} \le \left[V_{dd} - ICMR(+) - |V_{t3}|_{max} + |V_{t1}|_{min}\right]^2$$

$$\boxed{\left[\frac{W}{L}\right]_3 \ge \frac{2I_{D3}}{\mu_p C_{ox}\left[V_{dd} - ICMR(+) - \underline{|V_{t3}|_{max}} + \underline{|V_{t1}|_{min}}\right]^2}}$$

→ From Cadence

→ From Cadence differential pair



Apply $V_{CM} = 0.8$ and $1.6\,v$ to get

V_{t3} max, min

V_{t1} max, min in

differential pair.

We are taking

$V_{t3}\ (max) \simeq 502\,mv \longrightarrow 510\,mv\ (max)$

$V_{t1}\ (min) \simeq 482\,mv \longrightarrow 470\,mv\ (min)$

∴ From $\left[\frac{W}{L}\right]$

$$\left[\frac{W}{L}\right]_{m3,m4} = \frac{2 I_{D3}}{\mu_p C_{ox}\left[V_{dd} - ICMR(+) - V_{t3(max)} - V_{t1(min)}\right]^2}$$

$$= \frac{2\times 1\cancel{0}\cancel{\mu}}{6\cancel{0}\cancel{\mu}\left[1.8 - 1.6 - 0.51 + 0.47\right]^2}$$

$$= 13.02$$

$$\boxed{\left[\frac{W}{L}\right]_{m3,m4} \simeq 14}$$

$V_{dd} = 1.8$

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

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

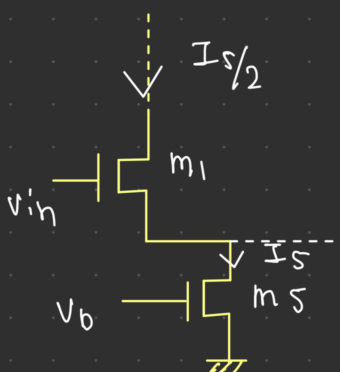
$\mu_n C_{ox} = 300\mu$

$ICMR(+) = 1.6V$

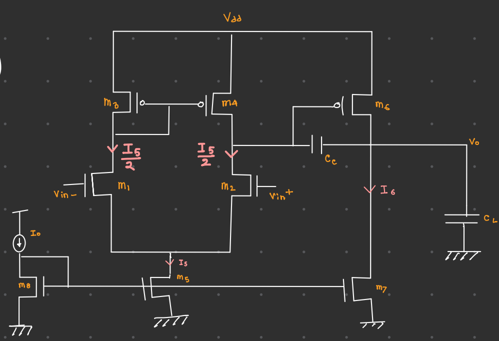
$V_{t3}(max) = 0.51$

$V_{t1}(min) = 0.47$

design of M_5 :



From ICMR (−)



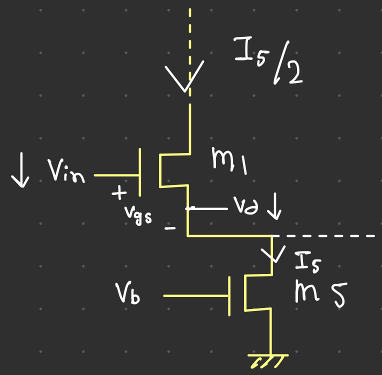
$V_g = V_{in}\big|_{m_1}$ $\quad V_s\big|_{m_1} = V_d\big|_{m_5}$

By decrease in Vin we decrease Vd $\longrightarrow$ To Support the Current Vgs almost remain Constant.

$V_{in} = V_{gs} + V_d$

so if $V_{in}\downarrow$

$V_d\downarrow$



Condition for m_5 to be in saturation while decreasing $V_{in}\downarrow$.

$\longrightarrow$ $V_{in}\downarrow$ $\quad V_d\downarrow$

for m_1

for m_5

$\downarrow V_{d5} > V_g - V_{t5}$

m_5 will go to triode Region.

$\therefore$ How should we decrease Vin So, m_5 will be in Saturation.

at $V_d = V_{dsat}$ = min value of Vd to keep m_5 in Saturation.

So, $V_{in(min)} \geq V_{gs} + V_{dsat}$

at Vd sat goes min Vin goes min by keeping m_5 in Saturation

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

$$\Rightarrow \boxed{ICMR(-) \geq V_{gs1(max)} + V_{Dsat}}$$

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

$$ICMR(-) \geq \sqrt{\frac{2I_{D1}}{\beta_1}} + V_{t1}(max) + V_{dsat}$$

We need the voltage across $M_5 = V_{Dsat(5)}$

$$\boxed{V_{Dsat(5)} \geq ICMR(-) - \sqrt{\frac{2I_{D1}}{\beta_1}} - V_{t1}(max)}$$

Putting all Values:

$$V_{Dsat}(5) \geq 0.8 - \sqrt{\frac{2\times 104}{3004 \times 5}} - V_{t1}(max)$$

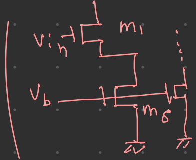
$V_{t1}(max) \rightarrow 0.590V$

From Cadence differential pair

$$\therefore V_{Dsat}(5) \geq 0.8 - 0.1154 - 0.59$$

$$\boxed{V_{dsat}(5) \geq 94.6\,mV}$$

Note: We got $V_{d\,sat} = 94.6\,mv$ for which we need to make a large MOSFET $\boxed{\frac{W}{L} \propto \frac{1}{V_d}}$ also the next MOSFET will be large.



→ Generally we prefer V_d of m_5 is > 100mv

So, to mak it greater than 100mv we only can increase $\left[\frac{W}{L}\right]$ of m_1 because other parameter can not be changed.

$\left[\frac{W}{L}\right]_{m_1}$ → if we increase it V_{dsat} will increase

So, at $[W/L]_{m_1} = 5 \longrightarrow V_{dsat} \geq 94.6\,mv$

$$\boxed{[W/L]_{m_1} = 6 \longrightarrow V_{dsat} \geq 105\,mv}$$

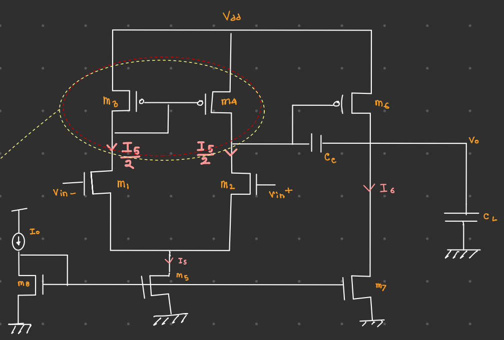
We know, $I_5 = \frac{\mu_n C_{ox}}{2}[W/L]_5 \left[V_{dsat}(5)\right]^2$

$$\text{or } [W/L]_5 = \frac{2 I_5}{\mu_n C_{ox}} \frac{1}{\left[V_{dsat}(5)\right]^2} \simeq 12.09$$

$$\boxed{\left[\frac{W}{L}\right]_5 = 12 \quad \left[\frac{W}{L}\right]_{1,2} = 6}$$

Design of m_6 :

for 60° PM $\rightarrow$ $g_{m6} \geq 10 g_{m1}$



$\therefore$ $g_{m6} \geq 10\, g_{m1}$

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

$$\boxed{g_{m6} \geq 1600\mu}$$

and

$V_{gs}\big|_{m3} = V_{DS}\big|_{m3}$

$V_{gs}\big|_{m4} = V_{gs}\big|_{m3} = V_{gs}\big|_{m6}$

$\therefore$ $V_{DS}\big|_{m3} = V_{DS}\big|_{m4} = V_{DS}\big|_{m6}$ in case of proper mirroring

So, currents will be proportional to the W/L of the MOSFET.

$$I_D = \mu_p C_{ox} \frac{W}{L} \frac{[V_{gs} - V_t]^2}{2}$$

$$\boxed{\frac{(W/L)_6}{(W/L)_4} = \frac{I_6}{I_4}} \qquad \boxed{\frac{[W/L]_6}{[W/L]_4} = \frac{g_{m6}}{g_{m4}}}$$

$g_m = \sqrt{\mu C_{ox} \left(\frac{W}{L}\right) 2 I_D}$

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

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

$$\boxed{\left(\frac{W}{L}\right)_6 = 172.82 \simeq 173}$$

Design of m7 : (m5)

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

$$(W/L)_7 = \frac{I_7 \, (W/L)_5}{I_5} = \frac{125\mu \times 12}{20} = 75$$

$$I_6 = \frac{(W/L)_6}{(W/L)_4} \times I_4 = \frac{174}{14} \times 10 = 124.28 \simeq 125\ \mu A = I_7$$

$$\boxed{\left[\frac{W}{L}\right]_7 = 75 \qquad \left[\frac{W}{L}\right]_6 = 173}$$

$I_5 = 20\mu$

$C_c = 800\ fF$

$m_{1,2} = 6 = \frac{3}{.5} \left[\frac{W}{L}\right]$

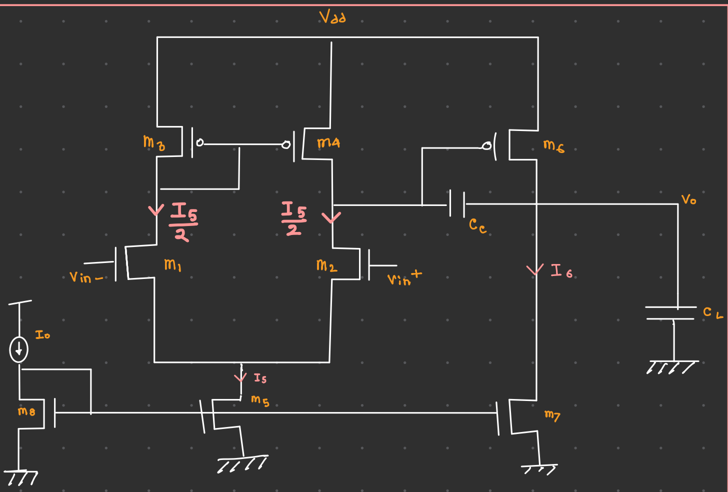
$m_{3,4} = 14 = \frac{7}{.5}$

$m_5 = 12 = \frac{6}{.5}$

$m_6 = 174 = \frac{87}{.5}$

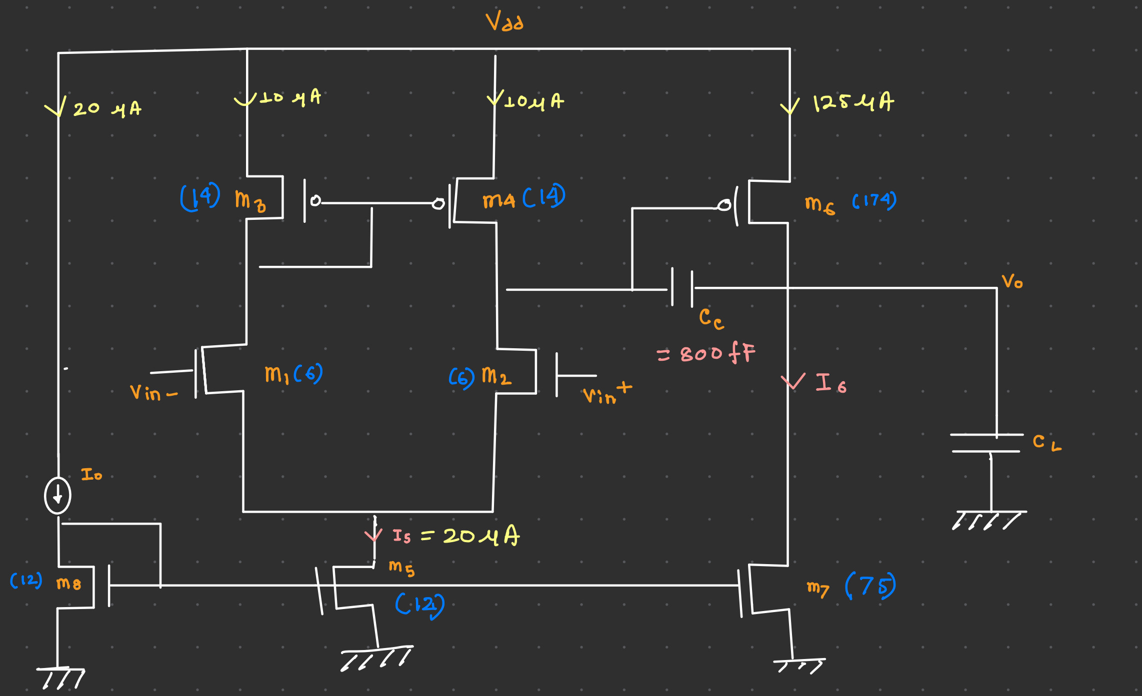
$m_7 = 75 = \frac{37.5}{.5}$

$I_6, I_7 = 125\mu$



$\boxed{L = 180nm}$

Fig: Two Stage Op-Amp



∴ power = 300 mW Vdd = 1.8 ∴ I = 166.66 μA

= 125 + 20 + 10 + 10

≃ 165 ≃ 166.66 μA

⊙ Design Specification: [Process : 180 nm]

DC gain : 1000 = 60 dB	Slew rate : 20 v/μSec
GBW : 30 MHz	ICMR (+) : 1.6 V
P.M : ≥ 60°	ICMR (−) : 0.8 V
Power : 300 μW	CL : 2 pF
	Vdd : 1.8 V

Blue no. are $\left[\frac{W}{L}\right]$ ratio

→ Lmin = 180 nm L ≥ 2 Lmin

$\boxed{L = 500 nm}$ Power = (125 + 20) = 145 μ × 1.8

= 261 mV < 300 mW

Practical Design Parameter and Specification:

[Cadence]