DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING

M.TECH in ELECTRONICS ENGINEERING (MICROELECTRONICS)

ANALOG and RF (ECE 5117)

Assignment 2:

DESIGN OF TWO STAGE OPAM USING 90nm CMOS technology

Submitted by

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Under the Guidence of:

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Abstract:

This report presents the design of a two-stage CMOS operational amplifier (op-amp) targeted for a 90 nm CMOS process. The design focuses on achieving high DC gain, adequate bandwidth, stable frequency response with Miller compensation, controlled slew rate, and reasonable power consumption for typical analog integrated circuit applications (e.g., ADC front-ends, comparators, and amplifiers

Objective:

The objective of this project was to design a robust two-stage Operational Transconductance Amplifier (OTA) in 90 nm CMOS technology, calculate the dimensions (W/L ratios) and bias currents for all transistors, and verify the resulting Total DC Voltage Gain (Av).

Theory and Design Parameters:

The OTA employs a standard two-stage architecture: a **NMOS input differential pair** (M1-M2) with PMOS current mirror loads (M3-M4) for the first stage, followed by an **PMOS common-source stage** (M6) with a PMOS current source load (M7) for the second stage. Miller compensation (c = 800 fF) is applied between the two stages to ensure stability**.**

Block Diagram:

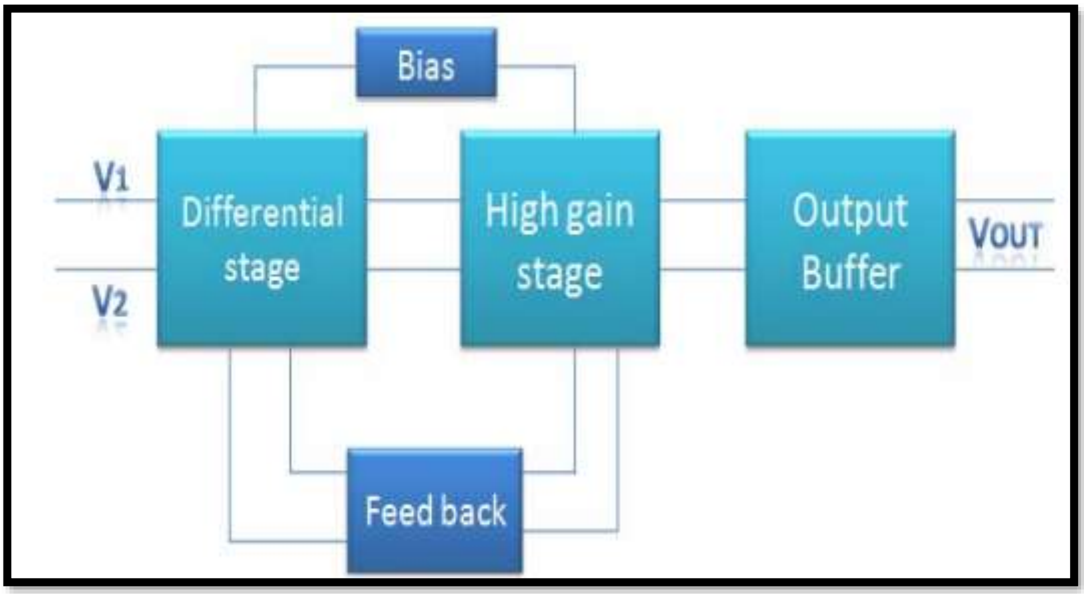


Figure 1: Block Diagram

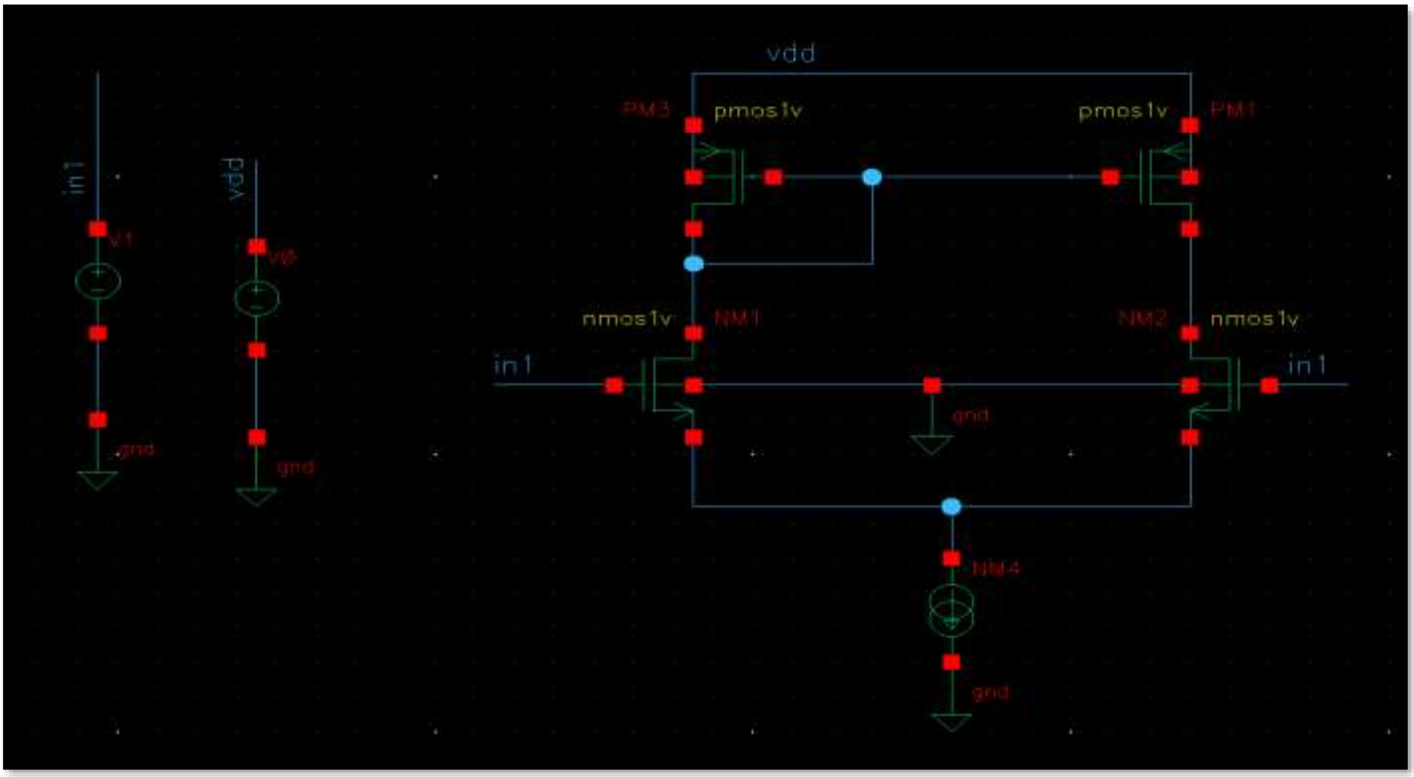


Figure 2: Differential Amplifier

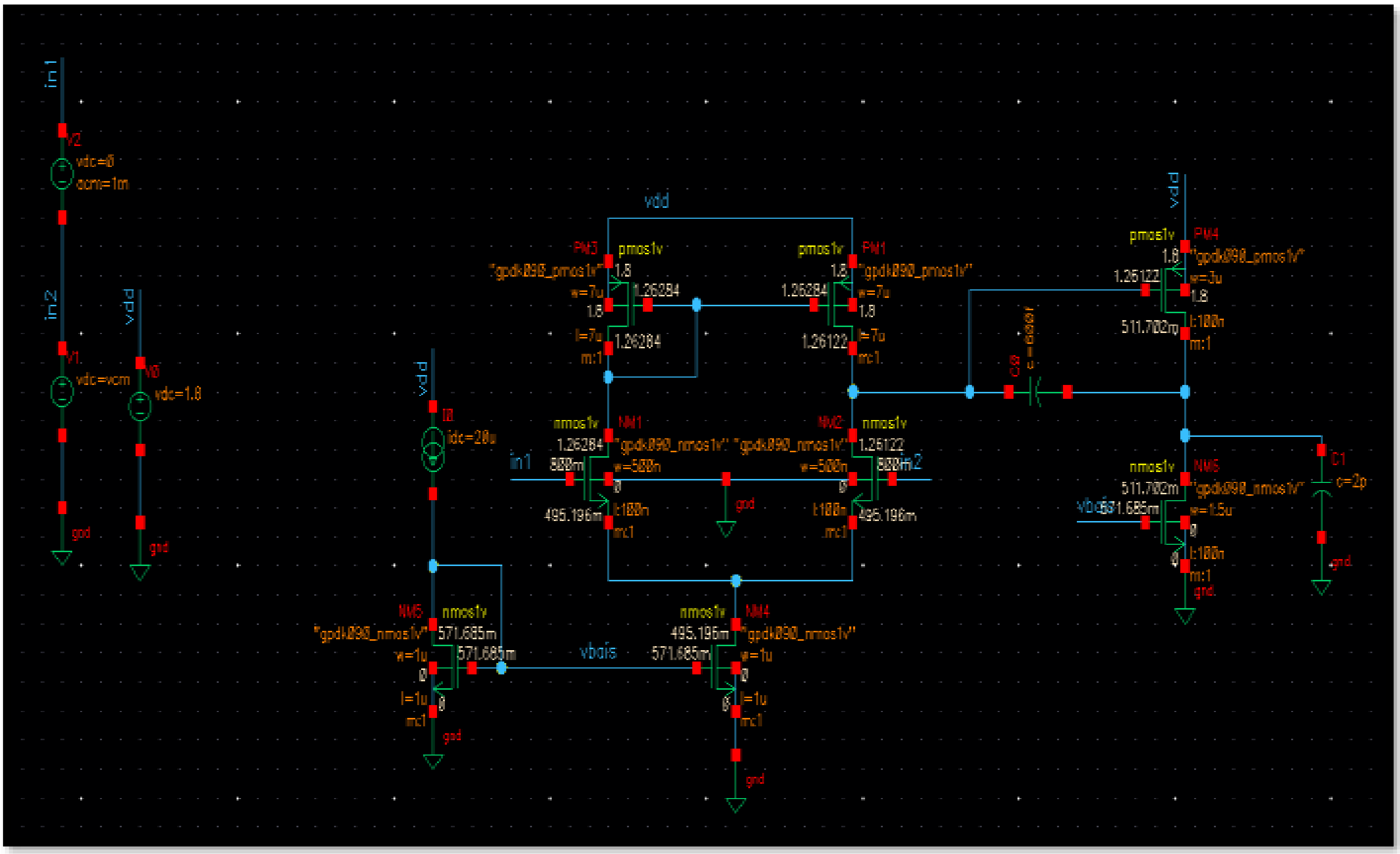
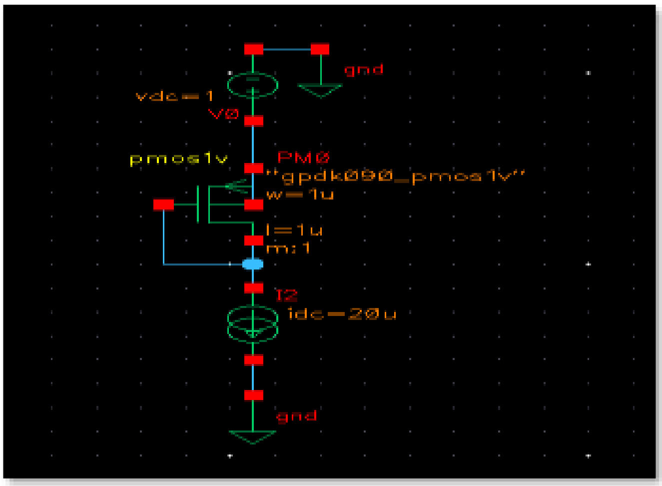


Figure 3: OPAM circuit

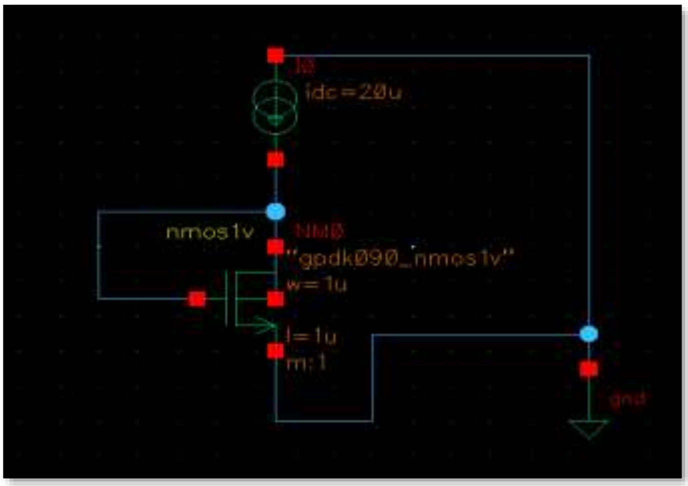
Calculations and Results:

The final design parameters, including the theoretically calculated W/L ratios and final bias currents, are summarized below**:**

PMOS TEST:



NMOS TEST:



VTHP BETAEFF

Window Expressions Info Help

signal	OP("/PM0" "??")
Iavl	NaN
beff	139.249u
betaeff	208.479u
cbb	111.222a

NMOS BETAEFF

Window Expressions Info Help

signal	OP("/NM0" "??")
Iavl	NaN
beff	245.509u
betaeff	300.632u

Vthp 1.6 V

vgs	-271.36m
vgsteff	15.1258m
vgt	24.1287m
vsat_marg	-217.625m
vsb	-0
vth	-295.689m
vth0	NaN
vth_drive	NaN

Vthn 1.6 V; ICMR+

vgt	92.9595m
vsat_marg	240.674m
vsb	1.18409
vth	322.947m

Vthp 800m

vgb	-271.604m
vgd	0
vgs	-271.604m
vgsteff	15.1407m
vgt	24.082m
vsat_marg	-217.656m
vsb	-0
vth	-295.686m

Vthn 800m

vsat_marg	903.134m
vsb	530.456m
vth	184.712m

VTHN differial test

vgs	518.254m
vgsteff	391.366m
vgt	397.489m
vsat_marg	192.11m
vsb	-518.254m
vth	120.765m

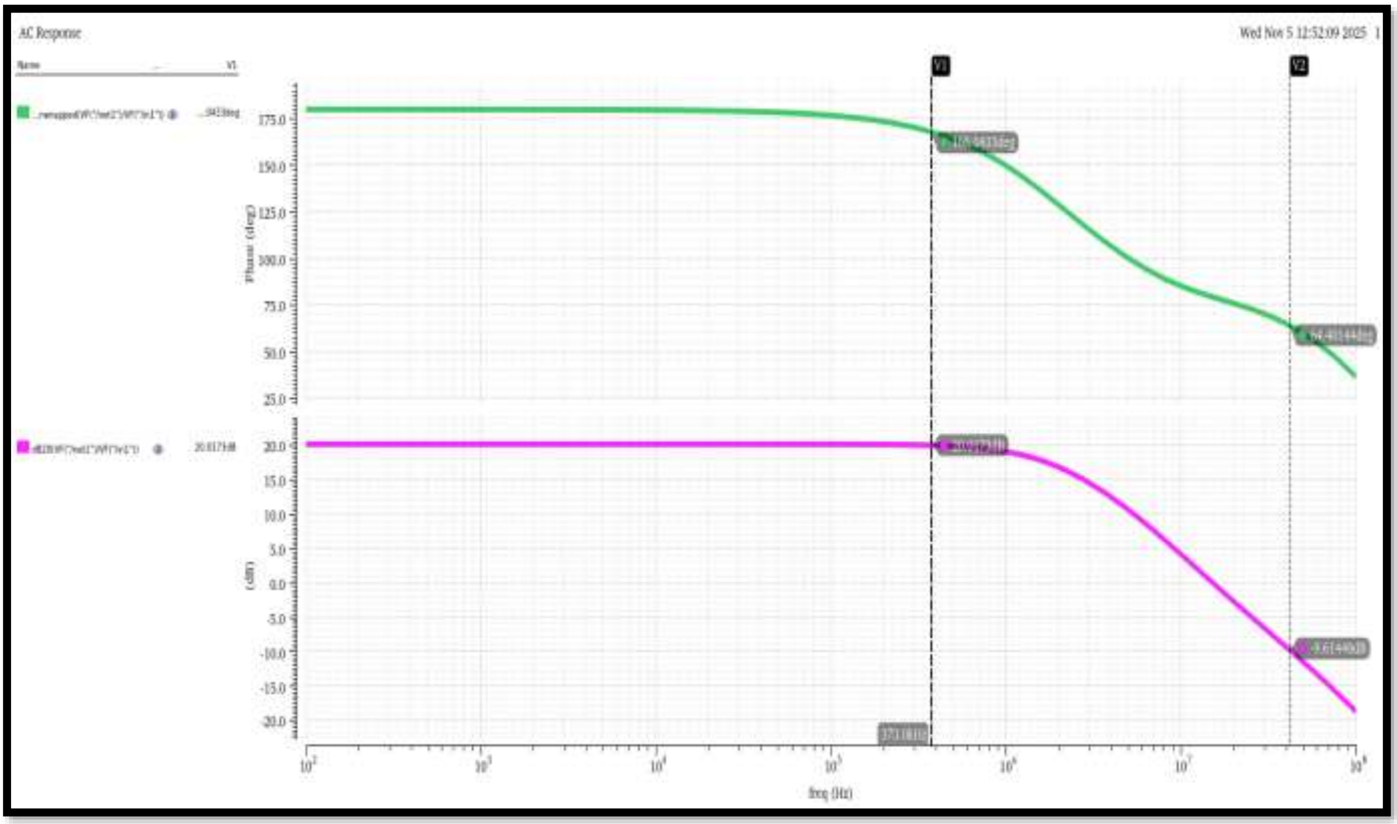


Figure 4: Gain bandwidth Phase Margin with 1.6V

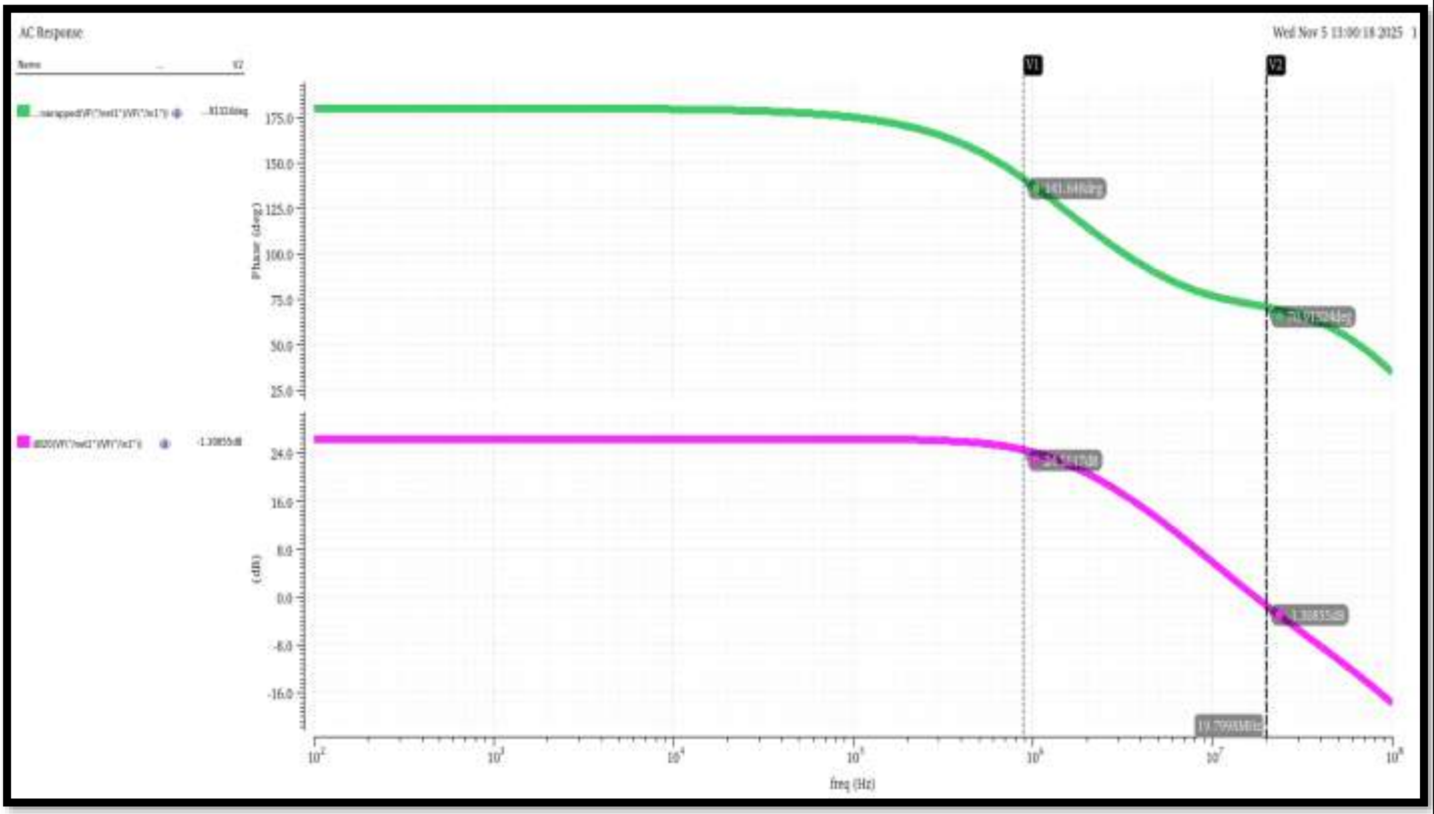


Figure 5: Gain bandwidth Phase Margin with 800 mV

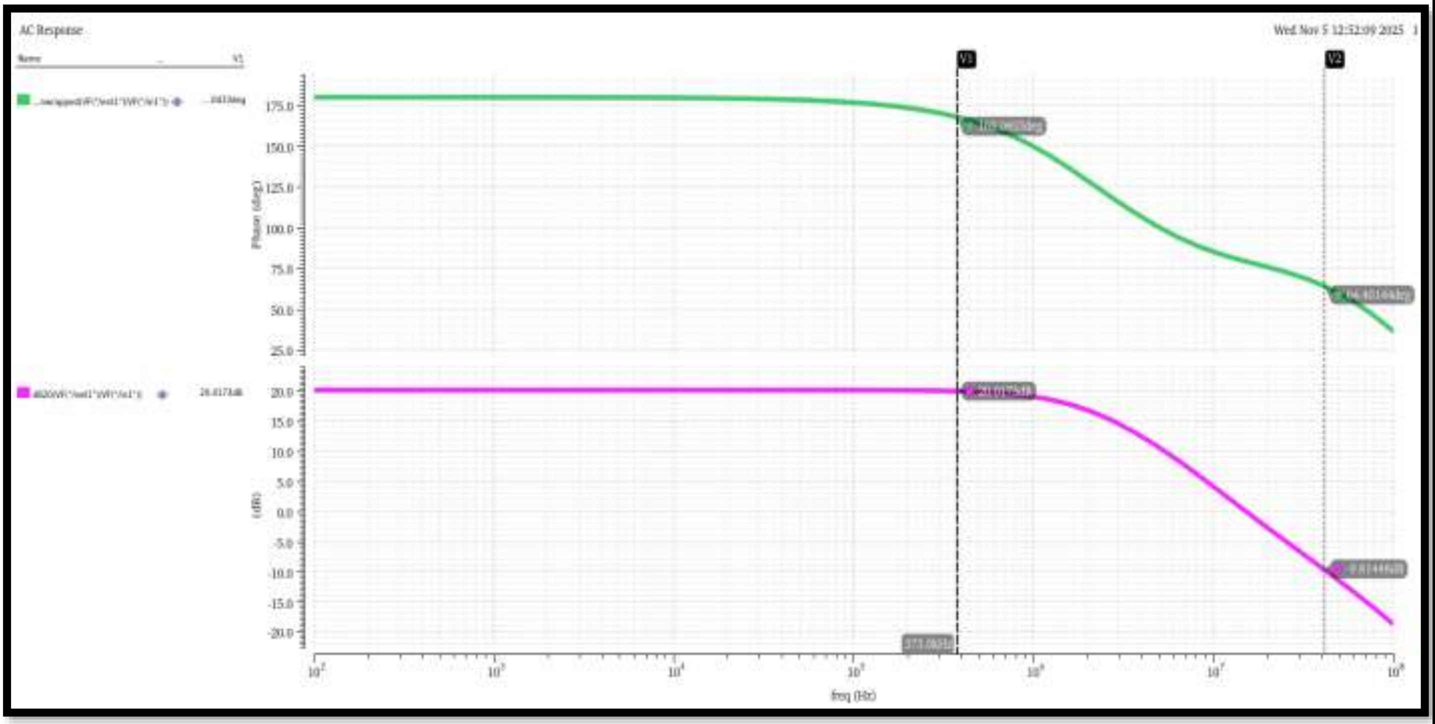
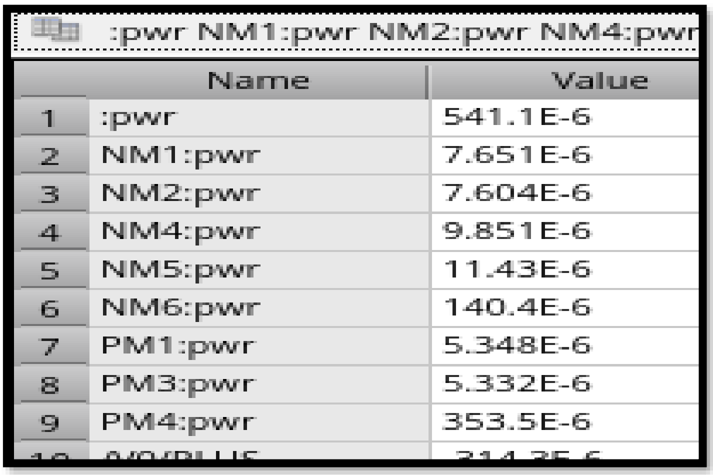


Figure 6: Gain bandwidth Phase Margin with 1.2V



:pwr NM1:pwr NM2:pwr NM4:pwr

	Name	Value
1	:pwr	541.1E-6
2	NM1:pwr	7.651E-6
3	NM2:pwr	7.604E-6
4	NM4:pwr	9.851E-6
5	NM5:pwr	11.43E-6
6	NM6:pwr	140.4E-6
7	PM1:pwr	5.348E-6
8	PM3:pwr	5.332E-6
9	PM4:pwr	353.5E-6

Figure 7: Total Power View with 1.6V

:pwr(W)=0.00054107608
NM1:pwr(W)=7.6514414e-06
NM2:pwr(W)=7.6036072e-06
NM4:pwr(W)=9.8511777e-06
NM5:pwr(W)=1.1432547e-05
NM6:pwr(W)=0.0001403929
PM1:pwr(W)=5.347841e-06
PM3:pwr(W)=5.3316341e-06
PM4:pwr(W)=0.00035346493

Figure 8: Total Power View with 800 mV

Conclusion:

Table 1: Theoretically calculated values

Parameter	Device/Stage	Theoretical Calculated Value	Units
Input $\mathbf{W/L}$	$\mathbf{M_{1,2}}$ (NMOS Differential Pair)	$\mathbf{4.27}$	Ratio
Current Mirror $\mathbf{W/L}$	$\mathbf{M_{3,4}}$ (PMOS Load)	$\mathbf{0.139}$	Ratio
Second Stage Driver $\mathbf{W/L}$	$\mathbf{M_6}$ (PMOS Driver)	$\mathbf{29.62}$	Ratio
Output Load $\mathbf{W/L}$	$\mathbf{M_7}$ (NMOS Load)	$\mathbf{15.0}$	Ratio
First Stage Bias Current	I_4	$10\mu A$	μA
Second Stage Bias Current	$I_6 = I_7$	$300\mu A$	μA
First Stage Gain ($\mathbf{A_{v1}}$)	$\frac{g_{m1}}{g_{ds2}+g_{ds4}}$	$\mathbf{3.01}$ (9.544 dB)	V/V (dB)
Second Stage Gain ($\mathbf{A_{v2}}$)	$\frac{g_{m6}}{g_{ds6}+g_{ds7}}$	$\mathbf{3.403}$ (10.63 dB)	V/V (dB)
Total DC Gain	$\mathbf{A_{v1}} + \mathbf{A_{v2}}$ (in dB)	$\mathbf{20.17}$ dB	dB

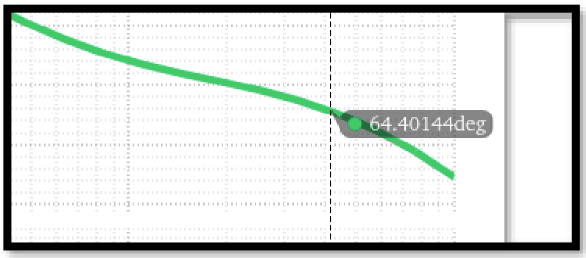


Figure 9: observed Phase Margin

Table 2: Comparsion Table

Parameter	Theoritical	Practical Results
DC Gain	20.17dB	24.57 dB (low due to device sizing)
PhaseMargin	64.401deg	64° (stable operation)
Power	571.6 µW (total)	541.1 µW (total)

Design of Two stage 90nm

i) $C_C = 800\,fF$

$I_5 = 20\mu A$

$g_{m_1} = 160\mu$

Beta Eff p $= 142.924\mu$

Beta Eff n $= 300.632\mu$

a) $M1$ & $M2$

$$\left(\frac{W}{L}\right)_1 = \frac{g_{m_1}^2}{\mu_n C_{ox} (2 I_{D_1})}$$

$$= \frac{(160\mu)^2}{(300.67\mu)(20\mu)}$$

$$\left(\frac{W}{L}\right)_1 = 4.266$$

$$\boxed{\left(\frac{W}{L}\right)_{1,2} \approx 5}$$

b) $M3$ & $M4$

$$\left(\frac{W}{L}\right)_3 = \frac{2 I_{D3}}{\mu_p C_{ox} [V_{DD} - ICMR^+ - V_{t3max} - V_{t1min}]^2}$$

$$= \frac{2(10\mu)}{145\mu [1.8 - 1.6 -}$$

c) $$\left(\frac{W}{L}\right)_{3,4} = \frac{2(10\mu)}{143\mu [1.8 - 1.6 - (\overset{0.295}{\cancel{295}} \times 10^{-3}) + 0.184]^2}$$

$\frac{W}{L} = 5$

$= 5 \times 100n$

$$\left(\frac{W}{L}\right)_{(3,4)} = 0.139 \approx 1$$

$W = L$

$\frac{2.5}{500} = 5$

d) $$V_{DSat} \geq ICMR^- - \sqrt{\frac{2 I_{D1}}{\beta_1}} - V_{t1\,max}$$

$$0.8 - \sqrt{\frac{2(10\mu)}{(300\mu)5}} - 0.322$$

$$= 0.8 - 0.115.4 - 0.322$$

$$= 0.3626$$

$$\boxed{V_{DSat} = 362mV}$$

V_{th_1} n max $= 322.947m$

V_{th_1} n min $= 184.71m$

$V_{th_p}^3$ max, min $= -295.m$

0.095 ← 95mV

362mV

e) $g_{m6} \geq 1600\mu$

$$\left(\frac{W}{L}\right)_4 = 1 \qquad \frac{\left(\frac{W}{L}\right)_6}{\left(\frac{W}{L}\right)_4} = \frac{g_{m6}}{g_{m4}}$$

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

$$= \sqrt{143(1)\,20}$$

$$g_{m4} = 53.47\,\mu$$

f) $= 2I_{D5} / \mu_n C_{ox} (V_{Dsat})^2$

$$\left(\frac{W}{L}\right)_5 = \frac{2(20\mu)}{300(362m)^2}$$

$$= \frac{40\mu}{300[0.131044]}$$

$$\left(\frac{W}{L}\right)_5 = 1.017$$

$$\boxed{\left[\frac{W}{L}\right]_5 = 1}$$

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

$$= \frac{1600\mu}{54\mu}(1)$$

$$\left(\frac{W}{L}\right)_6 = 29.62$$

h) $\frac{I_6}{I_4} = \frac{(W/L)_6}{(W/L)_4} = \frac{30}{1}$

$$I_6 = 30(I_4) = 30(10) = 300\,\mu A$$

$I_6 = 47$

$$\boxed{I_6 = 300\,\mu A}$$

i) $\frac{I_7}{I_5} = \frac{(W/L)_7}{(W/L)_5} \Rightarrow \left(\frac{W}{L}\right)_7 = \left(\frac{I_7}{I_5}\right)(W/L)_5$

$$= \frac{300}{20}(1)$$

$$\boxed{\left(\frac{W}{L}\right)_7 = 15}$$

→ From Calculations :-

I got $I_5 = 20\mu$

$C_C = 800fF$

$m_1, m_2 = 5 \Rightarrow \left(\frac{W}{L}\right)_{2,1} \Rightarrow \frac{0.5\mu}{100n}$

$m_3, m_4 = 1 \Rightarrow \left(\frac{W}{L}\right)_{3,4} \Rightarrow \frac{1\mu}{1\mu}$

$m_6 = 30 \Rightarrow \left(\frac{W}{L}\right)_6 = \frac{3\mu}{100n}$

$m_7 = 15 \Rightarrow \left(\frac{W}{L}\right)_7 = \frac{1.5\mu}{100n}$

$I_6, I_7 = 300\mu$

from above values, it is found that all mosfets are in Saturation

→ To Calculate gain in Each Stage

1st stage :- $A_{v_1} = g_{m_1}(r_{o_1} \| r_{o_4})$

As m_1 & m_2 ↑ g_{m_1} ↑

$\therefore g_{m_1} = 145.46\mu$

$g_{ds_1} = 48.065\mu$

$g_{ds_4} = 256.478n$

2nd stage

$g_{m_6} = 1.31m$

$g_{ds_6} = 162.591\mu$

$g_{ds_7} = 222.29\mu$

I^{st} stage

$$\text{Gain} = \frac{g_{m1}}{g_{ds1} + g_{ds4}} = \frac{145.46\,\mu}{48.065\,\mu + 256.478\,n}$$

$$= 3.01$$

$$\boxed{\text{gain}(dB) = 9.544}$$

II^{nd} stage

$$\text{Gain} = \frac{1310}{162.59 + 222.29} = 3.403$$

$$\text{gain}(dB) = 10.63$$

$$\boxed{\text{Total gain} = 20.17}$$

Total Power dissipation :-

$$P = V\, I_{\text{all current}}$$

$$= V_{dd}\ I_{\text{current through all mosfets.}}$$

$$= (1.8)(300\mu + 20\mu)$$

$$\boxed{P = 576\ \mu W}$$

Design Two Stage OPAMP :-

DC Gain = 1000 = 20log(100) = 60 dB

GBW = 30 MHz

PM ≥ 60°

Slew rate = 20 V/μ sec

ICMR(+) = 1.6V

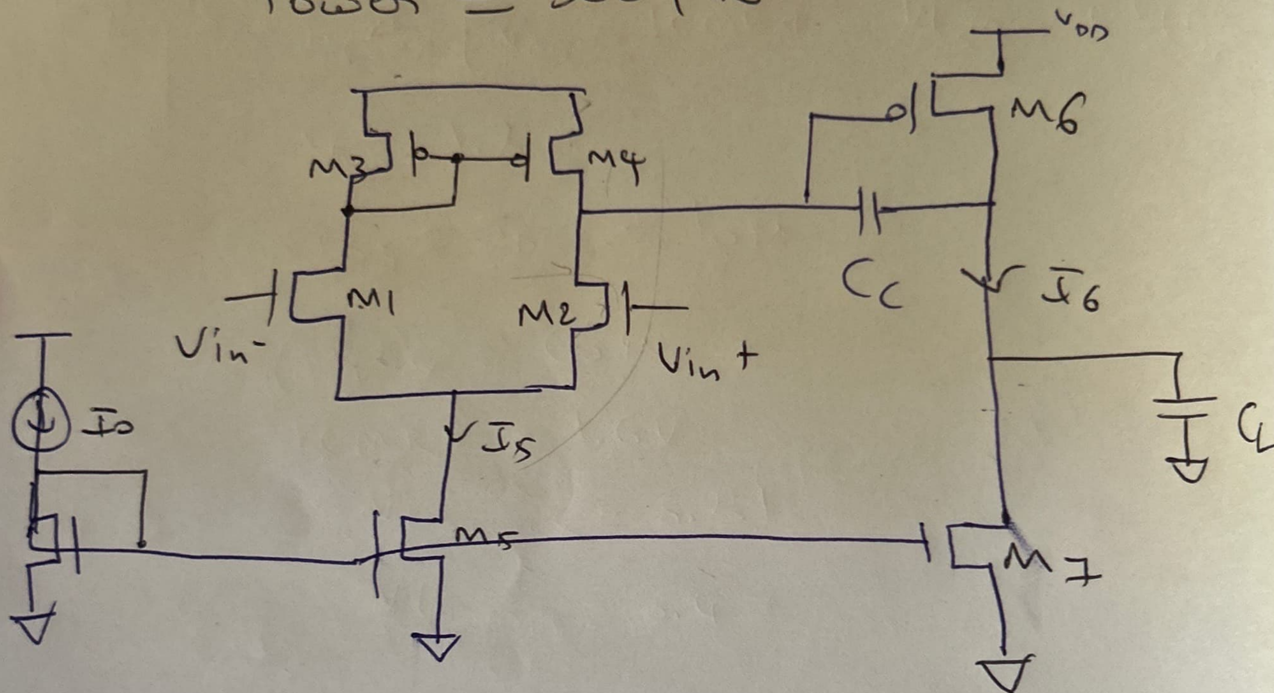
ICMR(−) = 0.8 V

C_L = 2 PF

Power ≤ 300 μW

V_{DD} = 1.8 V

Process = 180nm



m3 & m4 from → ICMR+

M1 & M2 → GBW

I5 → Slew rate

m7 ⟷ M5 → ICMR⁻ (min)

M6 from gain

Cc → Phase margin

beta eff = $\frac{\mu_n C_{ox}}{\mu_p C_{ox}}$

① L = 500nm

② $C_c \geq 0.22\, C_L$

$C_c \geq 0.22 \times 2pF$

$C_c \geq 0.44\, pF$

$\geq 440\, fF$ but

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

③ from GBW; M1 & M2?

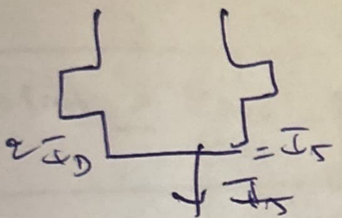
$g_{m1} = GB \times C_c \times 2\pi$

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

$g_{m1} = 150.79\mu$

$\boxed{g_{m1} = 160\mu}$

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



$\boxed{2 I_D = I_5}$

$I_D = \frac{I_5}{2}$

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

$$= \frac{g_{m1}^2}{\mu_n C_{ox} I_5}$$

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

$$\boxed{\therefore \left(\frac{W}{L}\right)_{1,2} = 5}$$

③ Slew rate; $\frac{I_5}{C_c}$?

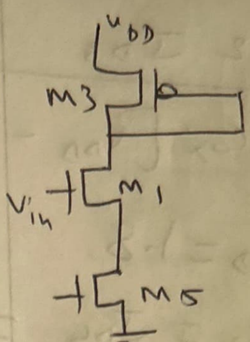
$I_5 = SR \cdot C_c$

$= \frac{20\, V}{\mu s} \cdot 800 fF$

$= 16\mu A$

$\boxed{I_5 = 20\mu A}$

④ M3 & M4



M3 is always saturation

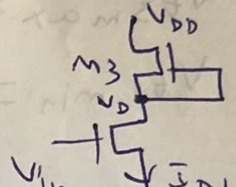
$V_{in}\uparrow$ $M_1 \rightarrow$ triode

$V_d \geq V_g - V_{tm1}$

$V_g < V_{d1} + V_{t1}$

$V_{in} < V_{d1} + V_{t1}$

$V_{in_{max}} = V_{d1} + V_{t1} \rightarrow ①$



$V_D = V_{DD} - V_{sg3}$

$I_3 = \frac{\mu_p C_{ox} \frac{W}{L}}{2} (V_s - V_t)^2$

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

$$\boxed{V_{gs_3} = \sqrt{\frac{2 I_3}{\beta_p}} + |V_{t3}|}$$

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

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

$V_{in_{max}} \leq \underbrace{V_{D1} + V_{t1}}_{min}$

$ICMR+ \leq V_{D1_{min}} + V_{t1_{min}}$

$\therefore ICMR+ \leq V_{DD} - \left[\sqrt{\frac{2 I_D}{\beta}} + |V_{t3}|\right]_{min} + V_{t1_{min}}$

$\leq V_{DD} - \sqrt{\frac{2 I_{D3}}{\beta_3}} - |V_{t3}|_{max} + V_{t1_{min}}$

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

$$\frac{2I_3}{\beta_3} = \left[V_{DD} - ICMR_{max} - |V_{t3}|_{max} + V_{t1min}\right]^2$$

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

$$\left(\frac{W}{L}\right)_3 = \frac{2 I_{D3}}{\mu_p C_{ox}\left[V_{DD} - ICMR^+ - V_{t3max} + V_{t1min}\right]^2}$$

$V_{DD} = 1.8$

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

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

$ICMR^+ = 1.6V$

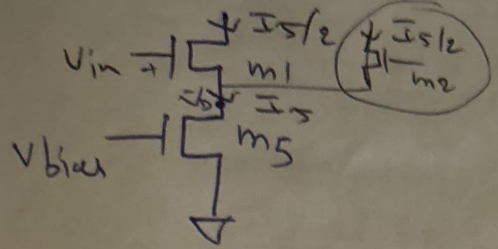
$V_{t3max} = 0.51$

$V_{t1min} = 0.47$

$$= \frac{2(10\mu)}{60\mu\left[1.8 - 1.6 - 0.51 + 0.47\right]^2}$$

$$\boxed{\left(\frac{W}{L}\right)_{3,4} = 13.02 \approx 14}$$

(5) Design for m5 :-



when $V_{in}\downarrow$

$V_D \downarrow$.

$V_{D_5} > V_g - V_t$

$\therefore$ M_5 goes to triode region

$V_{in\,(min)} \geq V_{gs_1} + V_{Dsat5}$ M_5 in sat

$ICMR\text{-ve}_{(min)} \geq V_{gs1} + V_{Dsat\,max}$

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

$$ICMR- \geq \sqrt{\frac{2I_{D1}}{\beta_1}} + V_{t\,max} + V_{D\,sat}$$

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

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

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

$$= 94.6mV$$

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

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

$$= 105mV$$

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

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

$$= \frac{2(20\mu)}{300\times(105mV)^2} = 12.05$$

$$\boxed{\left(\frac{W}{L}\right)_5 = 12} \qquad \boxed{\left(\frac{W}{L}\right)_{1,2} = 6}$$

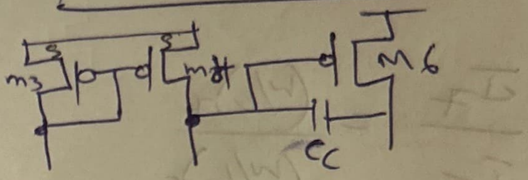
(6) Design for M6

for 60° PM

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

$$\geq 10(160\mu)$$

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



V_{GS} of m_3 & m_4 $\therefore$ V_{D3} & V_{D4}

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

$$V_{GS_{m3}} = V_{GS_{m4}} = V_{GS_{m6}}$$

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

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

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

$$= \sqrt{60(14)2(10)}$$

$$\boxed{g_{m4} = 129.61\mu}$$

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

$$= \frac{1600}{29.61}\times 14$$

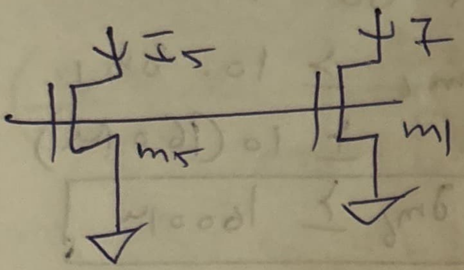
$$\boxed{\left(\frac{W}{L}\right)_6 = 173}$$

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

$$I_6 = \frac{\left(\frac{W}{L}\right)_6}{\left(\frac{W}{L}\right)_4} \times I_4 = \frac{174 \times 10}{14}$$

$$I_6 = 124.28$$

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



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

$$\left(\frac{W}{L}\right)_7 = \frac{I_7}{I_5} \cdot \left(\frac{W}{L}\right)_5$$

$$= \frac{125 \times 12}{20}$$

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

$V_{thp} = -295.68m$

$V_{thn} \rightarrow 184.71m$

$ICMR- \rightarrow 0.8$

$M3 \rightarrow -295.689m$

$ICMR+ \; 1.6$ M1

$V_{thn} \rightarrow 322.947m$

$V_{thn} \rightarrow 120.705m$

beff → 300.632μ

betaeff = 300.632μ

$V_{thp} \rightarrow -160.606m$

betaEff = 142.934μ