EECS 270A – Advanced Analog IC Design - 1

Fall 2021

Final Project

University of California, Irvine

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December 10, 2021

Contents:

<u>Design problem</u>:

Design an amplifier (with more than one stage) that satisfies the listed requirements:

- (Gain-bandwidth product) GBW > 210e9
- Rin > 500 kΩ
- Rout < 150 Ω
- DC Power Consumption < 18 mW
- Output Voltage Swing > 2.4 Vpp
- Vdd < 3.6

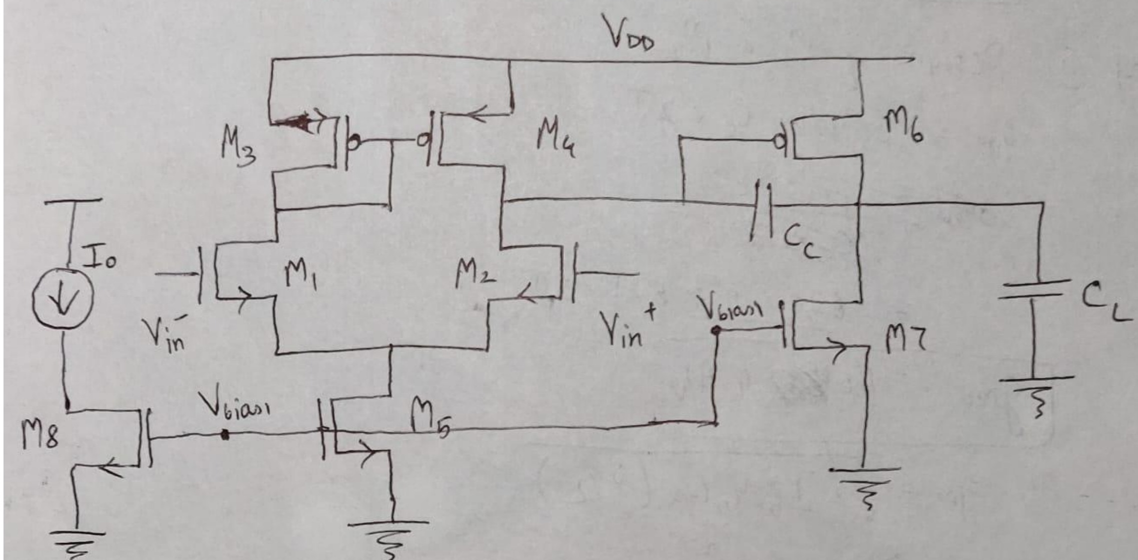
<u>Design approach:</u>

The amplifier was designed on paper and then simulated on Cadence. The details of the design are as shown below:

Design Steps

For $PM \geq 60^\circ$, $C_c \geq 0.22\, C_L$

Topology: Differential Pair with Active Load followed by common source stage



Let GBW = 30MHz
$PM \geq 60^\circ$
$SR = 10\, V/\mu s$
$ICMR(+) = 1.6\,V$
$ICMR(-) = 0.8\,V$
$C_L = 2pF$
Power dissipation $\leq 18mW$

Let $V_{DD} = 1.8\,V$
Process = 45nm

Step ① $C_L = 2pF$
$C_c \geq 0.22 \times 2pF$
$C_c \geq 440fF$
$\boxed{C_c = 800fF}$

Also, from simulation, I found the values of:

$\mu_p C_{ox} = 0.152m$ $\quad$ $\beta_{eff\,p} = 3.812m$ $\quad$ $L = 45nm$

$\mu_n C_{ox} = 80.46\,m$ $\quad$ $\beta_{eff\,n} = 11.67m$ $\quad$ $W = 1.125\mu m$

Step ② $SR = \frac{I_5}{C_c}$

$$I_5 = SR \times C_c$$

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

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

Step ③ Design of M_1 & M_2

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

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

$$= 30 \times 10^6 \times 800f \times 2\pi$$

$$\boxed{g_{m1} = 160 \mu A/V}$$

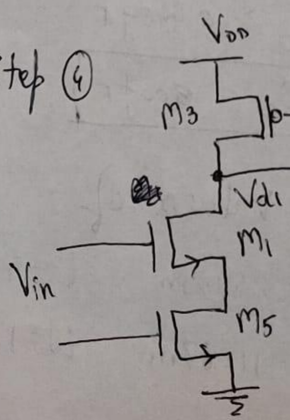
$$g_m = \sqrt{2 I_D \mu_n C_{ox} (W/L)}$$

$$\Rightarrow (W/L) = \frac{g_{m1}^2}{2 I_D \cdot \mu_n C_{ox}}$$

$$(W/L)_{1,2} = \frac{160^2 \times 10^{-12}}{20 \times 0.46m \times 10^{-6}}$$

$$= 2.78 \approx \underline{\underline{3}}$$

Step ④



If we increase V_{in}, M_1 enters triode.
For M_1 to be in saturation,

$$V_{d1} \geq V_{g1} - V_{t1}$$

$$V_{g1} \leq V_{d1} + V_{t1}$$

$$\Rightarrow V_{in} \leq V_{d1} + V_{t1}$$

$$V_{in(max)} = V_{d1} + V_{t1} \quad — \text{①}$$

$$V_{d1} = V_{DD} - V_{sg3}$$

$$V_{d1} = V_{DD} - \left[\sqrt{\frac{2I_D}{\beta_P}} + |V_{t3}|\right]$$

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

$$I_3 = \frac{\beta_P}{2}(V_{GS} - V_t)^2$$

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

From ①,

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

From ① & ②,

$$\Rightarrow ICMR(+) \leq \left[V_{DD} - \left(\sqrt{\frac{2I_D}{\beta_P}} + |V_{t3}|\right)\right]_{min} + V_{t1min}$$

$$\Rightarrow ICMR(+) \leq V_{DD} - \sqrt{\frac{2I_{D3}}{\beta_{P3}}} - |V_{t3}|_{max} + V_{t1min}$$

$$\Rightarrow \frac{2I_{D3}}{\beta_3} = \left(V_{DD} - ICMR_{max} - |V_{t3}|_{max} + V_{t1min}\right)^2$$

$$\Rightarrow \frac{2I_{D3}}{\mu_p C_{ox}(W/L)_3} = V_{DD} - ICMR - |V_{t3}|_{max} + V_{t1min}$$

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

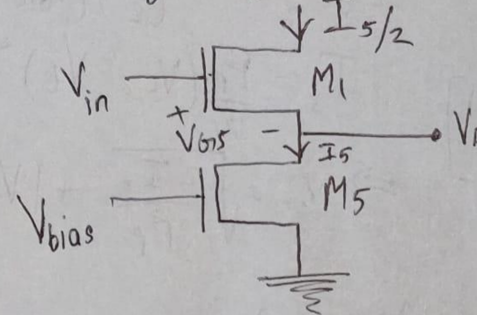
From simulation, $V_{t3max} = 0.51$

$V_{t1min} = 0.47$

$$\therefore (W/L)_3 = \frac{20\mu}{0.152m\left[1.8 - 1.6 - 0.51 + 0.47\right]^2}$$

$$\boxed{(W/L)_3 = } = 4.55 \approx \boxed{5}$$

Step ⑤ Design of M_5



$V_{DS} > V_g - V_t$

M_5 enters triode

$V_{Dsat} \rightarrow M_5$ to be saturation

$V_{in\,(min)} \geq V_{gs1} + V_{Dsat\,5}$

$ICMR_{min\,(-)} \geq \underset{(max)}{V_{gs1}} + \underset{(fixed)}{V_{Dsat}}$

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

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

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

$$V_{Dsat} \geq 0.8 - \sqrt{\frac{2 \times 104}{0.46m \times 31}} - V_{t1\,max}$$

From simulation $V_{t1\,max} = 0.59$

$$V_{Dsat} \geq 0.8 - 0.12 - 0.59$$

$$V_{Dsat} \geq 90\,m$$

$$V_{Dsat} = \underline{150m}$$

$$I_{D5} = \frac{1}{2}\mu_n C_{ox}\left(W/L\right)_5 V_{Dsat}^2$$

$$\boxed{(W/L)_5 = 3.86 \approx 4}$$

Step ⑥ **Design of M_6**

For PM of 60°, $g_{m6} \geq 10 g_{m1}$

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

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

$$V_{DS3} = V_{DS4} = V_{DS6}$$

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

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

$$g_{m4} = \sqrt{2 I_D \cdot \mu_p C_{ox} (W/L)_4}$$

$$g_{m4} = \sqrt{20\,\mu \times 0.152\,m \times 4}$$

$$g_{m4} = 110.27\,\mu A/V$$

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

$$= \frac{1600 \times 5}{110.27}$$

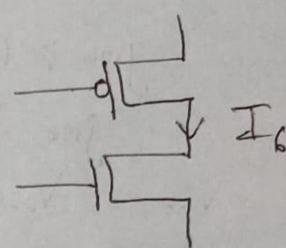
$$= 58.03$$

$$\boxed{(W/L)_6 \approx 59}$$

Step ⑦ <u>Design of M_7</u>

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

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



$$= \frac{59}{4} \times 10\mu$$

$$= 147.5\,\mu$$

$$\boxed{I_6 = 150\,\mu}$$

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

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

$$= \frac{150 \times 4}{20}$$

$$\boxed{(W/L)_7 = 30}$$

<u>Summary</u>:

① $(W/L)_{1,2} = 4 \longrightarrow \frac{180}{45}$

② $(W/L)_{3,4} = 5 \longrightarrow \frac{225}{45}$

③ $(W/L)_{5,8} = 4 \longrightarrow \frac{180}{45}$

④ $(W/L)_6 = 59 \longrightarrow \frac{2655}{45}$

⑤ $(W/L)_7 = 30 \longrightarrow \frac{1350}{45}$

$I_6, I_7 = 150\,\mu A$

DC Power consumption :

$P = V \times I$

$= 1.8 \times [(150\mu) + (20\mu)]$

$= 1.8 \times [170\mu]$

$= 0.3\,mW$

Output voltage Swing :

$V_{out(max)} = V_{DD} - V_{Dsat(6)}$

$= 1.8 - \sqrt{\dfrac{2 \cdot I_6}{K_6 \cdot (W/L)_6}}$

$= 1.8 - \sqrt{\dfrac{2 \times 150 \times 10^{-6}}{0.152m \times 59}}$

$= 1.8 - 0.1828$

$\boxed{\therefore V_{out(max)} = 1.61\,V}$

$V_{out(min)} = \sqrt{\dfrac{2 I_7}{K_7 \cdot (W/L)_7}} = V_{dsat(7)}$

$= \sqrt{\dfrac{2 \times 150 \times 10^{-6}}{0.46m \times 30}}$

$\boxed{V_{out(min)} = 0.147\,V}$

$\boxed{0.147 < V_{out} < 1.61}$

Input Resistance

$$R_{in} = r_{o1} \parallel r_{o3}$$

$$= \frac{1}{g_{ds1} + g_{ds3}}$$

$\Rightarrow$ From simulation: $g_{ds1} = 8.175\mu$; $g_{ds3} = 7.835\mu$

$$R_{in} = \frac{1}{(8.175 + 7.835)\mu}$$

$$\boxed{\Rightarrow R_{in} = 62.46\,k\Omega}$$

Output Resistance:

$$R_{out} = r_{o6} \parallel r_{o7}$$

$$= \frac{1}{g_{ds6} + g_{ds7}}$$

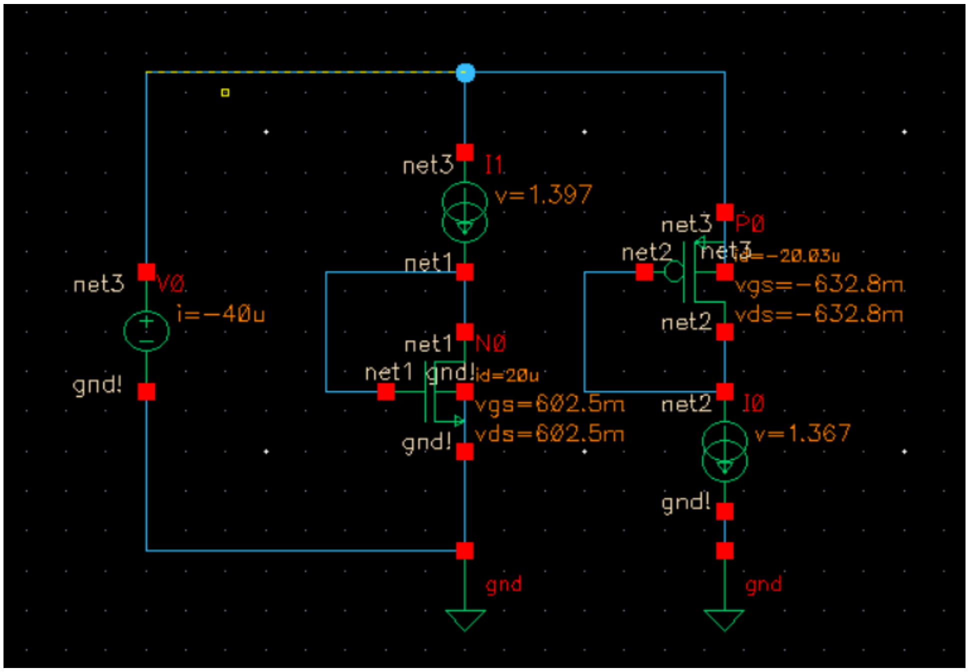
From simulation: $g_{ds6} = 115.8\mu$; $g_{ds7} = 88.78\mu$

$$\Rightarrow R_{out} = \frac{1}{(115.8 + 88.78)\mu}$$

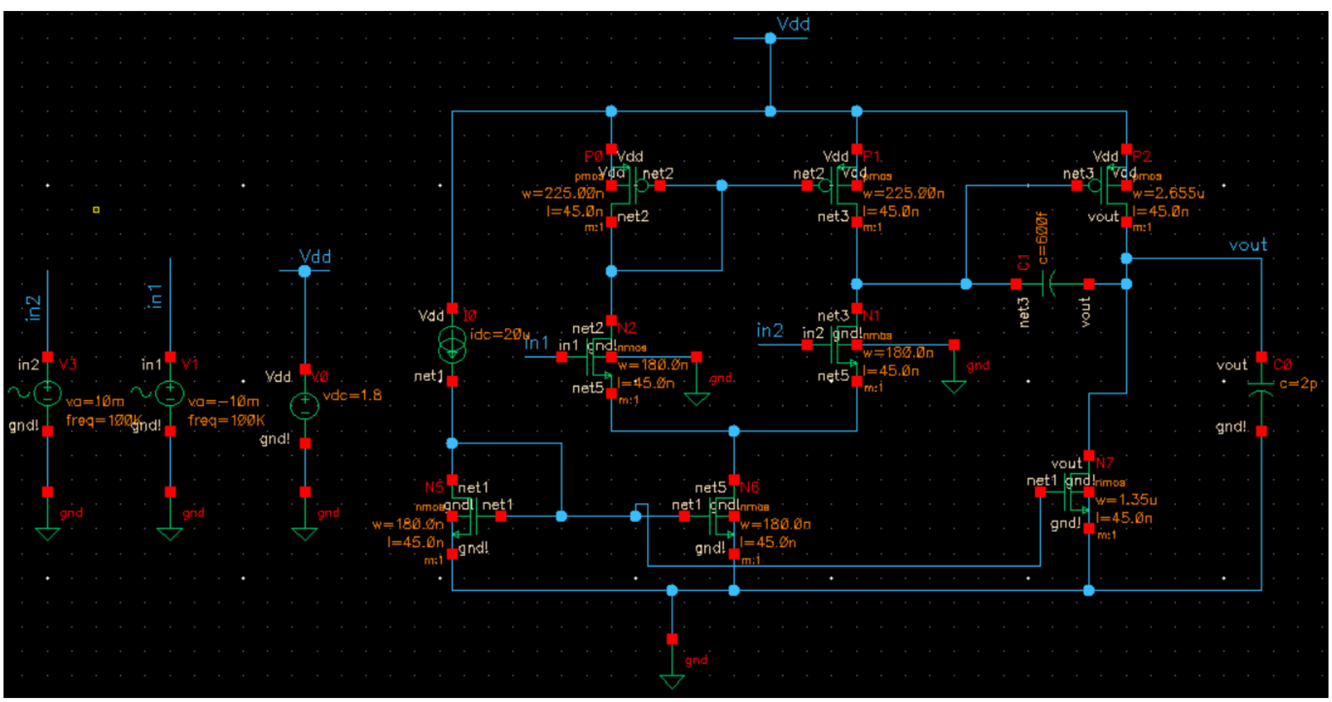
$$\Rightarrow \boxed{R_{out} = 4.88\,k\Omega}$$

Simulation results:

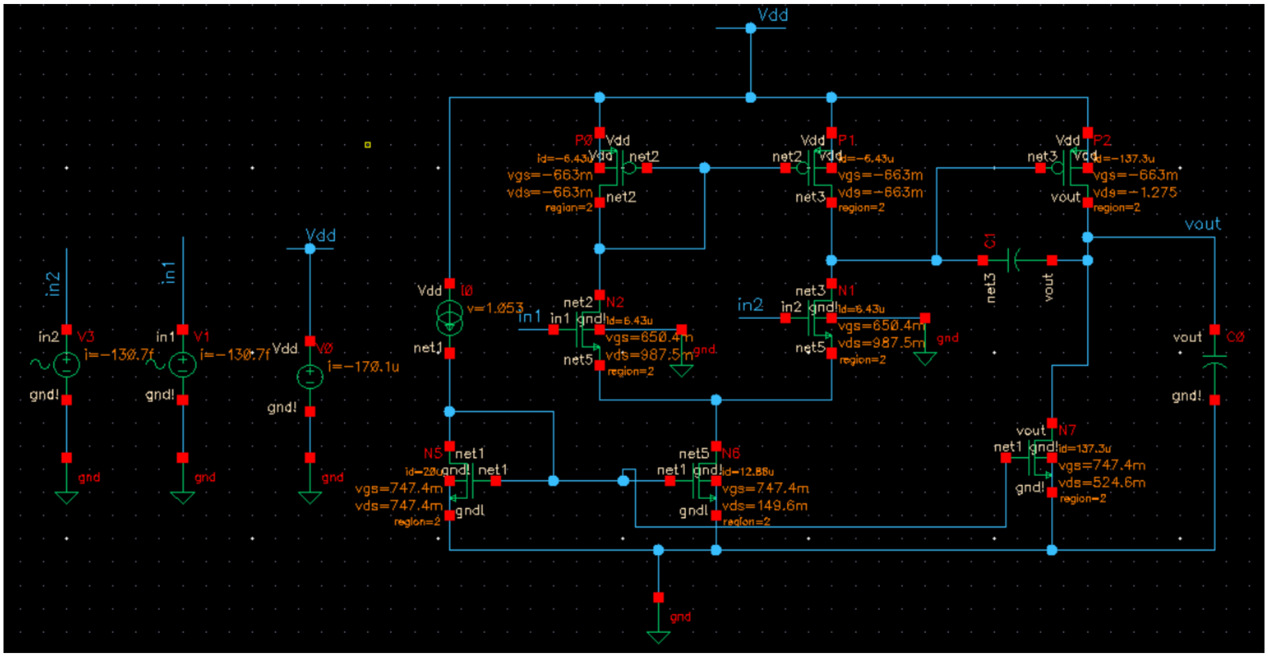
The circuit used to calculate the beta effective is as follows:



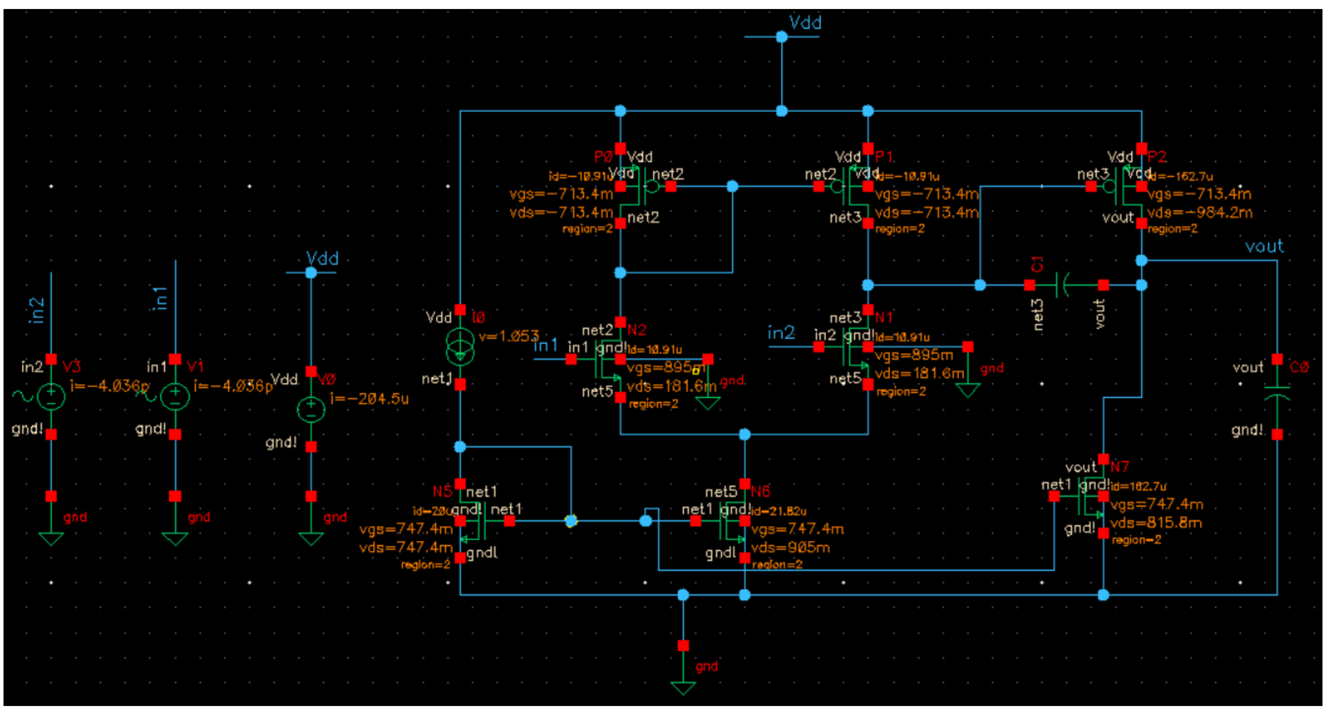
The amplifier circuit schematic is as shown: The dimensions of the transistors are depicted in the schematic.



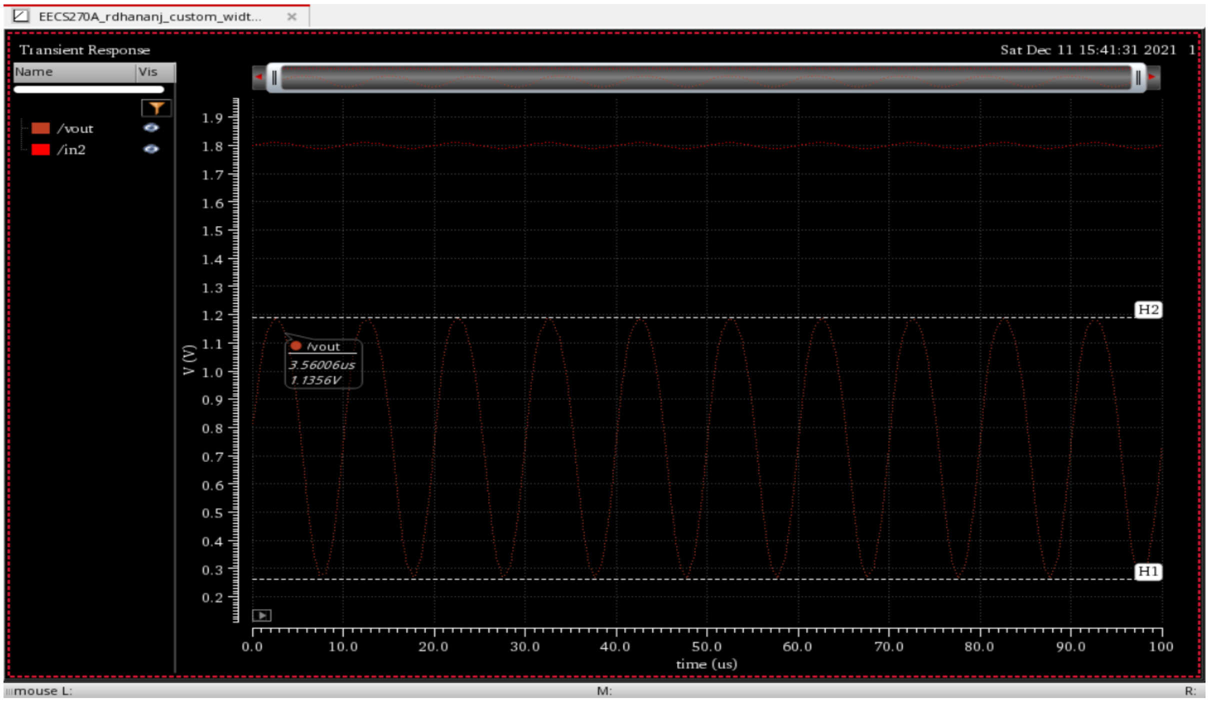
The DC analysis by setting ICMR = **<u>0.8V</u>** is as follows: All transistors are in region 2(saturation)



The DC analysis by setting ICMR = **<u>1.6V</u>** is as follows: All transistors are in region 2(saturation)



Running transient analysis:



Input amplitude vin (p to p) – 10mV

Input amplitude vip (p to p) – -10mV

Input frequency – 100kHz

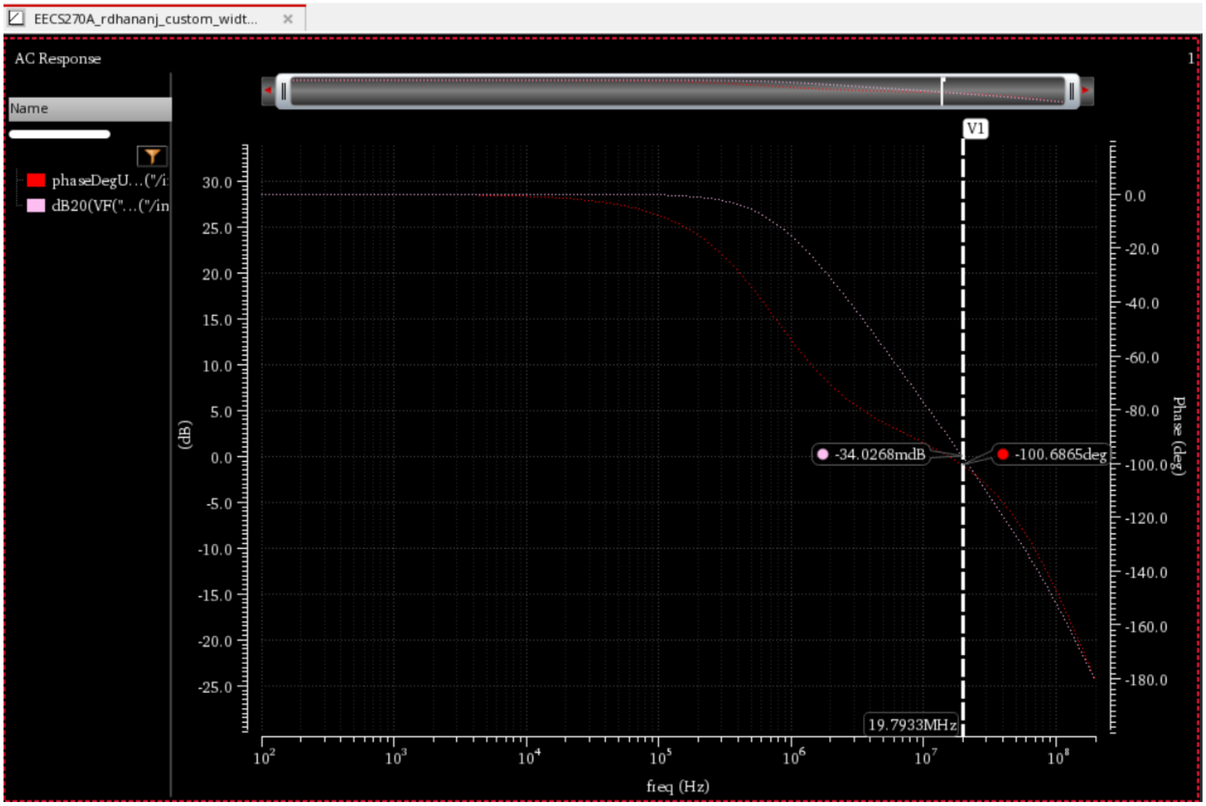
Start time – 0

Stop time – 100us

Common mode voltage – 1.6V

Output amplitude (p to p) – 0.92V

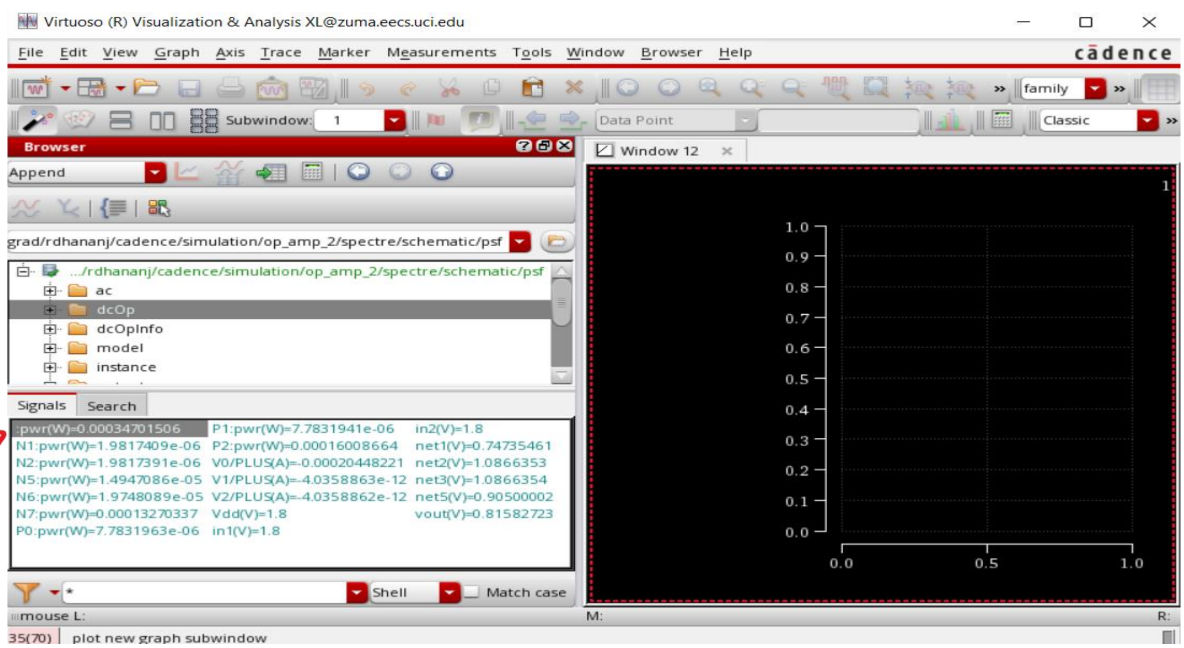
Running AC analysis and plotting the AC gain and phase:



It is observed that the GBW is **<u>19.79MHz</u>**. Gain is about **<u>27dB</u>**.

The phase margin is obtained as 180 – 100 = **<u>80 degrees</u>**

Simulation to find the power dissipation:



From the simulation, we see that the power dissipation is 0.00034701506W which is approximately **0.35mW**

Summary:

Simulation results observed:

1. Gain Bandwidth Product **- 19.79MHz**
2. Phase Margin – **80 degrees**
3. Gain – **27dB**
4. Power dissipation – **0.35mW**
5. Vdd used – **1.8V**
6. Rin – **62.46k ohm**
7. Rout – **4.88k ohm**