Department of Electrical, Computer, & Biomedical Engineering
Faculty of Engineering & Architectural Science

Ryerson University

Course Title:	CMOS Analog Integrated Circuits
Course Number:	ELE 727
Semester/Year (e.g.F2016)	F2025

Instructor:	Dr. Virgilio Valente

Assignment/Lab Number:	Project
Assignment/Lab Title:	Design of a CMOS CCIA

Submission Date:	Nov 28th, 2025
Due Date:	Nov 28th, 2025

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2. Design constraints and specifications

The design constraints are listed in **Table 1**, and the specifications of the CCIA are listed in **Table 2**. In this project, you will implement the op amp *A*, as a single-ended high-swing telescopic cascode, shown in **Fig. 3**.

Table 1. CCIA design constraints

Parameter	Unit	Value
V_{DD}	V	1.8
$V_{THN0} = |V_{THP0}|$ (no body effect)	V	0.45
$V_{THN} = |V_{THP}|$ (with body effect)	V	0.55
$\lambda_N = \lambda_P$ (for L=1μm)	1/V	0.045
K_N	μA/V^2	250
K_P	μA/V^2	65
$V_{EFF,min}$	V	0.1
$V_{EFF,max}$	V	0.6
C_L	pF	10

Table 2. CCIA design specifications.
IMPORTANT:
Parameter value XY = 'LAST TWO DIGITS OF YOUR ID'. If one of you last digits is a zero multiply the other digit by 10.
Parameter value Y= 'LAST DIGIT OF YOUR ID'. If this is 0, then use the second last digit.

Parameter	Unit	Value
Bandwidth $(f_L - f_H)$	Hz	X.Y – XY k^2 → 8.0 – 80K
Mid-band gain	V/V	100
Z_{IN} at 1kHz	MΩ	> Y → >8
Gain accuracy, α	%	> 99
Power consumption	μW	< 100
SR	V/μs	>0.1
Output swing	V_{pp}	> 0.5
Input-referred noise	μV$_{RMS}$	< 50

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[2] Note that the frequency range is from Hertz to kilohertz.

3. Design Procedure

PART I – Component value and parameter calculations

Assuming an ideal op amp, the CCIA mid-band gain, A_{MID}, is set by C_1/C_2 and for the case where $\hat{C}_1$ and $\hat{C}_L \gg \hat{C}_2$, the low-pass cut-off frequency f_H is set by $g_{m1}/(2\pi A_{MID}\hat{C}_L)$. The low frequency cut-off, f_L, of the ac-coupled amplifier is set by $1/(2\pi R_2 C_2)^1$. The amplifier input impedance is approximately equal to $Z_{IN}=2/(sC_1)$.
The noise efficiency factor (NEF) of the CCIA is determined by:

$$NEF = V_{n,in,RMS} \cdot \sqrt{\frac{2I_{tot}}{\pi \cdot U_T \cdot 4kT \cdot BW}}$$

Where $V_{n,in,RMS}$ is the total input-referred noise of the amplifier, I_{tot} is the total supply current of the amplifier, BW is the amplifier bandwidth in Hz, U_T is the thermal voltage equal to 25.9mV at room temperature and k is the Boltzmann's constant.

Table 1. CCIA design constraints

Parameter	Unit	Value
V_{DD}	V	1.8
V_{THN} = |V_{THN}| (no body effect)	V	0.45
V_{THN} = |V_{THP}| (with body effect)	V	0.55
$\lambda_n = \lambda_P$ (for L=1μm)	1/V	0.045
k_n	μA/V²	250
k_P	μA/V²	65
$V_{DS,min}$	V	0.1
$V_{DS,max}$	V	0.6
C_L	pF	10

Table 2. CCIA design specifications.
IMPORTANT:
Parameter value XY = 'LAST TWO DIGITS OF YOUR ID'. If one of you last digits is a zero multiply the other digit by 10.
Parameter value Y= 'LAST DIGIT OF YOUR ID'. If this is 0, then use the second last digit.

XY=08 = 8×10 = 80 XY

Parameter	Unit	Value
Bandwidth $(f_H - f_L)$	Hz	X.Y – XY k² (0.8 – 80) k²
Mid-band gain	V/V	100
Z_{IN} at 1kHz	MΩ	> Y >8
Gain accuracy, α	%	>99
Power consumption	μW	<100
SR	V/μs	>0.1
Output swing	V_{pp}	>0.5
Input-referred noise	μVrms	<50

Y=8.0

$$Z_{in} = \frac{2}{sC_1} > 8\,M\Omega$$

$Z_{in} > 8\,M\Omega$

$$\frac{2}{j\omega C_1} > 8\,M\Omega$$

$$\frac{2}{2\pi(1000)C_1} > 8\,M\Omega$$

$$2 > (8\times10^6)(2\pi)(1000)C_1$$

$$\boxed{\therefore C_1 < 39.79\,pF} \longrightarrow \therefore C_1 = 39.79\,pF$$

$A_{mid} = 100$

$$A_{Mid} = \frac{C_1}{C_2}$$

$$\rightarrow C_2 = \frac{C_1}{A_{mid}} = \frac{39.79\,pF}{100}$$

$$\boxed{\therefore C_2 = 397.89\,fF = 0.39789\,pF}$$

Table 1. CCIA design constraints

Parameter	Unit	Value
V_{DD}	V	1.8
$V_{tn0} = \|V_{tn0}\|$ (no body effect)	V	0.45
$V_{tn} = \|V_{tn}\|$ (with body effect)	V	0.55
$\lambda_n = \lambda_p$ (for L=1µm)	1/V	0.045
k_n	µA/V^2	250
k_p	µA/V^2	65
$V_{DS,sat}$	V	0.1
$R_{DS,sat}$	V	0.6
C_L	pF	10

Table 2. CCIA design specifications.
IMPORTANT:
Parameter value XY = 'LAST TWO DIGITS OF YOUR ID'. If one of you last digits is a zero multiply the other digit by 10.
Parameter value Y= 'LAST DIGIT OF YOUR ID'. If this is 0, then use the second last digit.

Parameter	Unit	Value
Bandwidth ($f_L - f_H$)	Hz	XY - XY k² (85 - 80) k²
Mid-band gain	V/V	100
Z_{in} at 1kHz	MΩ	> Y 78
Gain accuracy, α	%	> 99
Power consumption	µW	< 100
SR	V/µs	> 0.1
Output swing	V_{pp}	> 0.5
Input-referred noise	µV$_{rms}$	< 50

Assuming an ideal op amp, the CCIA mid-band gain, A_{MID}, is set by C_1/C_2 and for the case where C_1 and $C_L \gg C_2$, the low-pass cut-off frequency f_H is set by $g_{m1}/(2\pi A_{MID}C_L)$. The low frequency cut-off, f_L, of the ac-coupled amplifier is set by $1/(2\pi R_F C_2)$. The amplifier input impedance is approximately equal to $Z_{IN}=2/(sC_1)$.
The noise efficiency factor (NEF) of the CCIA is determined by:

$$NEF = V_{n,in,RMS} \cdot \sqrt{\frac{2I_{tot}}{\pi \cdot U_T \cdot 4kT \cdot BW}}$$

Where $V_{n,in,RMS}$ is the total input-referred noise of the amplifier, I_{tot} is the total supply current of the amplifier, BW is the amplifier bandwidth in Hz, U_T is the thermal voltage equal to 25.9mV at room temperature and k is the Boltzmann's constant.

$$f_H = \frac{g_{m1}}{2\pi A_{mid} C_L}$$

SINCE $C_L \gg C_2$

$$\therefore f_H = 80\ KHZ = 80,000\ Hz$$

$$\rightarrow g_{m1} = f_H (2\pi A_{mid} C_L)$$

$$\rightarrow \therefore g_{m1} = (80 \times 10^3)(2\pi)(100)(10 \times 10^{-12})$$

$$\boxed{\therefore g_{m1} = 5.0265 \times 10^{-4}}$$

$$f_L = \frac{1}{2\pi R_F C_2}$$

$$\rightarrow f_L = 8.0\ Hz$$

$$R_F = \frac{1}{2\pi C_2 f_L}$$

$$\therefore R_F = \frac{1}{2\pi (0.39789 \times 10^{-12})(8)}$$

$$\boxed{\therefore R_F = 50\ G\Omega}$$

Closed loop gain

$$\alpha A_{mid} = \frac{A_{OA}}{1 + \beta A_{OA}}$$

$$\rightarrow \therefore \alpha A_{mid} = (0.99)(100)$$

$$\boxed{\therefore \alpha A_{mid} = 99}$$

$$\alpha > 99\%$$

Part I. - Continued

Find minimum A_{OA} Value

$$\beta = \frac{C_2}{C_1} = \frac{0.3979\ pF}{39.79\ pF}$$

$$\boxed{\therefore \beta = 0.01}$$

$$\alpha A_{mid} = \frac{A_{OA}}{1 + \beta A_{OA}}$$

$$A_{OA}\beta\, \alpha A_{mid} + \alpha A_{mid} = A_{OA}$$

$$A_{OA}(1 - \beta\, \alpha A_{mid}) = \alpha A_{mid}$$

$$\therefore A_{OA} = \frac{\alpha A_{mid}}{1 - \beta\, \alpha A_{mid}}$$

$$\boxed{\therefore A_{OA} = 9900}$$

GBW

$$GBW = \frac{g_{M1}}{C_L}$$

$$\rightarrow \therefore GBW = \frac{5.0265 \times 10^{-4}}{10 \times 10^{-12}}$$

$$\boxed{\therefore GBW = 5.0265 \times 10^{7}}$$

Finding R_O

$$A_{OA} = g_{M1} R_O$$

$$\therefore R_O = \frac{A_{OA}}{g_{M1}} = 19.6956\ M\Omega$$

$$\boxed{\therefore R_O = 19.6956\ M\Omega}$$

Part I. - Continued

Fig.4 CCIA macromodel Test setup schematic (with ideal op amp)
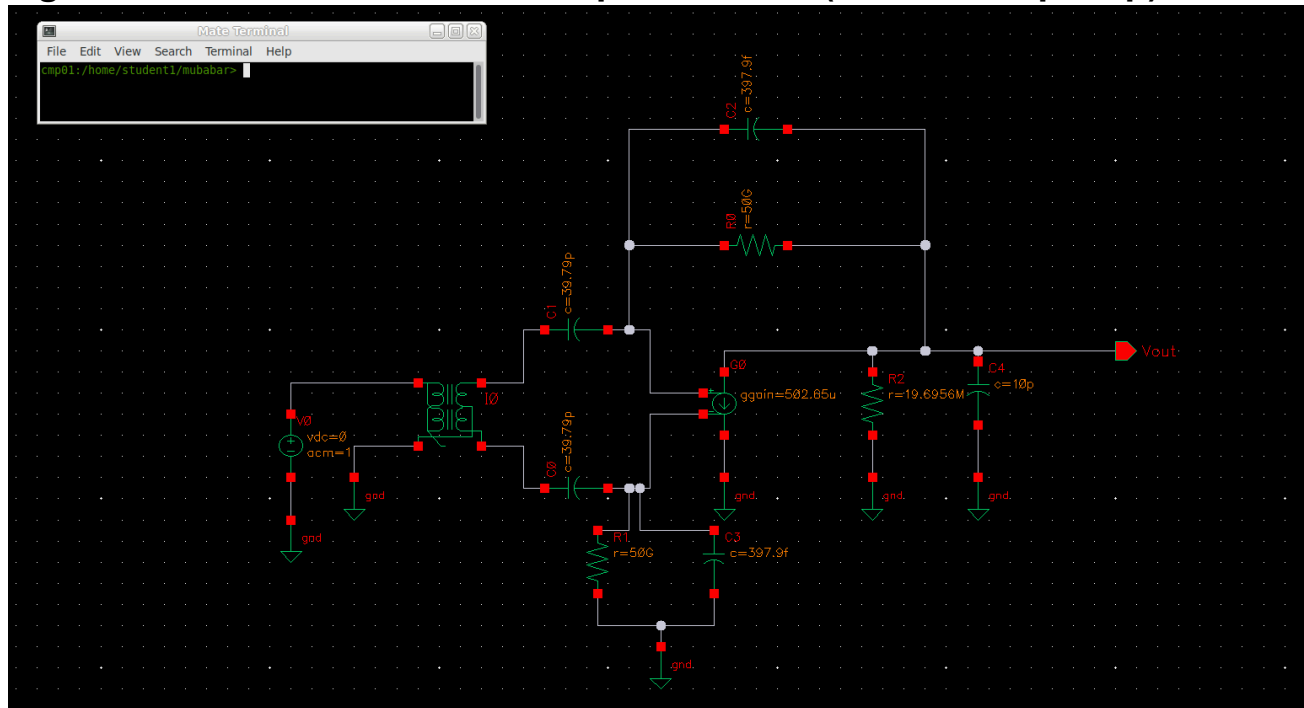
CCIA macromodel Test setup AC GAIN
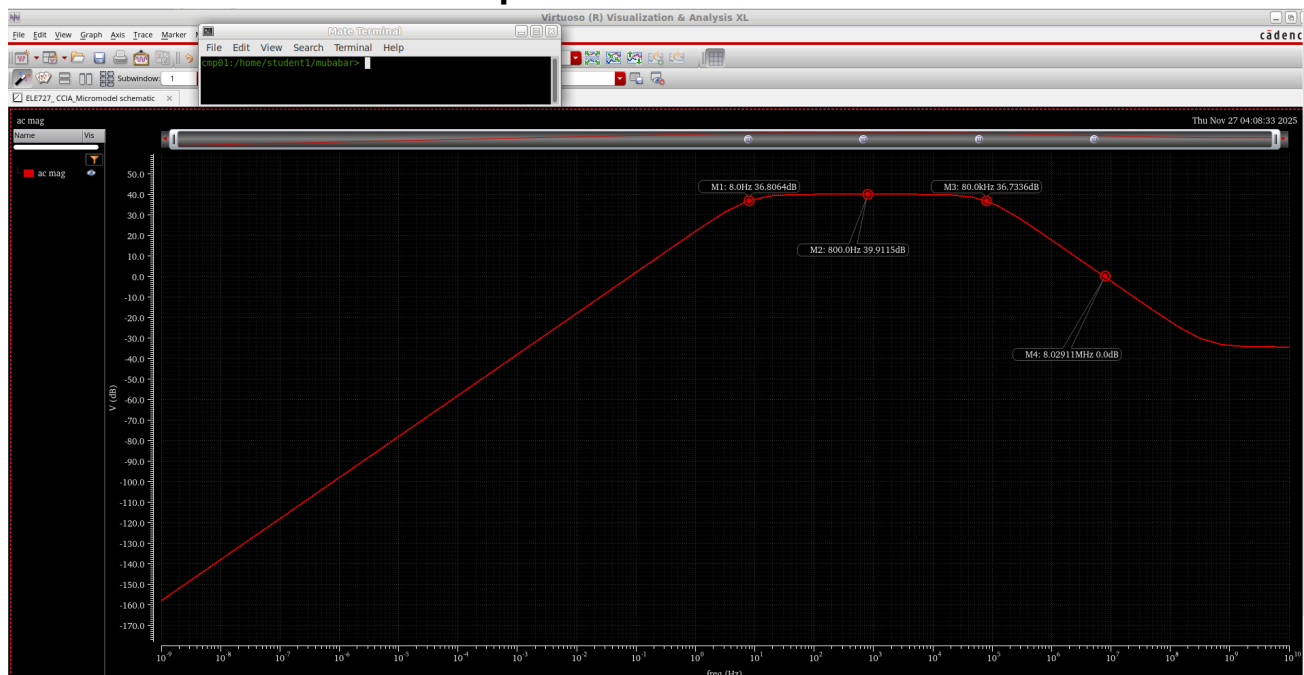
Part I. - Continued

$f_C = \sqrt{fl * fh} = \sqrt{8 * 80k}$ = 800 Hz @ 39.775 dB

f_L = 8 Hz @ 36.2365 dB

f_C = 80 kHz @ 36.1342 dB

Analyzing the waveform above, both points that are 3db below the Mid-band gain are at 8 Hz and 80 kHz, which perfectly match up with our design requirements. Moreover, comparing the waveform above with the waveform in Fig.2 of the Lab manual, both the frequency response of the CCIA and Fig.2 perfectly match up, meaning that the bandwidth requirement has been successfully achieved.

Design (Part I) - Continued

Table D1

Parameter	Calculated value
GBW (MHz)	50.265
$R_O(\Omega)$	19.6956M
A_{OA}	9900
β	0.01
αA_{mid}	99
$R_F(\Omega)$	50G
C_1 (pF)	< 39.79
C_2 (pF)	< 0.39789
G_{m1} (S)	5.0265 x 10^{-4}

PART II – Op amp design

Part II.

Fig. 4. Test setup for the macromodel of the CGA with small-signal equivalent circuit of the op amp
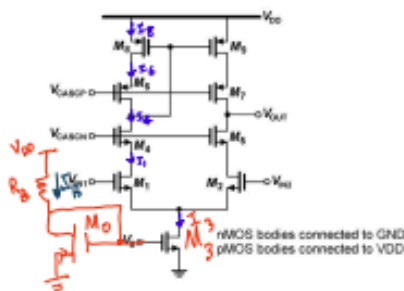
Fig. 3. Schematic of high-swing telescopic cascode op amp

The gain of the telescopic cascode op amp is given by $A_V = g_{m1} R_o$, where $R_o = (g_{m3} r_{o3} r_{o1} \| g_{m5} r_{o5} r_{o7})$ and its gain-bandwidth-product, GBW, is set by g_{m1}/C_L.

Assuming circuit is balanced & $V_{in1} = -V_{in2}$

$$\longrightarrow I_B = I_6 = I_4 = I_1 = \frac{I_B}{2}$$

$$P_{c,total} < 100 \mu W \rightarrow P_{c,total} \Rightarrow V_{DD}\underset{1.8V}{(I_3 + I_B)} < 100 \mu W$$

$$I_3 = I_{SS} \Rightarrow SR \cdot C_L = \left(\frac{0.1}{10^{-6}}\right)(10 \times 10^{-12}) \rightarrow 1.8 \underset{1\mu A}{(1\mu A + I_B)} < 100 \mu W$$

$$\longrightarrow \therefore I_3 = 1\mu A \qquad \boxed{\therefore I_B < 54.55 \mu A}$$

For output swing, in order for M_{6-9} to remain in saturation $\rightarrow V_{SD,sat} > V_{ov} \rightarrow V_{DD} - (V_{out_{max}} + V_{ov}) \geqslant V_{ov}$

$$\longrightarrow -V_{out_{max}} \geqslant 2V_{ov} - V_{DD}$$

$$\boxed{\therefore V_{out_{max}} \leqslant V_{DD} - 2V_{ov}}$$

Part II. - Continued

For M_{1-4} and current source to
stay in saturation: $\longrightarrow$ $V_{DS} \geqslant V_{ov}$

$$V_{out_{min}} - 2V_{ov} \geqslant V_{ov}$$

$$\boxed{\therefore V_{out_{min}} \geqslant 3V_{ov}}$$

Output Swing $> 0.5 V_{PP}$
$\underbrace{\qquad}$
$V_{out,max} - V_{out,min}$

$V_{DD} - 2V_{ov} - 3V_{ov} > 0.5$ $\qquad \rightarrow 1.8 - 5(0.8) > 0.5$

$1.8 - 5 V_{ov} > 0.5$ $\qquad \rightarrow \therefore 0.8 V_{PP} > 0.5 V_{PP}$
$\underbrace{\qquad}$
$\qquad\qquad\qquad\qquad\qquad\qquad$ Output Swing
$-5 V_{ov} > -1.3$

$\boxed{\therefore V_{ov} < 0.26 V}$

$$\boxed{\therefore \text{Output Swing} = 0.8 V_{PP}}$$

$I_{3,max} = I_{SS} = 54.55 \mu A$

$I_1 = \dfrac{I_{SS}}{2} = 27.278 \mu A \rightarrow g_{m1} = \dfrac{2I_1}{V_{ov}}$

$\quad\quad \hookrightarrow V_{ov} = \dfrac{2I_1}{g_{m1}} = \dfrac{2(27.278 \times 10^{-6})}{(5.0265 \times 10^{-4})} = 0.1085 V$

Although $0.1085 V$ is less than the maximum constraint, we're risking instability from the noise. Because of this, we'll have to come to terms and increase the drawn power in order to get a larger overdrive voltage.

- V_{ov} should be equal from somewhere between 0.15 and $0.2V$

$\therefore$ we'll set $V_{ov_1} = V_{ov_2} = 0.2V$ for better gain and swing tolerance

$$g_{m1} = \dfrac{2I_1}{V_{ov_1}} \longrightarrow I_1 = \dfrac{g_{m1} V_{ov_1}}{2}$$

$$= \dfrac{A(5.0265 \times 10^{-4})(0.2)V}{2}$$

$$\boxed{\therefore I_1 = 50.265 \mu A}$$

$$\boxed{\therefore I_3 = I_{SS} = 2I_1 = 100.53 \mu A}$$

$$\left(\frac{W}{L}\right)_1 = \left(\frac{W}{L}\right)_2$$

$$\left(\frac{W}{L}\right)_{1,2} = \frac{g_{m_{y_2}}}{\mu_n C_{ox} V_{ov_{1,2}}}$$

$$\rightarrow g_{m1} = g_{m2} = 5.0265 \times 10^{-4} \frac{A}{V}$$

$$\rightarrow = \frac{\left(5.0265 \times 10^{-4} \frac{A}{V}\right)}{\left(250 \times 10^{-6} \frac{A}{V^2}\right)(0.2V)}$$

$$V_{ov_1} = V_{ov_2} = 0.2V$$

$$K_N = \mu_n C_{ox} = 250 \frac{\mu A}{V^2}$$

$$\therefore \left(\frac{W}{L}\right)_{1,2} = 10.053$$

$$L_1 = L_2 = 0.5 \mu m$$

$$\left(\frac{W}{L}\right)_4 = \left(\frac{W}{L}\right)_5$$

$$\rightarrow W_{1,2} = (10.053)(0.5 \mu m)$$

For M4 and M5, $L = 1\mu m$

$$I_4 = I_5 = I_1 = 50.265 \mu A$$

$$\therefore W_{y_2} = 5.0265 \mu m$$

$$V_{ov_4} = V_{ov_5} = 0.2V$$

$$g_m = \mu_n C_{ox} \frac{W}{L}(V_{ov})$$

$$g_m = \frac{2 I_D}{V_{ov}}$$

Set both equations equal to each other

$$K_N = \mu_n C_{ox} = 250 \frac{\mu A}{V}$$

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

$$\therefore \left(\frac{W}{L}\right)_{4,5} = \frac{2 I_{4,5}}{K_n V_{ov}^2}$$

$$L_4 = L_5 = 1 \mu m$$

$$= \frac{2(50.265 \mu A)}{\left(250 \times 10^{-6} \frac{A}{V}\right)(0.2V)^2}$$

$$\therefore \left(\frac{W}{L}\right)_{4,5} = 10.053$$

$$\therefore W_{4,5} = 10.053 \mu m$$

$$\left(\frac{W}{L}\right)_{6-9}$$
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So for M_{6-9}, $L_{6-9} = 1 \mu m$

$\hookrightarrow V_{OV6-9} = 0.2V$

$I_{6-9} = 50.265 \mu A$

$K_p = \mu_p C_{ox} = 65 \mu \frac{A}{V^2}$

$g_m = \mu_n C_{ox} \frac{W}{L} (V_{ov})$

$g_m = \frac{2 I_D}{V_{ov}}$ $\Big\} \rightarrow$ Set both equations equal to each other

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

$\therefore \left(\frac{W}{L}\right)_{6-9} = \frac{2 I_{6-9}}{K_n V_{ov}^2}$

$= \frac{2 (50.265 \mu A)}{\left(65 \times 10^{-6} \frac{A}{V}\right)(0.2V)^2}$

$\therefore \left(\frac{W}{L}\right)_{6-9} = 38.665$
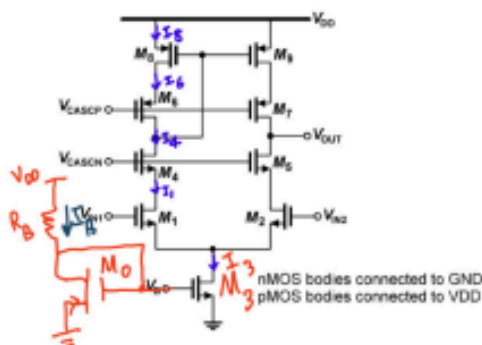
$\therefore W_{6-9} = 38.665 \mu m$
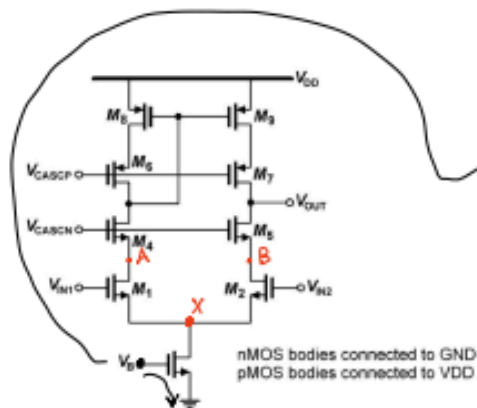
Fig. 3. Schematic of high-swing telescopic cascode op amp

The gain of the telescopic cascode op amp is given by $A_{DM} = g_{m1} R_o$, where $R_o = [g_{m5} r_{o5} r_{o6} \| g_{m7} r_{o7} r_{o9}]$ and its gain-bandwidth-product, GBW, is set by g_{m1}/C_L.

$V_B = V_{GS} = V_{THN} + V_{ovB}$

$\therefore V_B = 0.45 + 0.2 = 0.65V$

$\therefore V_B = 0.65V$

$W_{1,2}$ (redone)

Input referred noise was greater than $50 \mu Vrms$, so I increased $W_{1,2}$ and got the proper results

$\therefore W_{1,2} = (W_{1,2})(1.2) = (5.0265 \mu m)(1.2)$

$\rightarrow \therefore W_{1,2new} = 6.0318 \mu m$
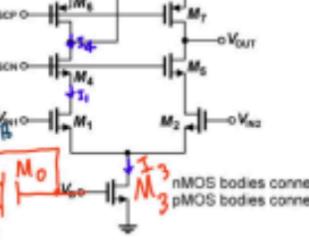
$g_{m,12} = 3.0159 \times 10^{-4}$

$L_{1,2} = 0.5 \mu m$

Fig. 3. Schematic of high-swing telescopic cascode op amp

The gain of the telescopic cascode op amp is given by $A_{DM} = g_{m1} R_0$, where $R_0 = [g_{m7} r_{o7} r_{o5} \| g_{m3} r_{o3} r_{o1}]$ and its gain-bandwidth-product, GBW, is set by g_{m1}/C_L.

$$\frac{\left(\frac{W}{L}\right)_3}{}$$

$$I_{SS} = 100.53\,\mu A = I_3$$

$$2 I_3 = \mu_n C_{ox} \left(\frac{W}{L}\right)_3 V_{OV3}^2$$

$$L_3 = 1\,\mu m$$

$$\left(\frac{W}{L}\right)_3 = \frac{2 I_3}{\mu_n C_{ox} V_{OV3}^2}$$

$$= \frac{2(100.53\mu)}{(250\mu)(0.2)^2}$$

$$\boxed{\therefore \left(\frac{W}{L}\right)_3 = 20.106}$$

$$\boxed{\therefore W_3 = 20.106\,\mu m}$$

$$\therefore I_B < 54.55\,\mu A$$

$$\hookrightarrow Let\ I_B = 50\,\mu A$$

$$\frac{I_3}{\left(\frac{W}{L}\right)_3} = \frac{I_B}{\left(\frac{W}{L}\right)_0}$$

$$\hookrightarrow \left(\frac{W}{L}\right)_0 = \left(\frac{W}{L}\right)_3 \frac{I_B}{I_3}$$

$$\hookrightarrow \left(\frac{W}{L}\right)_0 = (20.106)\left(\frac{50}{100.53}\right) = 10 \longrightarrow L_0 = 1\,\mu m$$

$$\boxed{\therefore W_0 = 10\,\mu m}$$

$$I_0 = \frac{1}{2} K_n \left(\frac{W}{L}\right)_0 (V_{OV0})^2 \to V_{OV0} = \sqrt{\frac{2I}{K_n\left(\frac{W}{L}\right)_0}} = \sqrt{\frac{2\times 50}{250\times 10}} = 0.2V$$

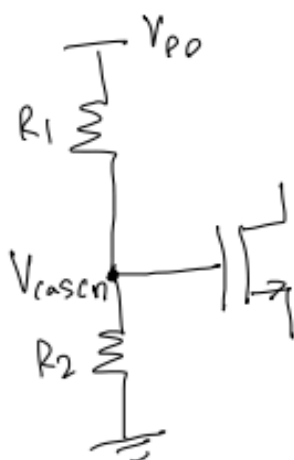$$\boxed{V_{GS0} = V_{OV0} + V_{THO} = 0.2 + 0.45 = 0.65}$$

$$V_{GSO} = V_{DO} - I_B R_B = 1.8 - (50 \times 10^{-6}) R_B$$

$$\hookrightarrow 0.65 = 1.8 - (50 \times 10^{-6}) R_B$$

$$\therefore R_B = 23 K \Omega$$

V_{cascn} and V_{cascp} Biasing Circuits
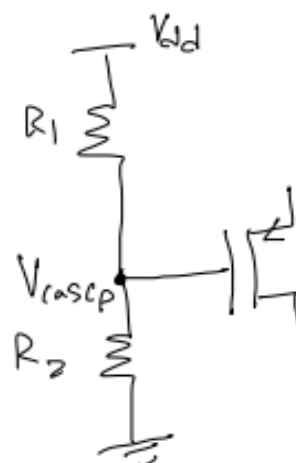
$V_{cascn} = 1.35 V \longleftarrow$ gotten from simulation

$$V_{cascn} = V_{DD} \left(\frac{R_2}{R_1 + R_2} \right) \rightarrow \frac{R_2}{R_1 + R_2} = \frac{1.35}{1.8} = \frac{3}{4} = \frac{3K}{(3+1)K} \begin{array}{l} \nearrow R_{2n} = 3K\Omega \\ \searrow R_{1n} = 1K\Omega \end{array}$$

$V_{cascp} = 0.7 V \longleftarrow$ gotten from simulation

$$V_{cascn} = V_{DD} \left(\frac{R_2}{R_1 + R_2} \right) \rightarrow \frac{R_2}{R_1 + R_2} = \frac{0.7}{1.8} = \frac{7}{18} = \frac{7K}{7K + 11K} \begin{array}{l} \nearrow R_{2p} = 7K\Omega \\ \searrow R_{1p} = 11K\Omega \end{array}$$

Part II. - Continued

NEF

$$NEF = V_{n,in,RMS} \cdot \sqrt{\frac{2I_{tot}}{\pi \cdot U_T \cdot 4kT \cdot BW}}$$

$$\frac{I_{tot}}{I_3}$$

$$I_{tot} = I_{tail} + I_B + \frac{V_{pp}}{R_{1,p} + R_{2,p}} + \frac{V_{DD}}{R_{1,n} + R_{2,0}}$$

$$= 100.53 \mu A + 50 \mu A + \frac{1.8}{18k} + \frac{1.8}{4k}$$

$$V_{n,in,RMS} < 50 \mu V_{RMS}$$

$$\rightarrow \therefore V_{n,in,RMS} = 50 \mu V_{RMS}$$

$$\boxed{\therefore I_{tot} = 7.0053 \times 10^{-4}}$$

$$U_T = 25.9 mV$$

$$k = 1.3806 \times 10^{-23} \ J/K$$

$$T = 300K \leftarrow kelvin$$

$$BW = 80k - 8 = 79.992 KHZ$$

$$NEF = (50 \times 10^{-6}) \sqrt{\frac{2(7.0053 \times 10^{-4})}{\pi (25.9 \times 10^{-3})(4)(1.3806 \times 10^{-23})(300)(79.992k)}}$$

$$\boxed{\therefore NEF = 180.23}$$

Part II. - Continued

$\underline{V_{casc,N}}$

$V_{DS2} = V_{ov,2} \nearrow 0.2$

$V_{D_2} - V_{S2} = V_{ov,2}$

$V_{D2} = V_{ov,2} + V_{S2} = 0.2 + 0.2 = 0.4 V = \underline{V_{SS}}$

$V_{GS5} = V_{THN} + V_{ov,5} = 0.45 + 0.2 = 0.65 V$

$\hookrightarrow V_{CASCN} = V_{SS} + V_{GS5} = 0.4 + 0.65 = 1.05 V$

$\boxed{\therefore V_{cascN} = 1.05 \, V}$

$\underline{V_{casc,P}}$

$V_{SD8} \approx V_{ov,8} = 0.2 \, V$

$V_{S6} = V_{DD} - V_{SD8} = 1.8 - 0.2 = 1.6 \, V$

$V_{SG6} = |V_{THP}| + V_{ov,6} = 0.45 + 0.2 = 0.65 V$

$\rightarrow V_{cascp} = V_{G6} = V_{S6} - V_{SG6} = 1.6 - 0.65 = \underline{\underline{0.95 \, V}}$

$\boxed{\therefore V_{cascp} = 0.95 V}$

Design (Part II) - Continued

Table D1

Parameter	Calculated value
V_{CASCP} (V)	0.7
V_{CASCN} (V)	1.35
NEF	180.23
I_{tot} (µA)	700.53
$(W/L)1,2$	12.0636
$L_{1,2}$ (µm)	0.5
$(W/L)4,5$	10.053
$(W/L)6-9$	38.665
$(W/L)3$	20.106
$(W/L)0$	10
$L_{0, 3-9}$ (µm)	1
R_B (Ω)	23
$I_3 = I_{SS}$ (µA)	100.53
V_{OV} (V)	0.2
I_D (µA)	50.265

V_B (V)	0.65
$R_{1n}(\Omega)$	1K
$R_{2n}(\Omega)$	3K
$R_{1p}(\Omega)$	11K
$R_{2p}(\Omega)$	7K
I_B (μA)	50

Simulations

4. Performance Evaluation

Telescopic cascode op amp (designed circuit schematic)
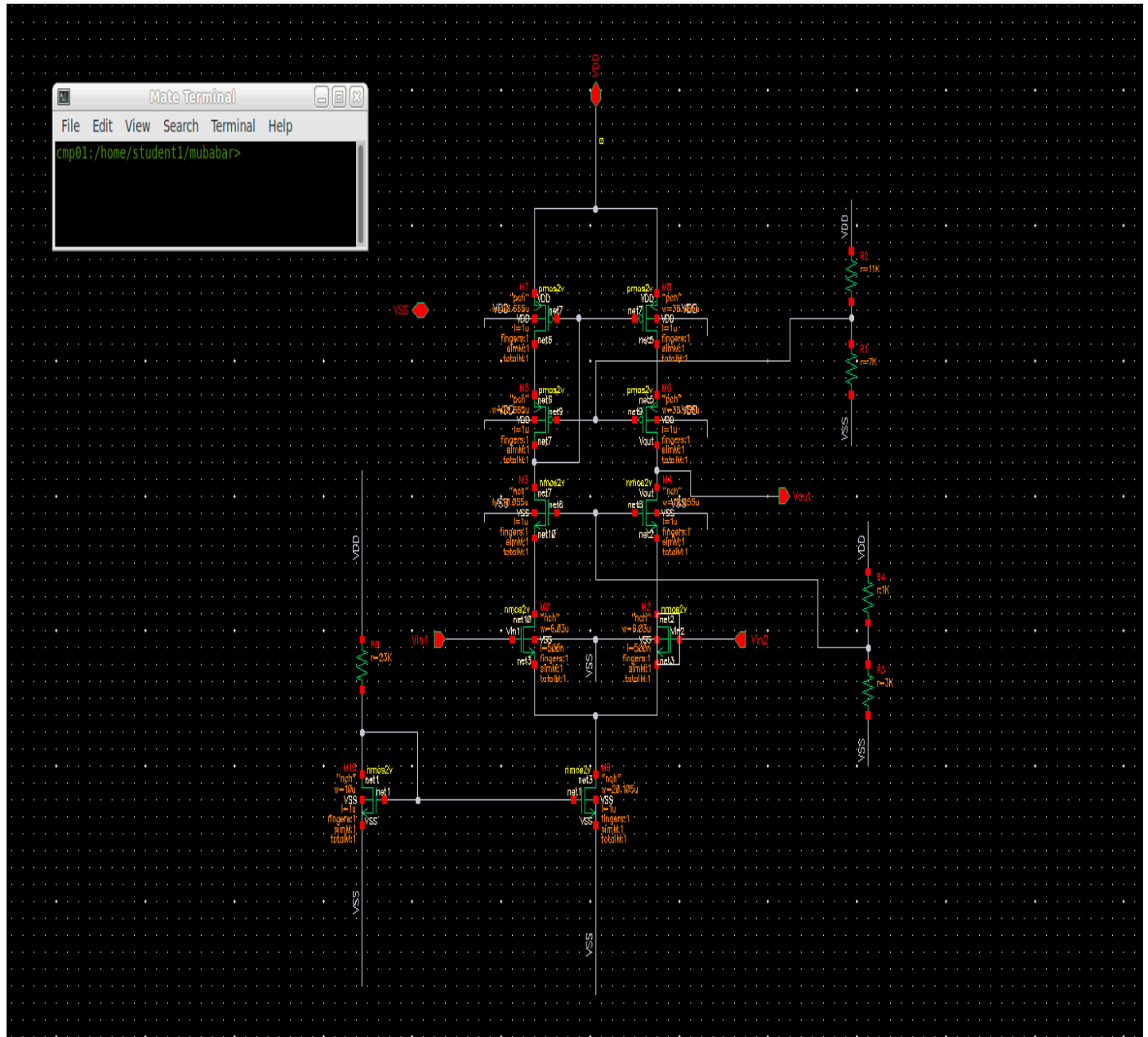
4.1 - OP AMP

For these simulations use a balun to convert a single-ended input signal to a differential-ended signal. The CM value should be set for maximum op amp gain.

i. DC operating points, open-loop gain and DC sweeps. At this step, use parametric analysis to find the optimal value of V_{CASCN} that results in the highest gain (**Setup: Fig. 5**)
ii. Output swing (**Setup**: Fig. 6)
iii. Slew rate (**Setup**: Fig. 7)
iv. Output impedance (**Setup**: Fig 8)

I.

Fig 5. Schematic along with DC operating points
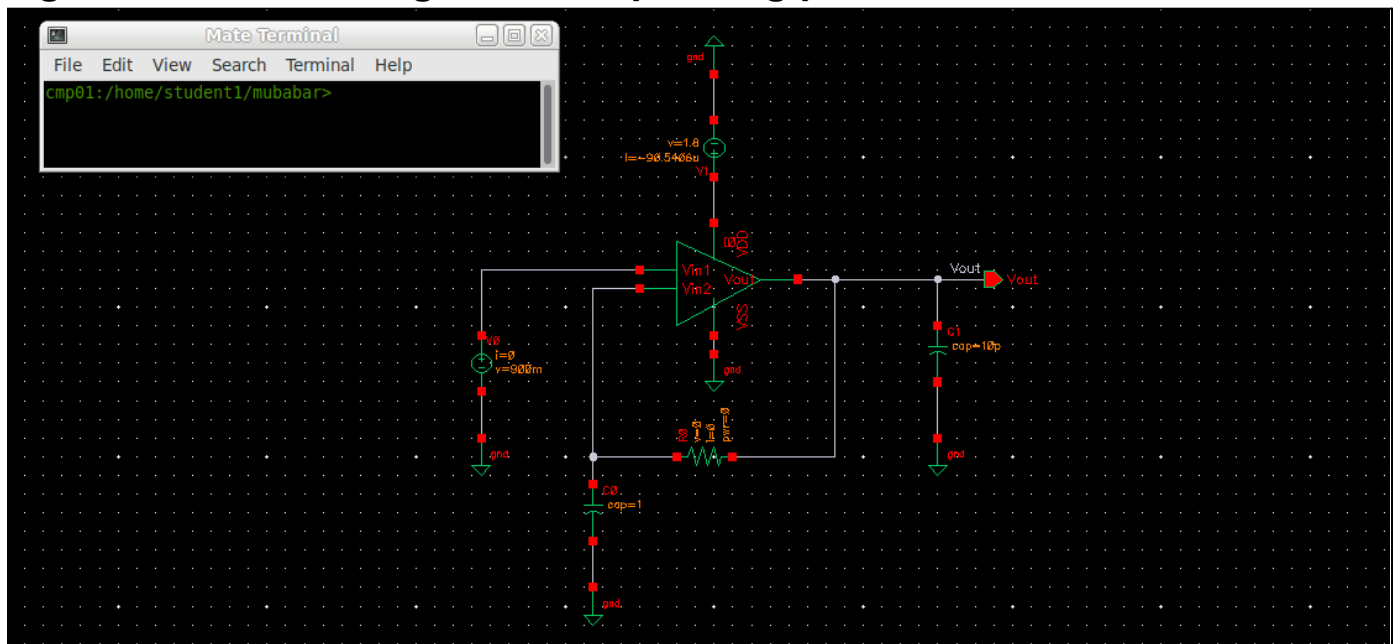
I. - Continued

OP AMP magnitude plot
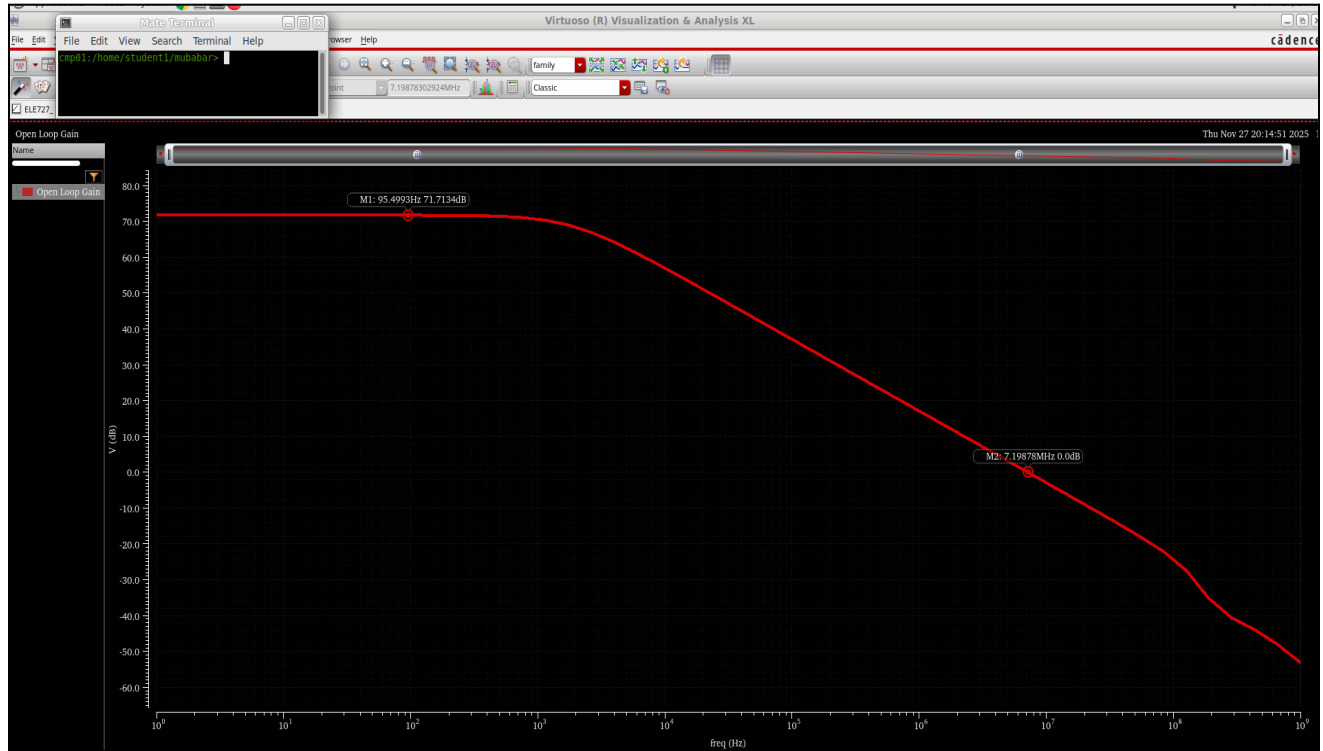
Therefore, from the markers:

Simulated OP AMP Open-Loop Gain = **71.7134 dB**

Calculated Open-loop Gain = **80 dB**

Simulated GBW = **7.1988 MHz**

Calculated GBW = **50.265 MHz**

Although our simulated Open Loop Gain is a little off from our calculated one, after many trials and errors and testing, this was the closest I was able to get. The simulated lower gain is mainly due to imperfections of the PDK devices compared to the ideal long-channel model used in the hand calculations. Despite the lower open-loop gain, when the amplifier is inserted in the CCIA (Fig. 4), the closed-loop gain accuracy remains above 99%, and all other specifications (bandwidth, input impedance, and slew rate) were achieved.

I. - Continued

Vcascn Parametric Analysis
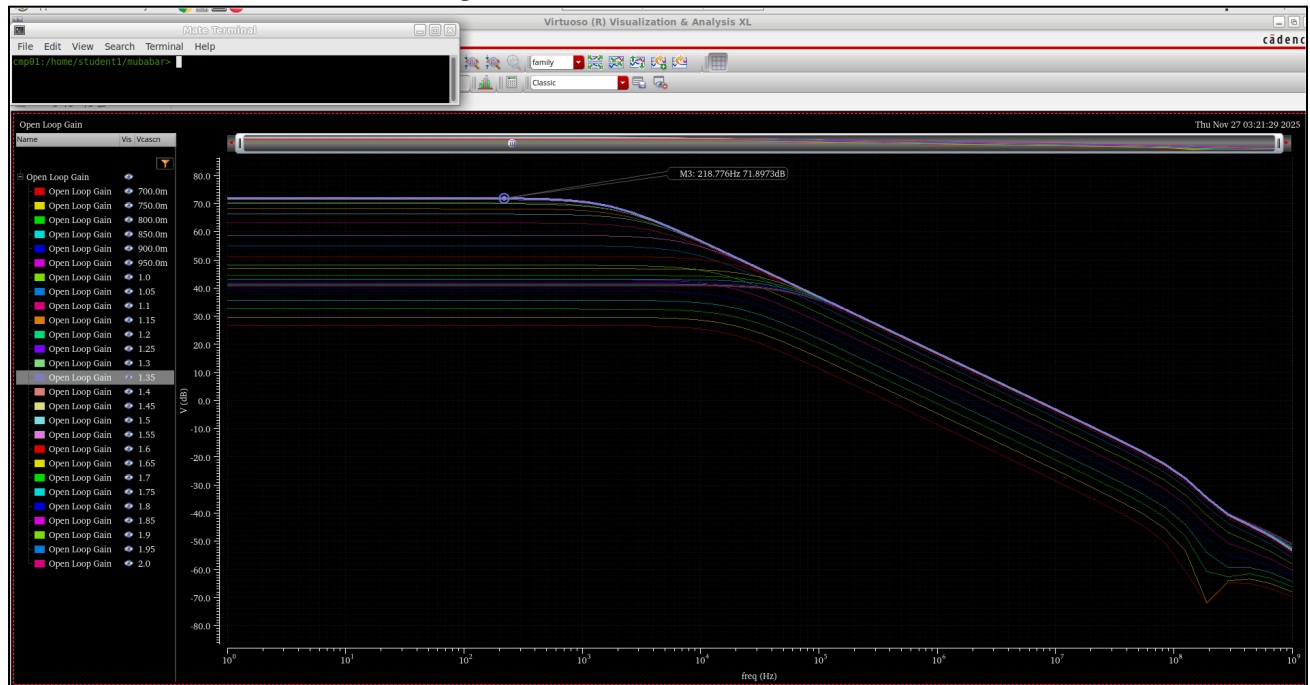
Looking at the Parametric analysis above, it is clear that the optimal value of Vcascn that results in the highest gain is 1.35 V.

Therefore, Vcascn = **1.35 V**, where Open Loop Gain = **71.8973 dB**
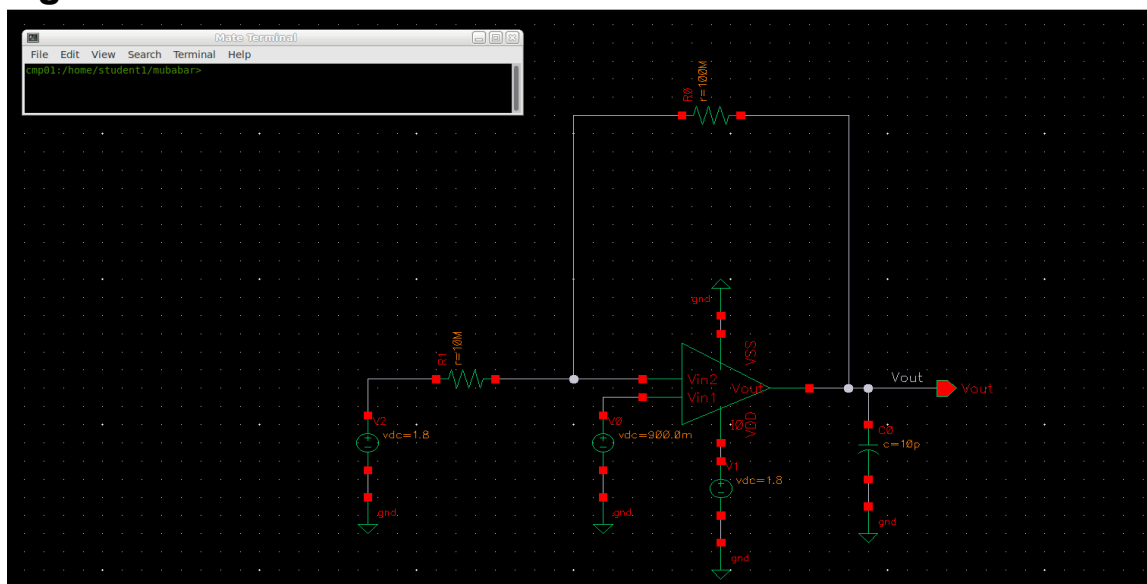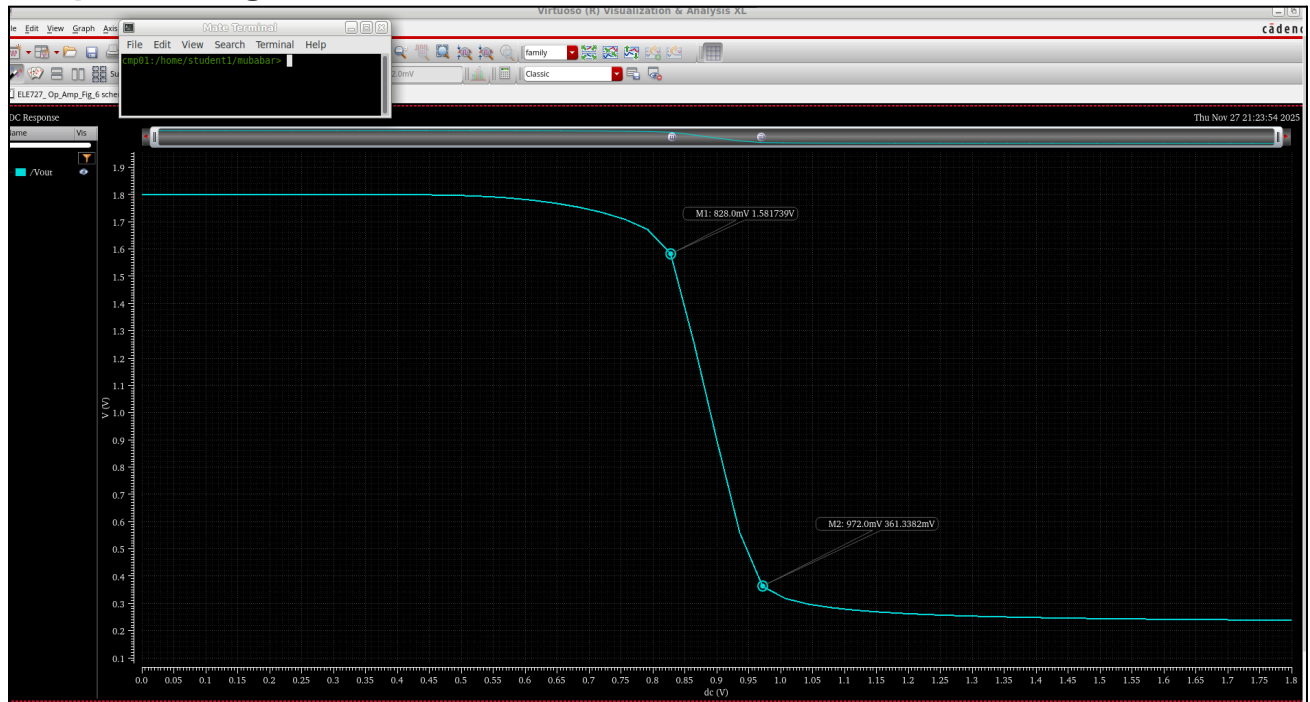
I. - Continued

Vcascp Parametric Analysis
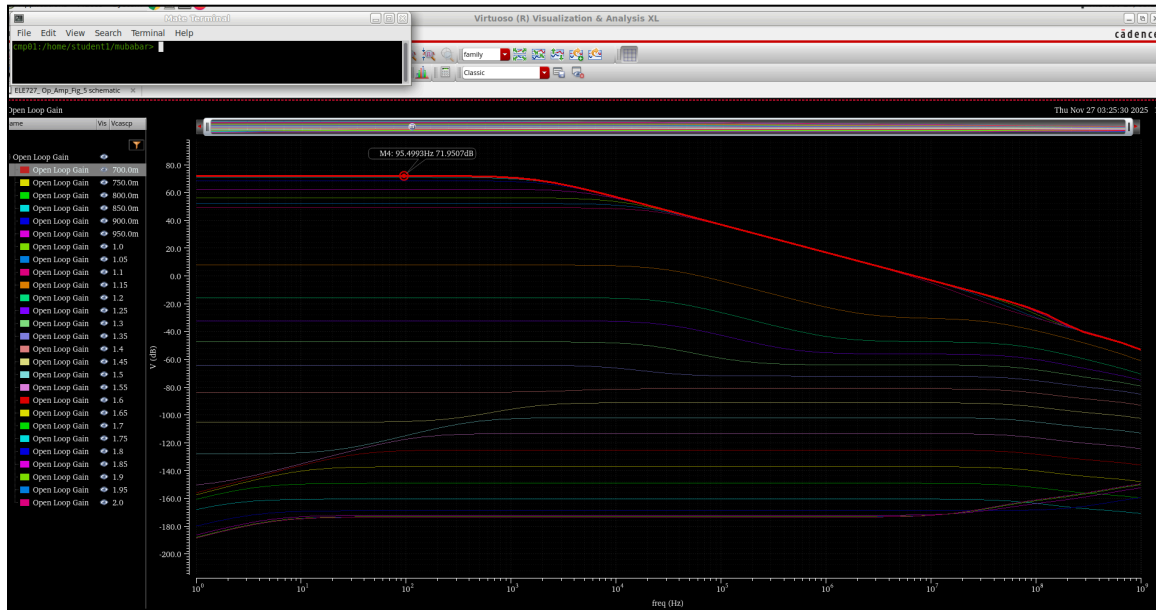
Looking at the Parametric analysis above, it is clear that the optimal value of Vcascp that results in the highest gain is 0.7 V.

Therefore, Vcascn = **0.7 V**, where Open Loop Gain = **71.9507 dB**

II.

Fig 6. Schematic

II. - Continued

Output Voltage Plot

Looking at the linear region of the output voltage waveform, we can calculate the simulated output voltage swing:

$V_{Out,max}$ **= 1.581739 V**
$V_{out,min}$ **= 0.3613382 V**

$V_{Out, max}$ **-** $V_{Out, min}$ **> 0.5 Vpp**

→ **1.2204008 Vpp > 0.5 Vpp**

Hand Calculated Output swing = 0.8 Vpp

Although the calculated and simulated values differ slightly, because the design requirement is met, there are very few issues or concerns about this discrepancy.

Therefore, the **Output swing = 1.22 Vpp**, which meets the design requirement for the Output swing to be greater than **0.5 Vpp**.

II. - Continued

From our design specifications, A_{mid} = 100 V/V, meaning the output in the linear region is around 100 times that of the input voltage.

Moreover, our input was 10 mV, and the output was 1.22 Vpp, which is around 122 times the input, meaning it comes very close to the required Mid-band gain.

Overall, after the initial settling, the waveform becomes steady, stable, and regular, with no signs of clipping or distortion.
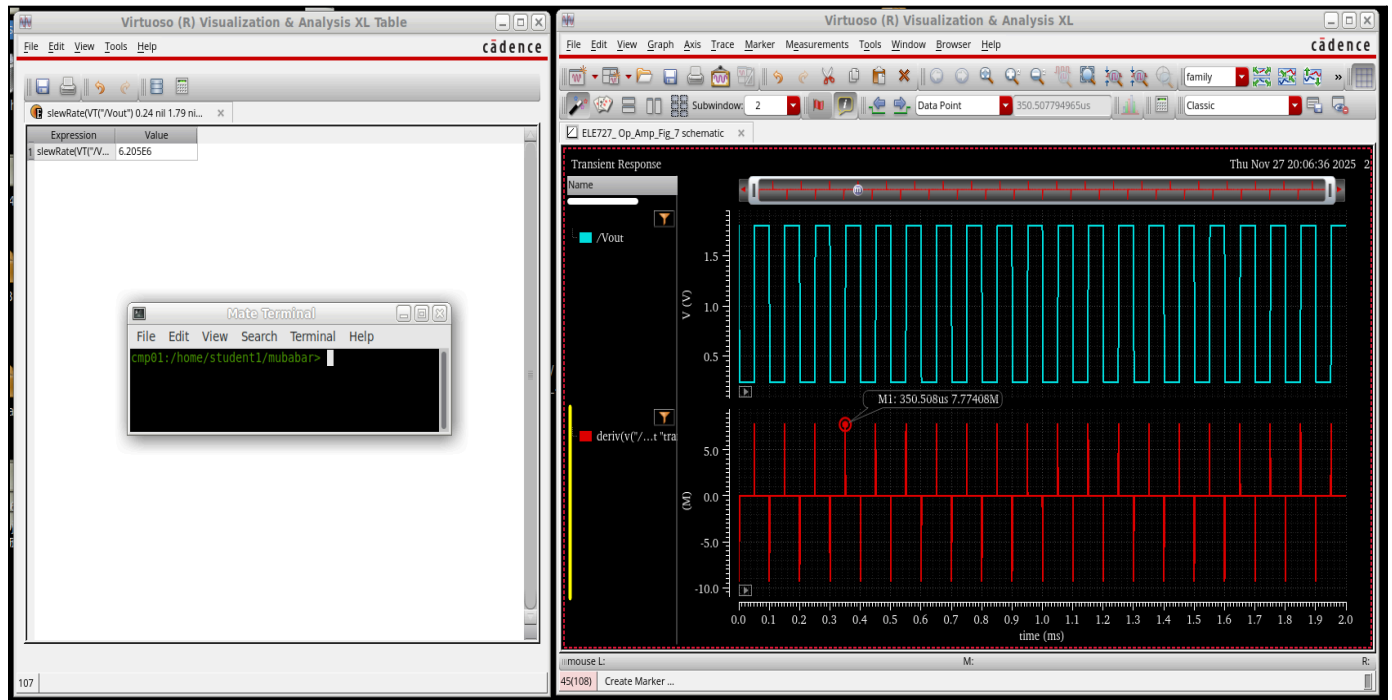
III.

Fig 7. Schematic
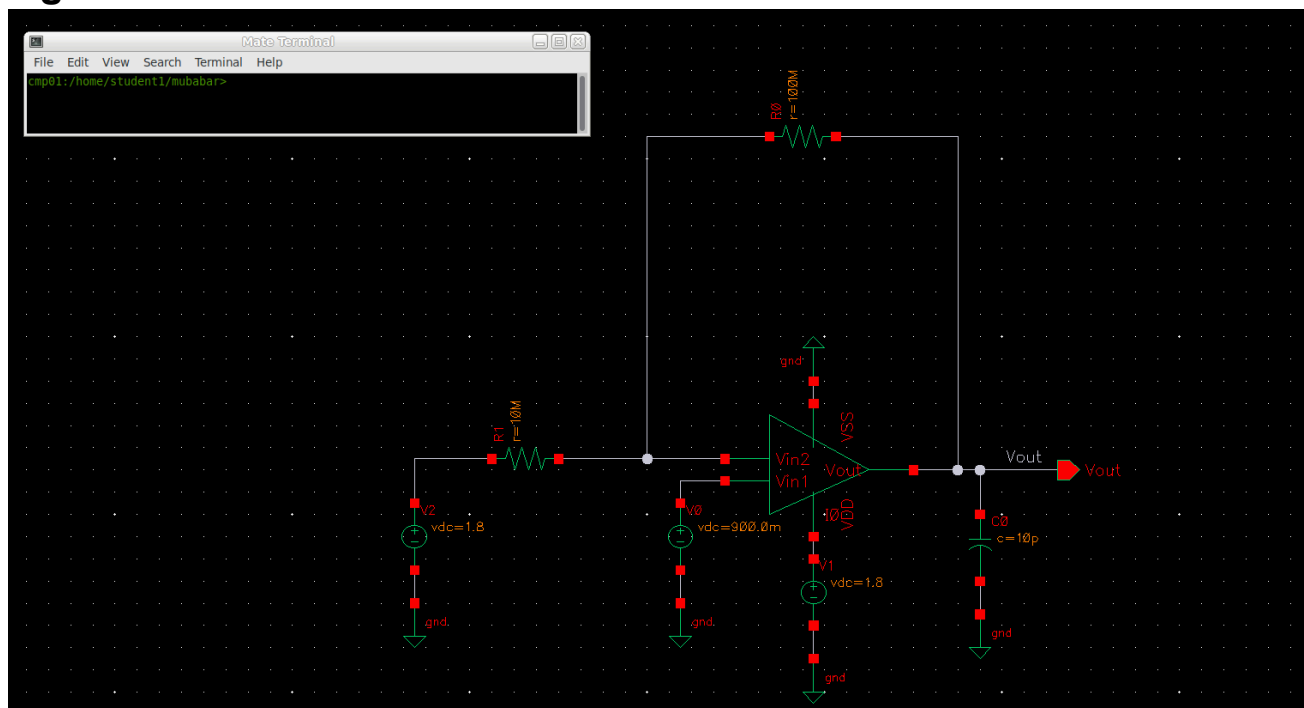
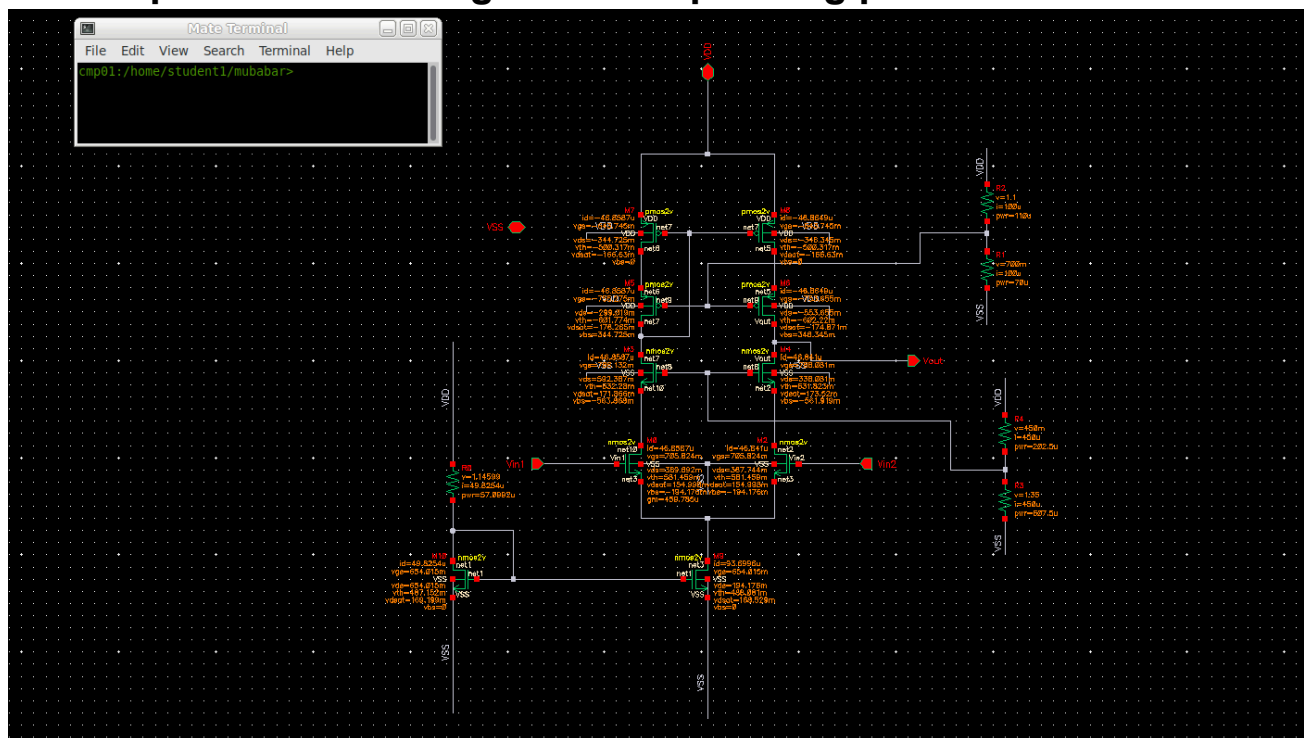## Slew Rate Simulation

Looking at our simulation results above:

The **<u>Slew rate</u>** = **6.205** $\frac{V}{us}$, which is much greater than **0.1** $\frac{V}{us}$, meaning that the slew rate specification was successfully achieved.

IV.

Fig 8. Schematic along with DC operating points
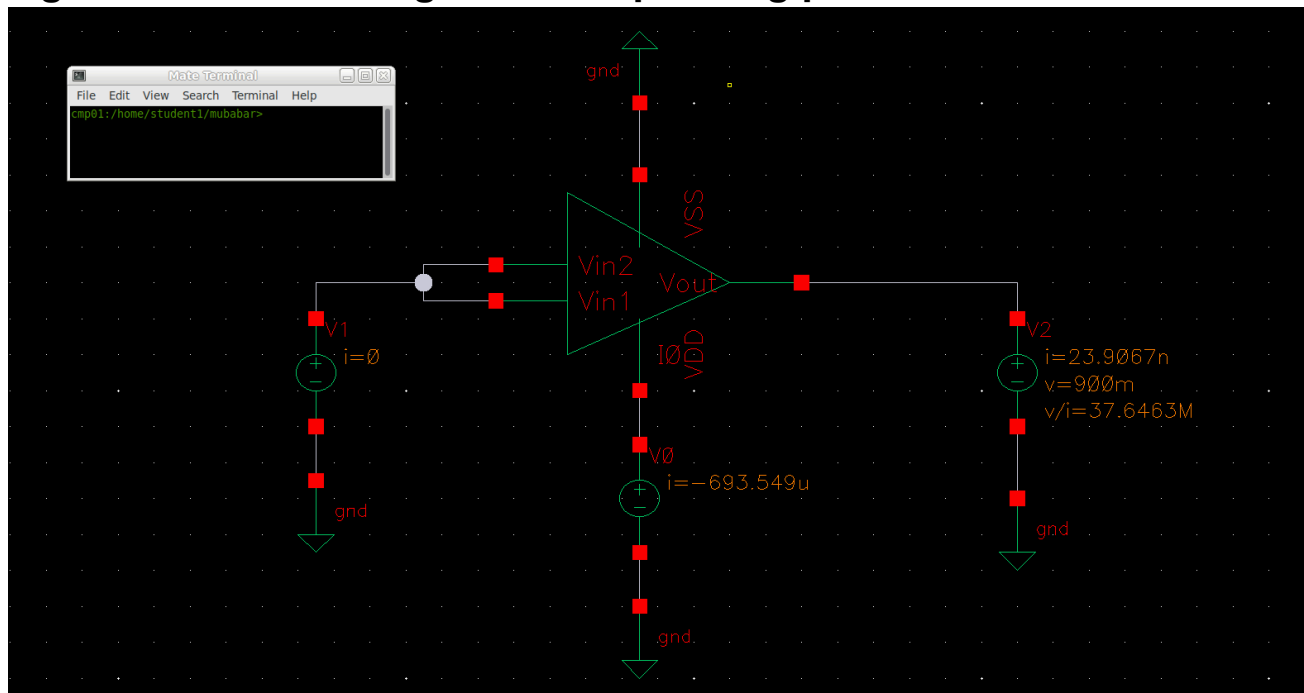
Telescopic OP AMP along with DC operating points

IV. - Continued

Therefore, from the above two schematics and their DC operating points:

Simulated Input Impedance, Rout = 37.6463 MΩ

Calculated Input Impedance, Rout = 19.6956 MΩ

Simulated Gm_1 = 459.785u S = 4.59785×10^{-4} S

Calculated G_{m1} = 5.0265×10^{-4} S

Using these 2 simulated Values, we can calculate the Open-Loop Gain (A_{OA}):

A_{OA} = G_{m1}*Rout = (37.6463M)*(4.59785×10^{-4}) =17309.20405

αAmid = $\frac{Aoa}{1 + B*Aoa}$ = $\frac{17309.20405}{1 + (0.01*17309.20405)}$ = 99.4256 → α = $\frac{99.4256}{100}$ x 100% = 99.4256 % > 99 %

Therefore, since the gain accuracy is over 99 %, the design requirement for the gain accuracy has been successfully achieved.

Moreover, although the input impedance and G_{m1} values differ quite a bit from our calculated values, because the design requirement is met, there are very few issues or concerns about this discrepancy.

4.2 - CCIA

For these simulations use a balun to convert a single-ended input signal to a differential-ended signal. The CM value should be set for maximum op amp gain.

    i.   AC gain and phase
    ii.   Transient analysis with input signal $V_{IN} = 10 \cdot \cos{(2\pi f_c t)}$ [mV], where f_c is the center frequency of the CCIA bandwidth
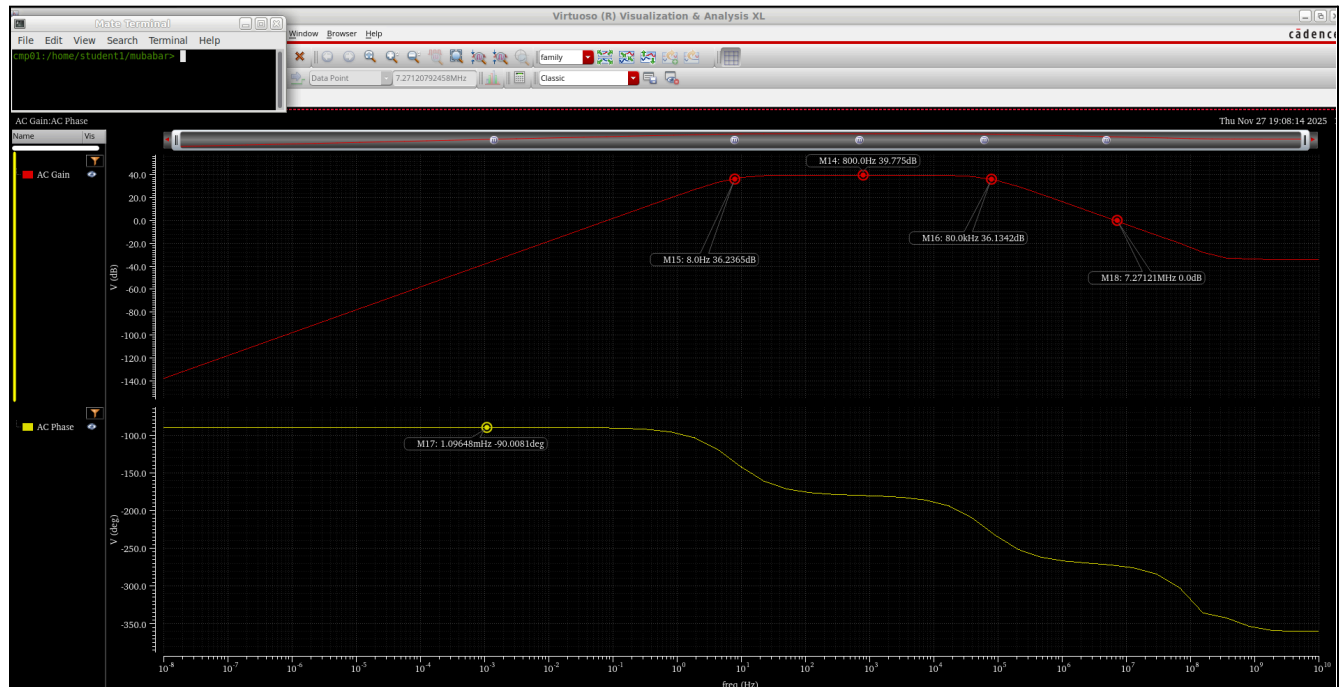   iii.   Signal spectrum (FFT)
    iv.   Noise spectral density

I.

Fig 4. Schematic with designed OP AMP
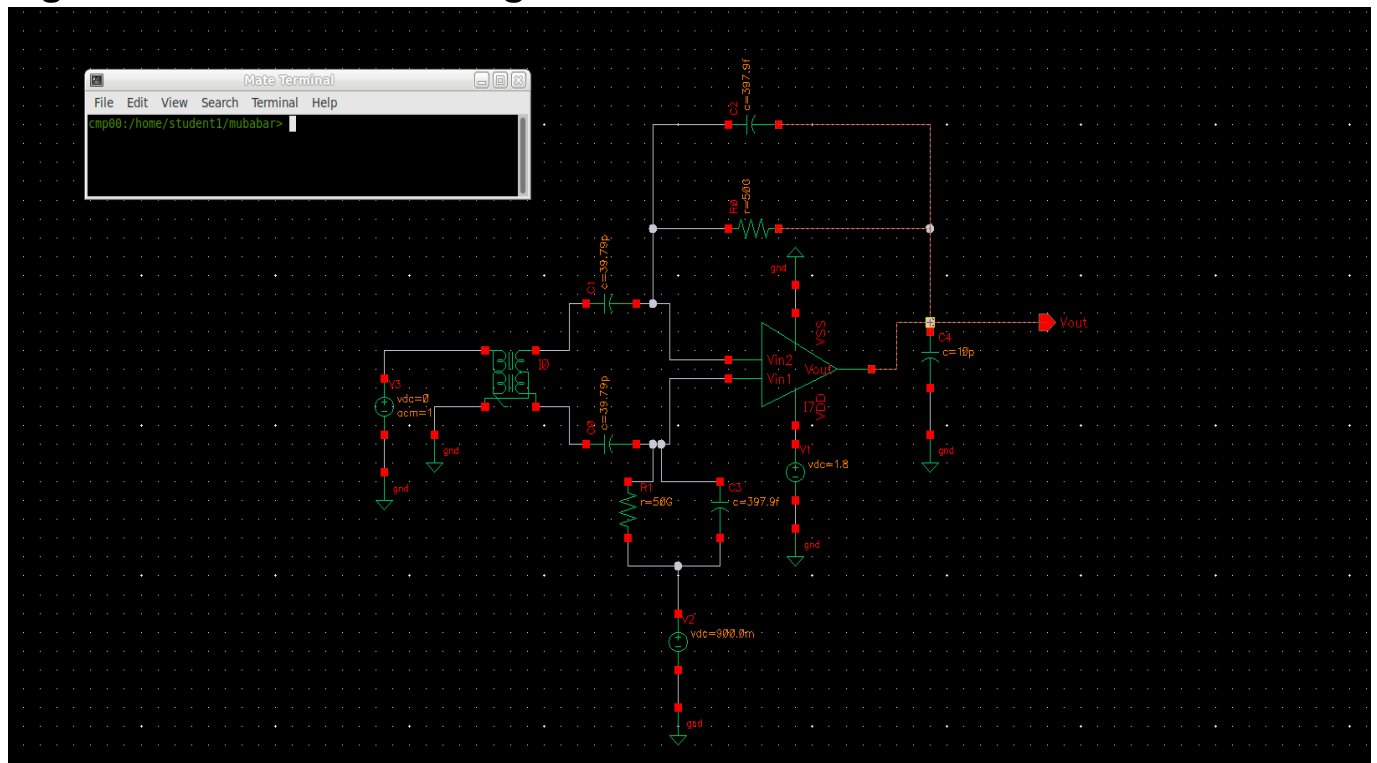
I.- Continued

CCIA AC GAIN AND PHASE

$f_C = \sqrt{fl * fh} = \sqrt{8 * 80k}$ = 800 Hz @ 39.775 dB

f_L = 8 Hz @ 36.2365 dB

f_C = 80 kHz @ 36.1342 dB

Phase = -90 degrees @ 1.09648 mHz

Analyzing the waveform above, both points that are 3db below the Mid-band gain are at 8 Hz and 80 kHz, which perfectly match up with our design requirements, meaning that the bandwidth requirement has been successfully achieved. Moreover, comparing the waveform above with the waveform done for the CCIA test setup with the ideal Op Amp, both the AC gain and phase are pretty much the same for both simulations, with very little discrepancy.

Fig 4. Schematic (with Vsin source) with designed OP AMP
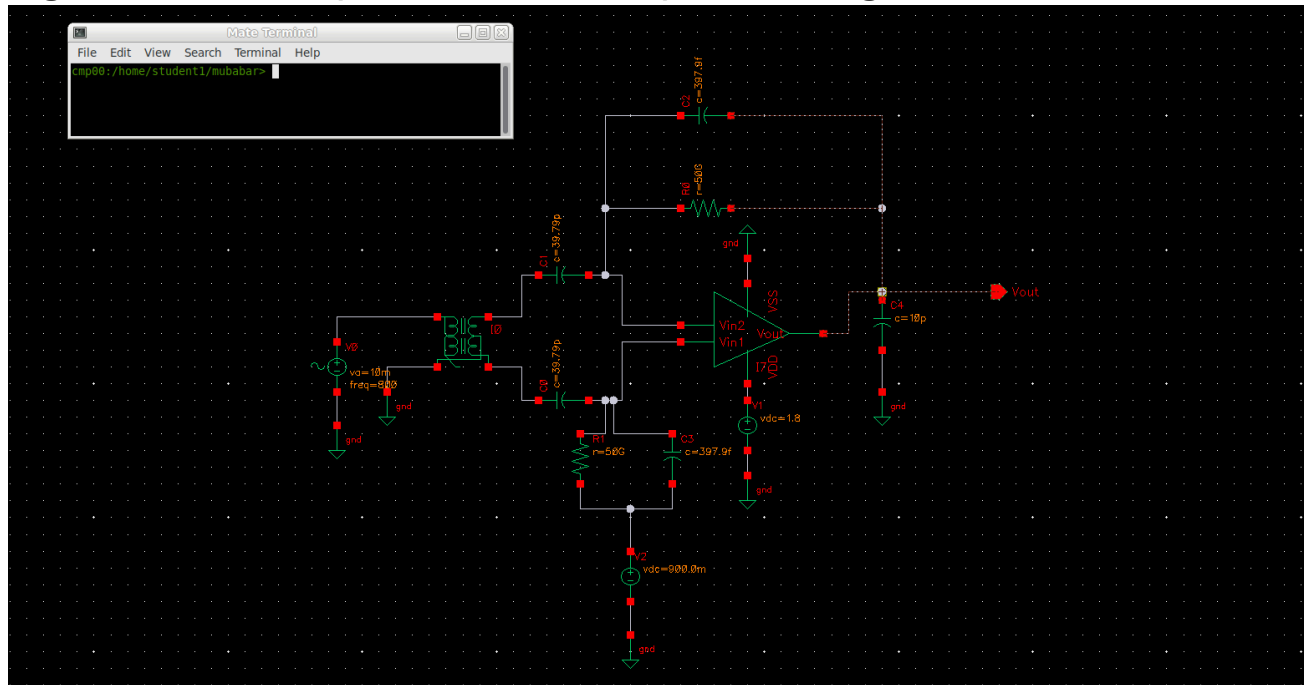
CCIA Transient Output Waveform
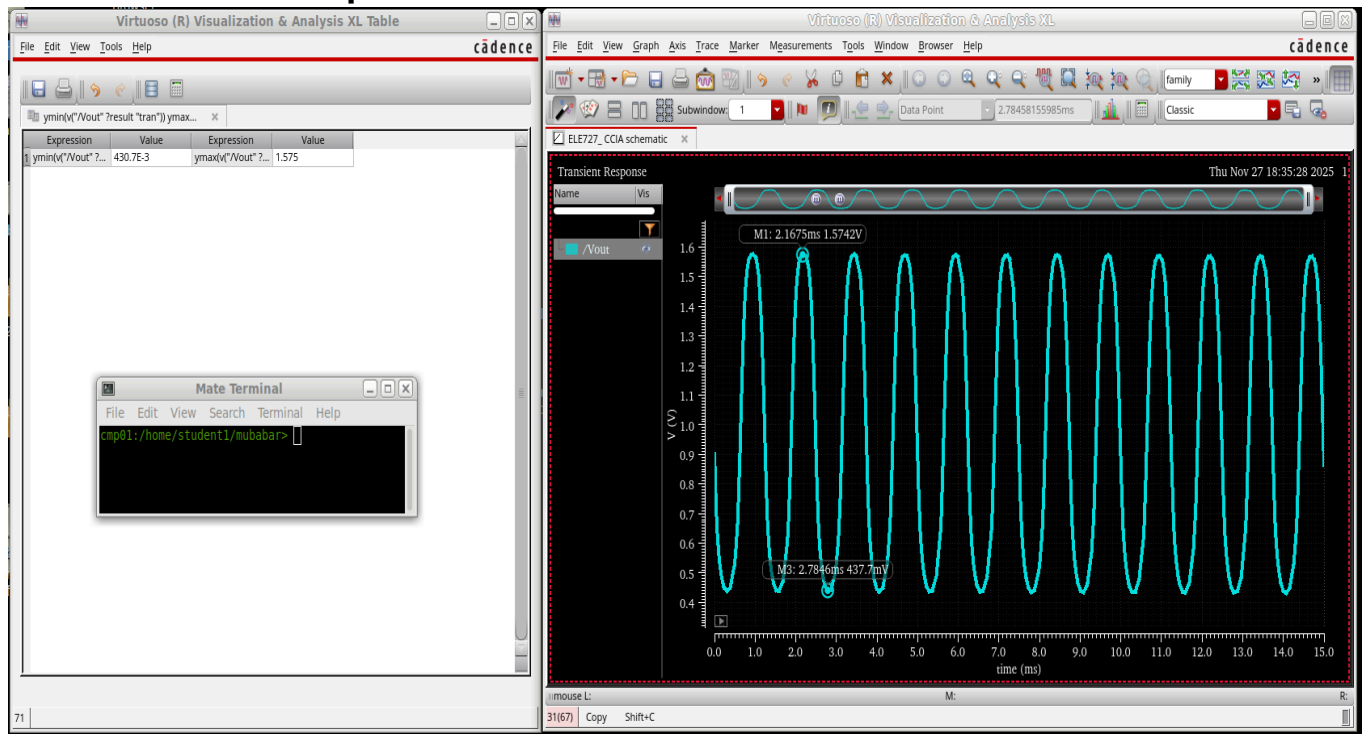
II.- Continued

From the Waveform above:

$V_{out, p-p} = V_{out,max} - V_{out,min} = 1.575\ V - 0.4307\ V = 1.1443\ Vpp > 0.5\ Vpp$

Therefore, because the output swing is greater than 0.5 Vpp, the output swing requirement was successfully achieved. Compared to the found Output swing value of 1.22 V in the Op Amp performance analysis, both values are quite close to each other, with very small discrepancy.

Hand Calculated Output swing = 0.8 Vpp

Although the calculated and simulated values differ slightly, because the design requirement is met, there are very few issues or concerns about this discrepancy.

From our design specifications A_{mid} = 100 V/V, meaning output in the linear region is around 100 times that of the input voltage.

Moreover, our input was 10 mV, and the output was 1.1443 Vpp, which is around 114.43 times the input, meaning it comes very close to the required Mid-band gain.
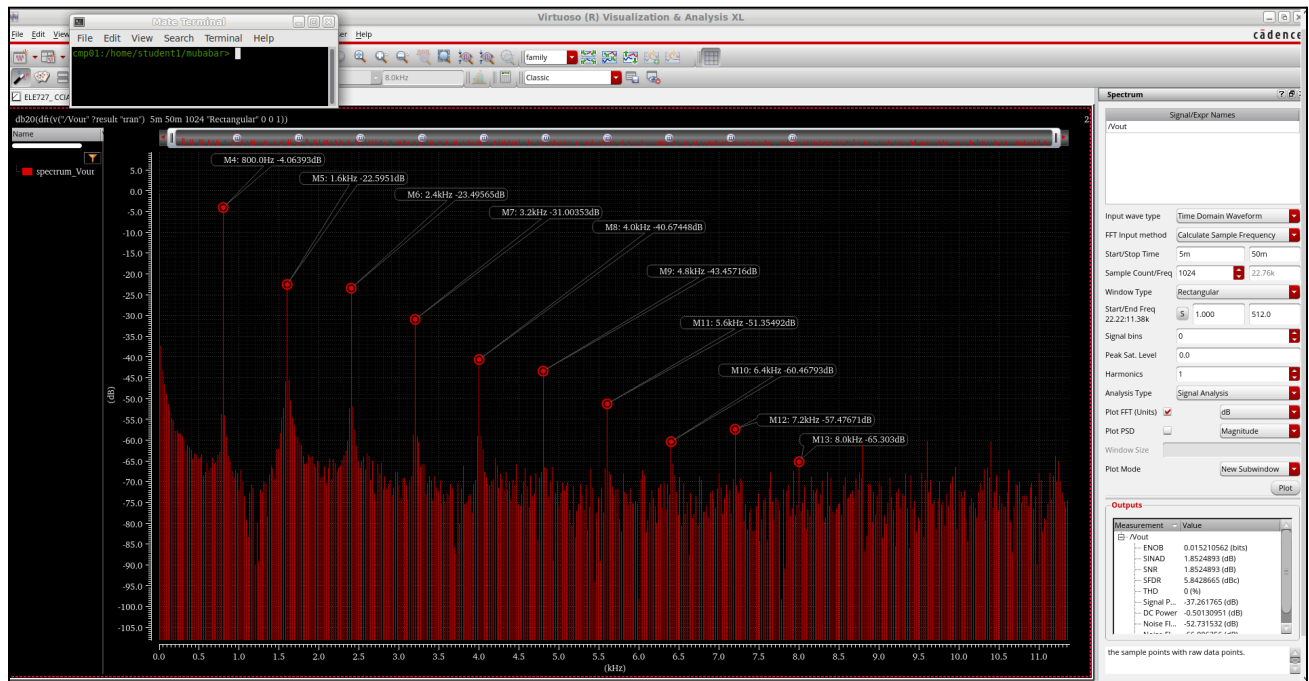
Overall, after the initial settling, the waveform becomes steady, stable, and regular, with no signs of clipping or distortion.
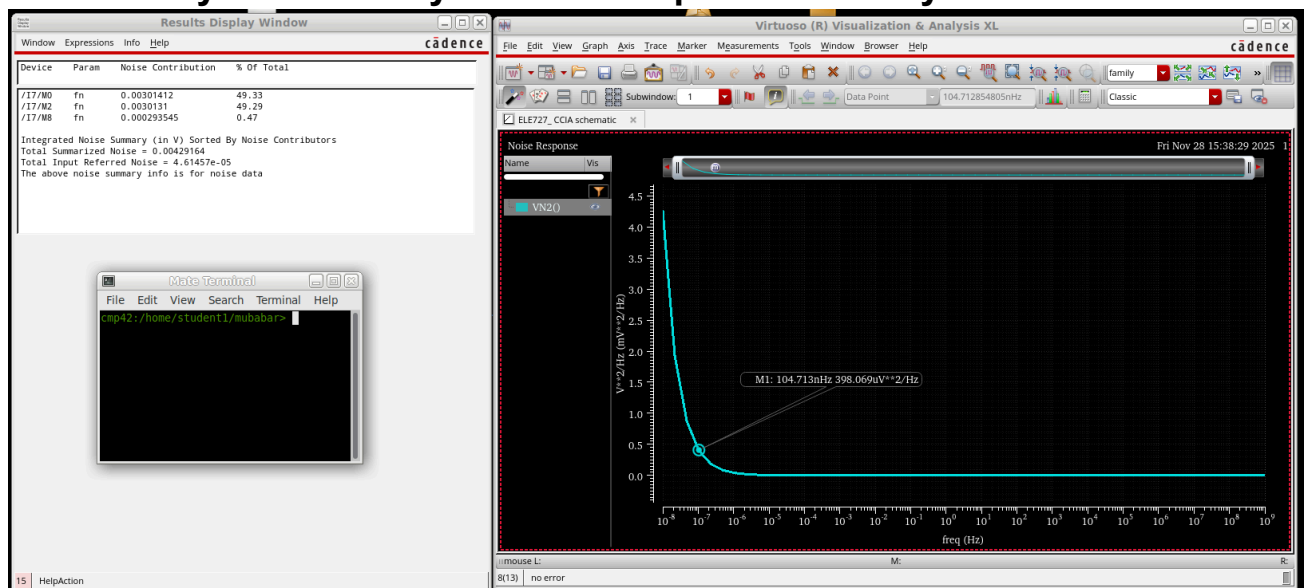
III.

Signal Spectrum (FFT)
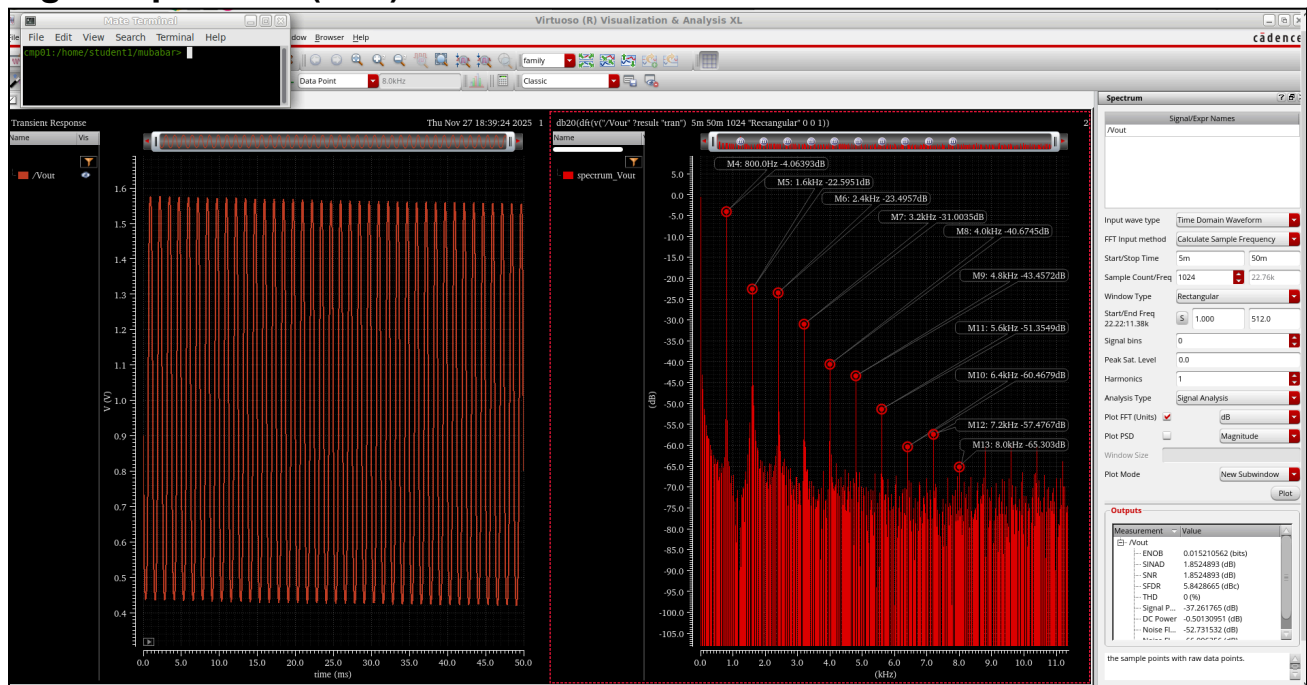
III. - Continued

Looking at the FFT spectrum at f_C = 800 Hz above, there is a strong peak at my center frequency of 800 Hz, with an amplitude of -4.06393 dB. Therefore, there are peaks at $2f_C$, $3f_C$, $4f_C$, and so on.

IV.

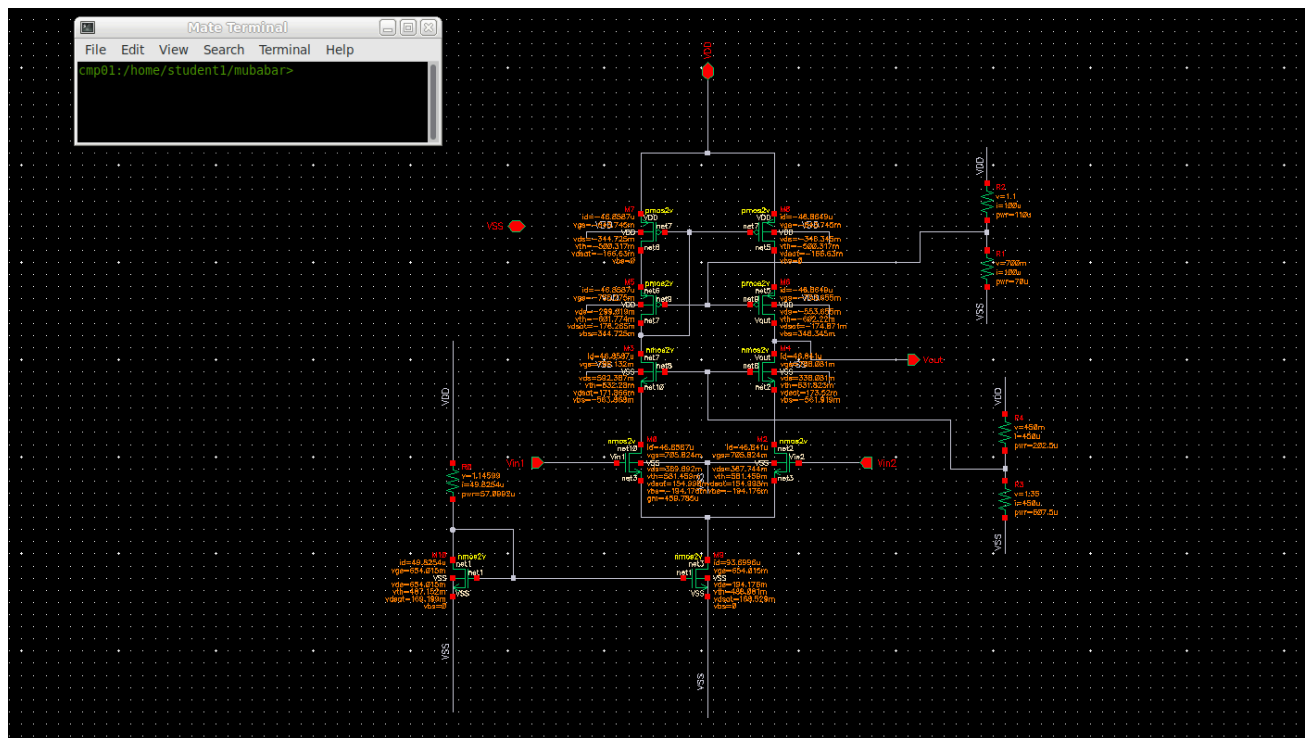# Noise Analysis Summary and Noise Spectral Density

IV - Continued.

From the noise analysis above:

Total input-referred noise ($V_{n,in,RMS}$) = 46.1457 uV$_{RMS}$ < 50 uV$_{RMS}$

Therefore, since the simulated total input-referred noise is less than 50 uV$_{RMS}$, the input-referred noise design requirement has been successfully achieved.

From this, we can calculate the simulated NEF:

$I_{tot} = I_B + I_3 + I_{CASCN} + I_{CASCP}$ = 49.8254 uA + 93.6996 uA + 450 uA + 100 uA
 = 6.93525 x 10^{-4} A

P = V_{DD} (I_B) = 1.8*(49.8254 uA) = 89.68572 uW < 100 uW

Therefore, as you can see above, the total power consumption of 89.68 μW is lower than 100 μW, successfully achieving the requirements for Power consumption of less than 100 μW.

IV - Continued.

Simulated NEF calculation

NEF

$$NEF = V_{n,in,RMS} \cdot \sqrt{\frac{2I_{tot}}{\pi \cdot U_T \cdot 4kT \cdot BW}}$$

I_{tot}

$$I_{tot} = 6.93525 \times 10^{-4} A$$

$$V_{n,in,RMS} < 50 \mu V_{RMS}$$

$$\rightarrow \therefore V_{n,in,RMS} = 46.1457 \mu V_{RMS}$$

$$U_T = 25.9 mV$$

$$k = 1.3806 \times 10^{-23} \ J/K$$

$$T = 300 K \leftarrow Kelvin$$

$$BW = 80K - 8 = 79.992 KHz$$

$$NEF = (46.1457 \times 10^{-6}) \sqrt{\frac{2(6.93525 \times 10^{-4})}{\pi (25.9 \times 10^{-3})(4)(1.3806 \times 10^{-23})(300)(79.992k)}}$$

$$\rightarrow \boxed{\therefore NEF = 165.5}$$

Comparing the simulated and hand-calculated values for NEF, the values of 165 and 180 are very close, with a small discrepancy. Moreover, although the simulated values differ quite a bit from our calculated values, because the design requirement is met, there are very few issues or concerns about this discrepancy.

5. Discussion & Conclusion

Discuss your design procedure, simulation results, challenges, tradeoffs and potential solutions. Compare the performance of the CCIA using a macromodel to the one using the op amp you have designed.

The Capacitively Coupled Instrumentation Amplifier (CCIA) design successfully verified the overall design procedure by meeting most of the project specifications. The design procedure focused on implementing the core Op-Amp as a single-ended high-swing telescopic cascode, and the successful outcome for bandwidth and stability confirmed this choice. However, the simulation process required constant adjustments to achieve the requirements. The most significant of these was the input-referred noise, where after an initial value of 51 uV$_{RMS}$, we successfully decreased it to 46 uV$_{RMS}$ by increasing the W/L ratio of the input pair, M1 and M2, by 20%. This modification proved to be highly effective and efficient and had negligible impact on other previously achieved performance requirements.

The primary discrepancy from the theoretical ideal was the open-loop gain, which was simulated at approximately 70 dB, which is a bit off from the 80 dB calculated value. This highlights a crucial difference between the ideal macromodel and the physical transistor-level implementation. The macromodel, used for initial calculations (Section 4), assumes perfect, infinite gain and zero noise. However, in real time, the full Op-Amp design is restricted by the finite output resistance of the cascode stage and intrinsic device noise. This experimental restraint resulted in the observed 10 dB drop in gain. The inability to fully close this gap suggests a trade-off between the maximum achievable DC gain and other parameters, such as power consumption or area, within the chosen CMOS technology and circuit topology.

In conclusion, the CCIA design is practically strong and successfully satisfies all required specifications, including noise, bandwidth, and stability. The project confirms the necessity of an iterative design procedure when taking theoretical models to physical circuits, as the required device sizing (like the M1/M2 adjustment) is essential for meeting specifications. While the ideal open-loop gain was not reached, the achieved performance of 70 dB is considered a strong, practical result, validating the understanding of both theoretical modeling and physical implementation challenges in analog integrated circuits.