Information Technology Institute

CMOS Analog IC Design

Lab 8

Negative Feedback

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PART 1: Feedback with Behavioral OTA

we will create two schematic views. One is the transistor level schematic that you created in the previous lab, and the other is the behavioral schematic you will create in this lab

The device sizing results from the previous lab are presented below

Transistor	W (µm)	L (µm)	gm (µS)	ID (µA)	gm/ID (S/A)	VDSsat (V)	Vov (V)	V∗ (V)
M1, M2	**20.48**	**0.45**	**318**	**20**	**16**	**0.1**	**0.019**	**0.122**
M3, M4	**30.55**	**0.39**	**275.7**	**20**	**14**	**0.143**	**0.143**	**0.143**
M5	**9.8**	**0.5**	**403.3**	**40**	**10.2**	**0.1689**	**0.133**	**0.198**

Final Design Results from the Previous Lab

Specification	Requirement	Achieved Result	Status
DC Voltage Gain	≥ 34 dB	35.25 dB	✅
Gain-Bandwidth (GBW)	≥ 10 MHz	10.05 MHz	✅
CMRR @ DC	≥ 74 dB	80.47 dB	✅
Phase Margin	≥ 70°	~89.9°	✅
CM Input Range (Low)	≤ 1 V	0.90 V	✅
CM Input Range (High)	≥ 1.5 V	1.78 V	✅

Schimatic :

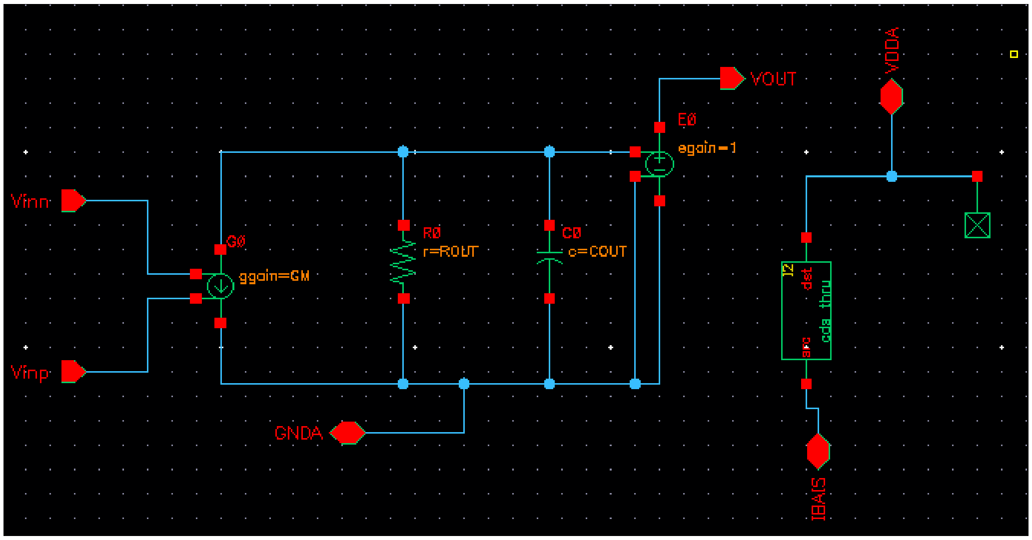

Figure 1 : Behavioral model schematic of the 5T OTA.Behavioral model schematic of the 5T OTA.

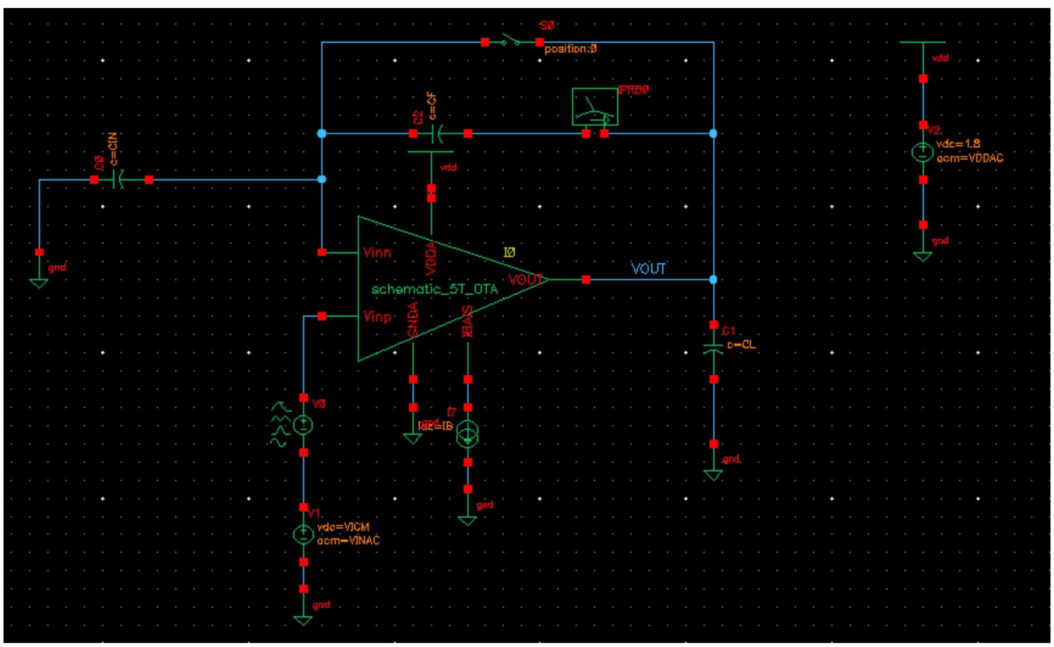

Figure 2 : Testbench schematic for the non-inverting feedback amplifier

Switch set DC = IC = 1 and Ac=0 mean is closed in DC and IC and open in AC

Closed loop gain vs frequency :

FOR ALL GRAPHS Red curve : at CIN = 4P, yellow curve : at CIN = 12p

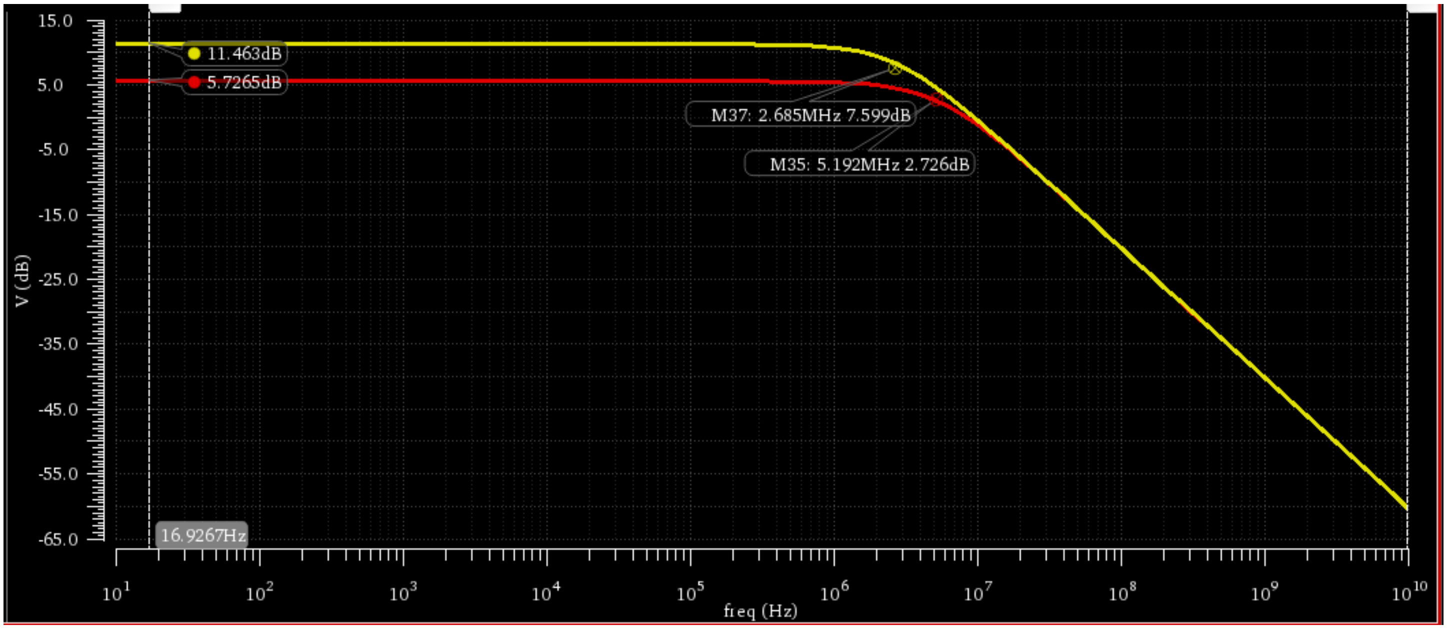

Figure 3 : Closed loop gain vs. frequency for the behavioral OTA model.

Point	Test	Output	Nominal
Parameters: CIN=4p			
1	5T_OTA:feedback_tb:1	dB20(VF("/VOUT"))	
1	5T_OTA:feedback_tb:1	ymax(dB20(VF("/VOUT")))	5.726
1	5T_OTA:feedback_tb:1	ymax(mag(VF("/VOUT")))	1.933
1	5T_OTA:feedback_tb:1	bandwidth(VF("/VOUT") 3 "lo...	5.192M
1	5T_OTA:feedback_tb:1	gainBwProd(VF("/VOUT"))	10.06M
Parameters: CIN=12p			
2	5T_OTA:feedback_tb:1	dB20(VF("/VOUT"))	
2	5T_OTA:feedback_tb:1	ymax(dB20(VF("/VOUT")))	11.46
2	5T_OTA:feedback_tb:1	ymax(mag(VF("/VOUT")))	3.742
2	5T_OTA:feedback_tb:1	bandwidth(VF("/VOUT") 3 "lo...	2.685M
2	5T_OTA:feedback_tb:1	gainBwProd(VF("/VOUT"))	10.07M

Figure 4 : Dc gain & BW & GBW from Simulatuion

Analytical :

$$A_{CL} = 1 + \frac{C_{IN}}{C_F}$$

$$\text{DC Gain (dB)} = 20\log_{10}(A_{CL})$$

$$BW_{CL} \approx \frac{GBW_{\text{OTA}}}{A_{CL}}$$

$$GBW_{CL} = A_{CL} \times BW_{CL}$$

Parameter	CIN	Hand Analysis	Simulation Result
DC Gain	4 pF	2 (6.02 dB)	1.93 (5.73 dB)
	12 pF	4 (12.04 dB)	3.74 (11.46 dB)
Bandwidth (BW)	4 pF	5.025 MHz	5.192 MHz
	12 pF	2.5125 MHz	2.685 MHz
GBW	4 pF	10.05 MHz	10.06 MHz
	12 pF	10.05 MHz	10.07 MHz

Comment :

increasing CIN raises the closed-loop gain but reduces the bandwidth in inverse proportion, while the GBW remains essentially constant in the ideal behavioral model; differences in simulation arise from non-ideal effects.

Loop gain vs frequency :

Run STB simulation (10Hz:10Gz, logarithmic, 10 points/decade).

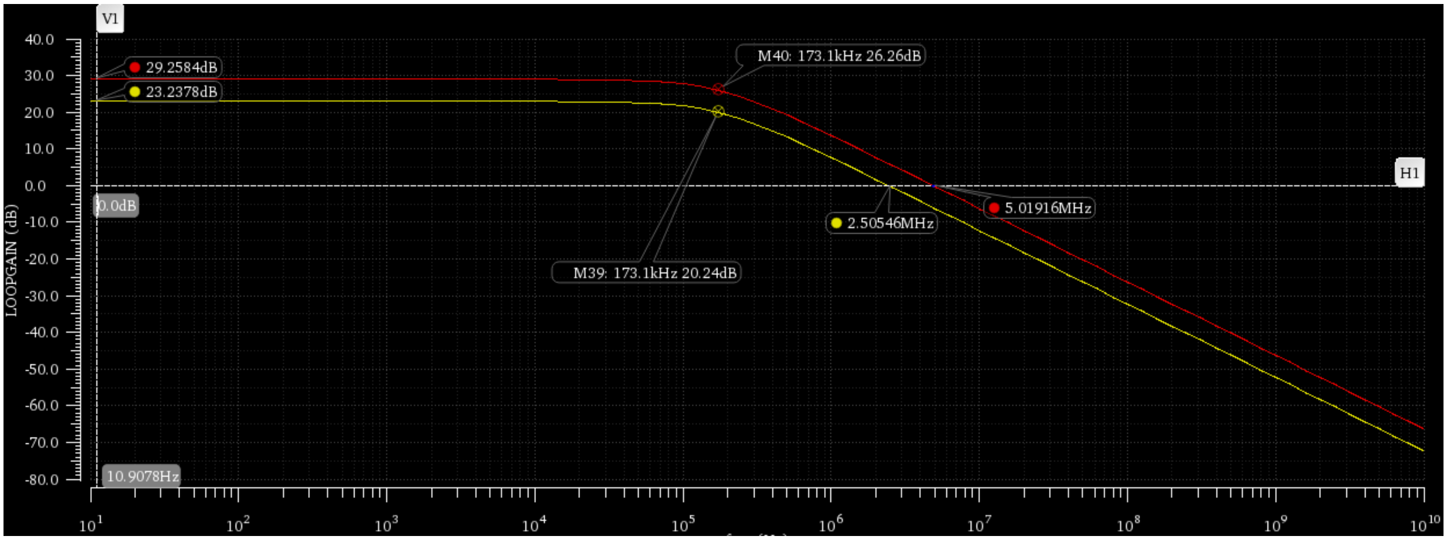

Figure 5 : Loop gain vs. frequency for the behavioral OTA mode

Output	Nominal
dB20(getData("loopGain" ?result "stb"))	
ymax(dB20(getData("loopGain" ?result "stb")))	29.26
ymax(mag(getData("loopGain" ?result "stb")))	29.03
unityGainFreq(mag(getData("loopGain" ?result "stb")))	5.02M
phase(getData("loopGain" ?result "stb"))	
bandwidth(getData("loopGain" ?result "stb") 3 "low")	173.1k
gainBwProd(getData("loopGain" ?result "stb"))	5.038M
dB20(getData("loopGain" ?result "stb"))	
ymax(dB20(getData("loopGain" ?result "stb")))	23.24
ymax(mag(getData("loopGain" ?result "stb")))	14.52
unityGainFreq(mag(getData("loopGain" ?result "stb")))	2.506M
phase(getData("loopGain" ?result "stb"))	
bandwidth(getData("loopGain" ?result "stb") 3 "low")	173.1k
gainBwProd(getData("loopGain" ?result "stb"))	2.519M

Figure 6 : : Dc gain & BW & UBW & GBW from Simulatuion

Analytical :

The loop gain is given by:

$$LG = A_{OL} \cdot \beta$$

where

$$\beta = \frac{C_F}{C_{IN} + C_F}$$

Case 1 — $C_{IN} = 4\ \mathrm{pF}$

1. **Feedback factor:**

$$\beta = \frac{4}{4+4} = 0.5$$

2. **Loop gain:**

$$LG = 58.07 \times 0.5 = 29.04$$

3. **In dB:**

$$LG_{dB} = 20 \log_{10}(29.04) = 29.27\ \mathrm{dB}$$

Case 2 — $C_{IN} = 12\ \mathrm{pF}$

1. **Feedback factor:**

$$\beta = \frac{4}{12+4} = 0.25$$

2. **Loop gain:**

$$LG = 58.07 \times 0.25 = 14.52$$

3. **In dB:**

$$LG_{dB} = 20 \log_{10}(14.52) = 23.24\ \mathrm{dB}$$

and the GBW

$$\text{Loop GBW} \approx BW_{CL} \approx \frac{GBW_{OTA}}{A_{CL}}$$

Parameter	C_{IN} Value	Hand Analysis	Simulation Result
DC Loop Gain (dB)	4 pF	29.27 dB	29.26 dB
	12 pF	23.24 dB	23.24 dB
Loop GBW (MHz)	4 pF	5.03 MHz	5.038 MHz
	12 pF	2.51 MHz	2.519 MHz

Comment :

Increasing CIN from 4 pF to 12 pF reduces the feedback factor β\betaβ, which lowers the DC loop gain and narrows the loop bandwidth. The hand analysis and simulation results match closely for both cases, confirming that the dominant-pole model accurately predicts the effect of input capacitance on loop gain and GBW.

Gain Desensitization :

AC simulation to sweep design variable (Av = 50:50000)

Plot closed loop DC gain (magnitude at 10Hz, not dB) vs Av.

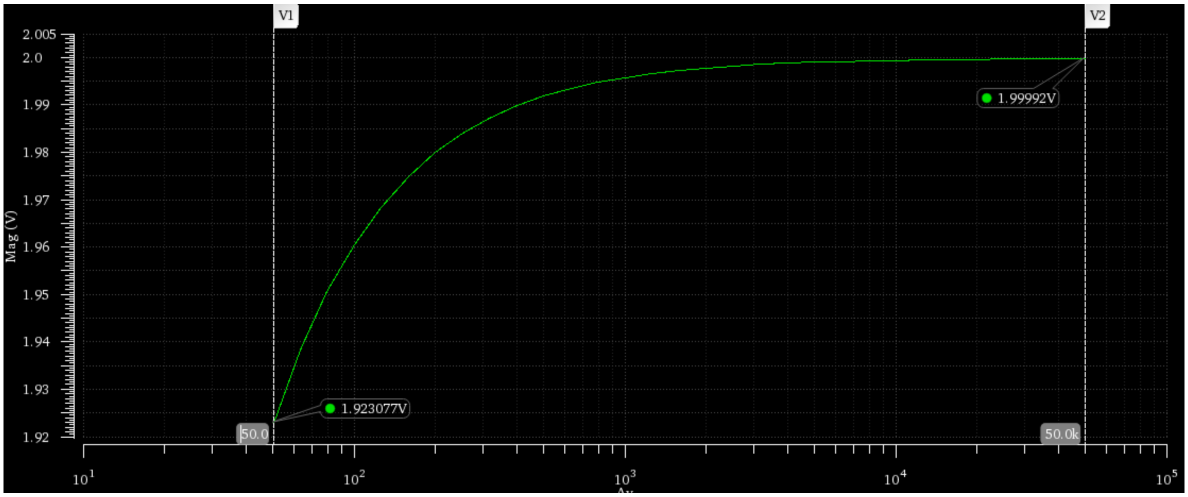

Figure 7 : Gain desensitization: Closed-loop gain vs. open-loop gain.

- **Initial Closed-Loop Gain** (Acl,initial) at Av=50: **1.923077**
- **Final Closed-Loop Gain** (Acl,final) at Av=50,000: **1.99992**

$$\text{Percent Change}(\%) = \frac{A_{cl,final} - A_{cl,initial}}{A_{cl,initial}} \times 100$$

Plugging in the values:

$$\text{Percent Change}(\%) = \frac{1.99992 - 1.923077}{1.923077} \times 100$$

$$\text{Percent Change}(\%) = \frac{0.076843}{1.923077} \times 100 \approx \mathbf{3.996\%}$$

Comment :

Even though the open-loop gain changed by a factor of **1000** (60 dB), the closed-loop gain moved from **1.923** to nearly the **ideal value of 2** (set by the feedback network). This small change (~4%) shows that **negative feedback** makes the gain strongly determined by the feedback factor (here 2) rather than the amplifier's internal gain, keeping performance stable despite large variations in Av

PART 2: Feedback with Real 5T OTA

Schimatic :

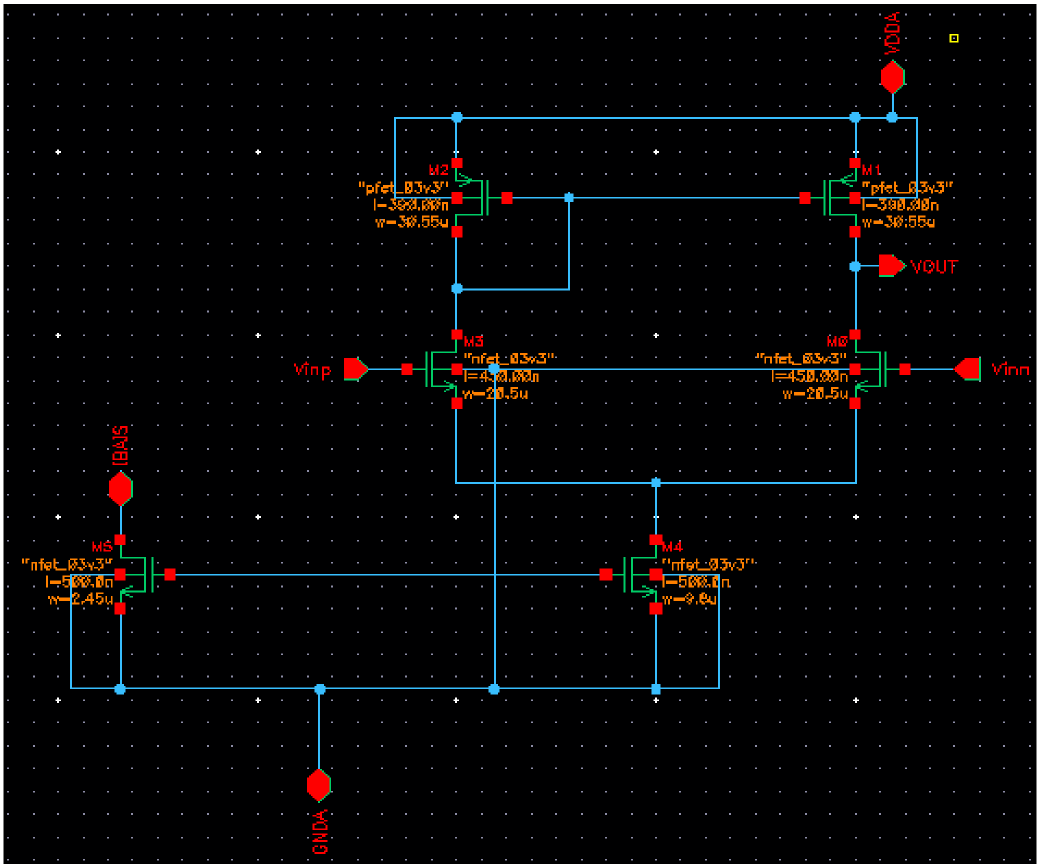

Figure 8 : Transistor-level schematic of the 5T OTA.

Closed loop gain vs frequency :

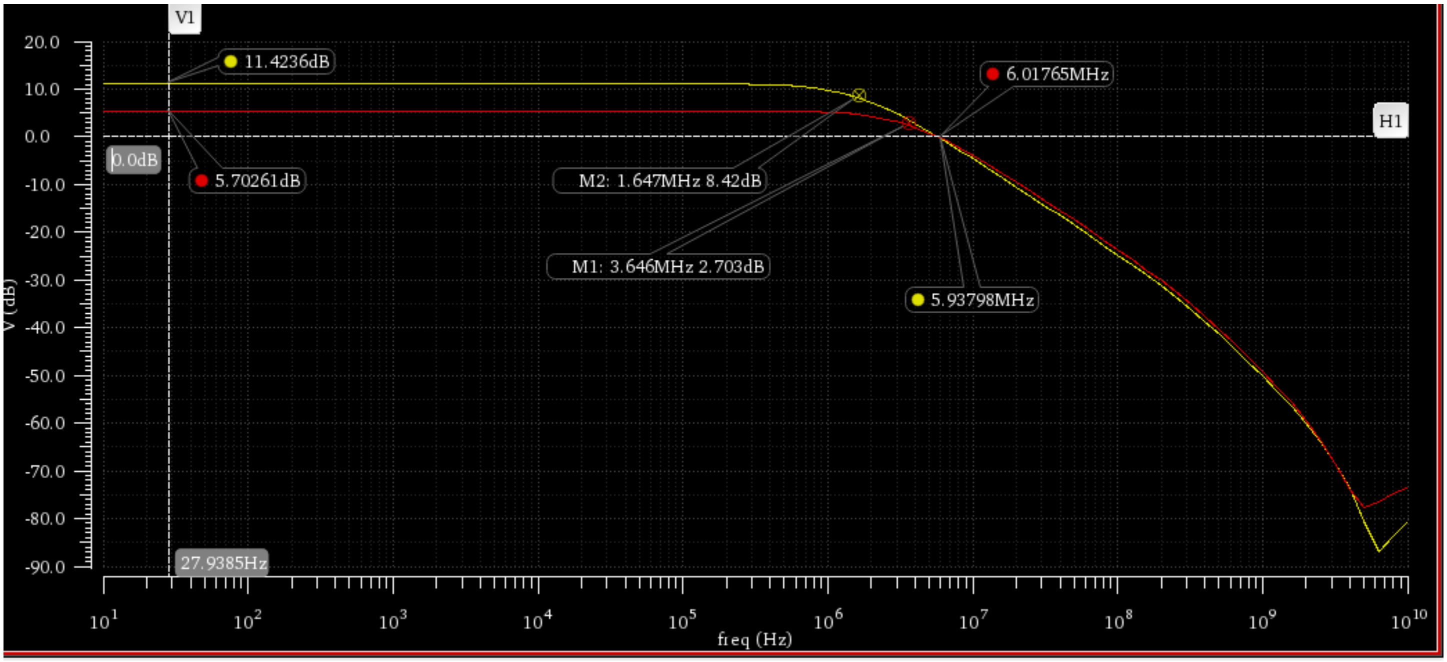

Figure 9 : Closed-loop gain versus frequency for the transistor-level 5T OTA.

dB20(VF("/VOUT"))	
ymax(dB20(VF("/VOUT")))	5.703
ymax(mag(VF("/VOUT")))	1.928
bandwidth(VF("/VOUT") 3 "lo...	3.646M
gainBwProd(VF("/VOUT"))	7.046M
dB20(VF("/VOUT"))	
ymax(dB20(VF("/VOUT")))	11.42
ymax(mag(VF("/VOUT")))	3.725
bandwidth(VF("/VOUT") 3 "lo...	1.647M
gainBwProd(VF("/VOUT"))	6.151M

Figure 10 : Dc gain & BW & GBW from Simulation

Analytical :

Av_ol= 58.07 from lab 7

- **Formula:**

$$A_{\mathrm{cl}} = \frac{A_{\mathrm{ol}}}{1 + A_{\mathrm{ol}} \cdot \beta}, \quad \beta = \frac{C_F}{C_{\mathrm{IN}} + C_F}$$

- **Case 1 – C_IN = 4 pF:**

$$\beta = \frac{4}{4+4} = 0.5$$

$$A_{\mathrm{cl}} = \frac{58.07}{1 + 58.07 \cdot 0.5} \approx 1.933 \quad (5.72\ \mathrm{dB})$$

- **Case 2 – C_IN = 12 pF:**

$$\beta = \frac{4}{12+4} = 0.25$$

$$A_{\mathrm{cl}} = \frac{58.07}{1 + 58.07 \cdot 0.25} \approx 3.742 \quad (11.46\ \mathrm{dB})$$

$$C_{L,\mathrm{total}} = C_L + C_F = 5\,\mathrm{pF} + 4\,\mathrm{pF} = 9\,\mathrm{pF}$$

Loaded Open-Loop Pole:

$$f_{p,\mathrm{loaded}} = \frac{1}{2\pi R_{\mathrm{out}} C_{L,\mathrm{total}}} = \frac{1}{2\pi \cdot 180.8\mathrm{k} \cdot 9\mathrm{pF}} \approx 97.8\,\mathrm{kHz}$$

Closed-Loop Bandwidth:

$$\mathrm{BW_{CL}} = f_{p,\mathrm{loaded}} \cdot (1 + A_{\mathrm{ol}} \cdot \beta)$$

Case 1 – C_IN = 4 pF:

$$\mathrm{BW_{CL}} = 97.8\,\mathrm{kHz} \cdot 30.04 \approx 2.94\,\mathrm{MHz}$$

Case 2 – C_IN = 12 pF:

$$\mathrm{BW_{CL}} = 97.8\,\mathrm{kHz} \cdot 15.52 \approx 1.52\,\mathrm{MHz}$$

Parameter	CIN	Hand Analysis	Simulation Result
DC Gain (dB)	4 pF	5.72 dB	5.703 dB
	12 pF	11.46 dB	11.42 dB
Bandwidth (MHz)	4 pF	2.94 MHz	3.646 MHz
	12 pF	1.52 MHz	1.647 MHz
GBW (MHz)	4 pF	5.683 MHz	7.046 MHz
	12 pF	5.69 MHz	6.151 MHz

Compare between the results you obtained here and the results in Part 1 in a table

Parameter	CIN	Part 1 Result (Behavioral)	Part 2 Result (Real OTA)
DC Gain (dB)	4 pF	5.73 dB	5.703 dB
	12 pF	11.46 dB	11.42 dB
Bandwidth (MHz)	4 pF	5.192 MHz	3.646 MHz
	12 pF	2.685 MHz	1.647 MHz
GBW (MHz)	4 pF	10.06 MHz	7.046 MHz
	12 pF	10.07 MHz	6.151 MHz

Observation:

- **DC Gain:** Almost identical for both behavioral and real OTA.
- **Bandwidth & GBW:** Significantly lower in the real OTA due to parasitic capacitances and non-ideal effects.

the bandwidth, and consequently the GBW are much smaller than Part 1. Why?

- The feedback capacitor CF adds extra capacitance to the OTA output, increasing the total load.
- This **lowers the dominant pole frequency**:

$$f_p = \frac{1}{2\pi R_{\text{out}} C_{L,\text{total}}}$$

- Consequently, **BW_CL decreases**, and since GBW=Acl * BWCL, GBW also decreases.
- Real-world loading reduces both BW and GBW compared to ideal calculations that ignore feedback and parasitic capacitances.

Comment :

The real 5T-OTA's bandwidth and GBW are smaller than ideal because the feedback capacitor increases the output load, lowering the dominant pole frequency. DC gain matches well, but loading reduces speed, showing the effect of real-world parasitics.

Loop gain vs frequency :

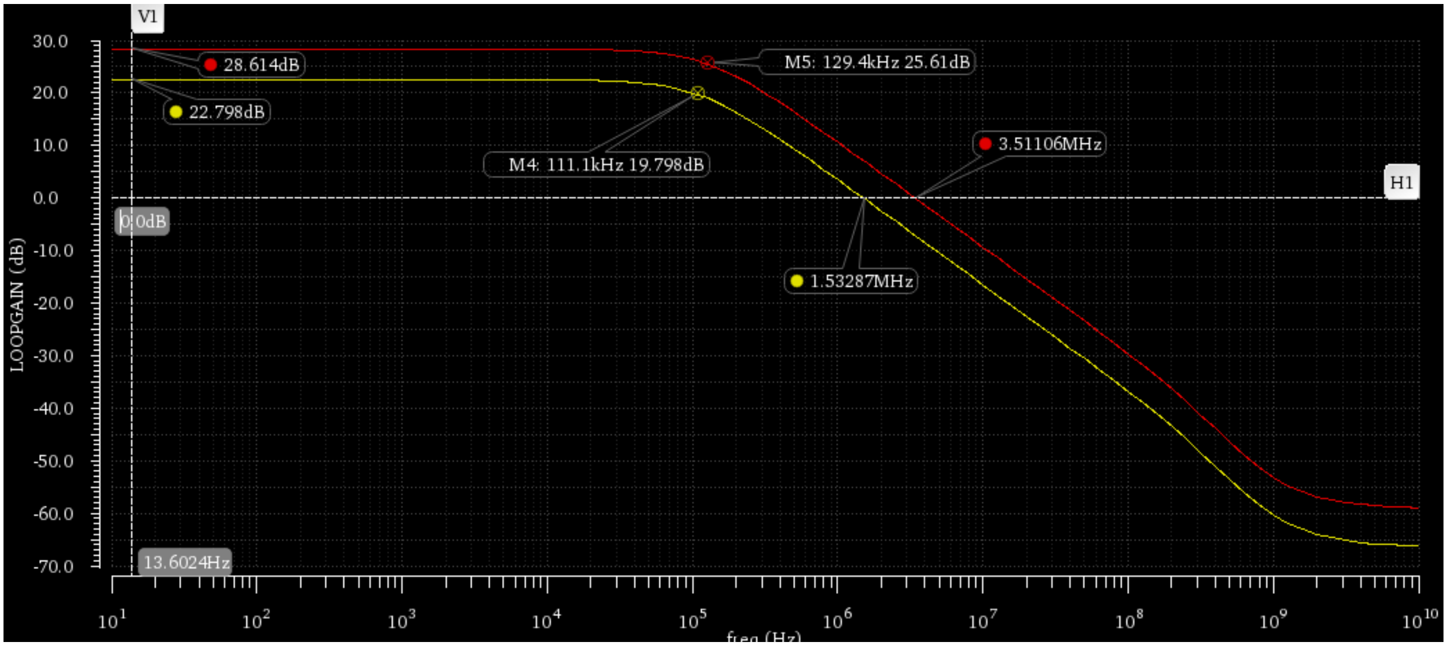

Figure 11 : Loop gain versus frequency for the transistor-level 5T OTA.

dB20(getData("loopGain" ?re...	
ymax(dB20(getData("loopGa...	28.61
unityGainFreq(mag(getData(...	3.534M
bandwidth(getData("loopGai...	129.4k
gainBwProd(getData("loopG...	3.497M
dB20(getData("loopGain" ?re...	
ymax(dB20(getData("loopGa...	22.8
unityGainFreq(mag(getData(...	1.538M
bandwidth(getData("loopGai...	111.1k
gainBwProd(getData("loopG...	1.537M

Figure 12: Dc gain & BW & UBW &GBW from Simulatuion

Analytical :

Formula:

$$LG_{dc} = A_{ol} \cdot \beta, \quad \beta = \frac{C_F}{C_{IN} + C_F}$$

Case 1: C_IN = 4 pF

$$\beta = \frac{4}{4+4} = 0.5, \quad LG_{dc} = 58.07 \cdot 0.5 \approx 29.04\,(29.27\text{ dB})$$

Case 2: C_IN = 12 pF

$$\beta = \frac{4}{12+4} = 0.25, \quad LG_{dc} = 58.07 \cdot 0.25 \approx 14.52\,(23.24\text{ dB})$$

Closed-Loop Bandwidth / Loop GBW:

$$\text{Loop GBW} \approx f_{p,\text{loaded}} \cdot (1 + LG_{dc})$$

Case 1: C_IN = 4 pF

$$\text{Loop GBW} \approx 97.8\text{ kHz} \cdot (1 + 29.04) \approx 2.94\text{ MHz}$$

Case 2: C_IN = 12 pF

$$\text{Loop GBW} \approx 97.8\text{ kHz} \cdot (1 + 14.52) \approx 1.52\text{ MHz}$$

Parameter	CIN	Hand Analysis	Simulation Result
DC Gain (dB)	4 pF	5.72 dB	5.703 dB
	12 pF	11.46 dB	11.42 dB
GBW (MHz)	4 pF	10.05 MHz	7.046 MHz
	12 pF	10.05 MHz	6.151 MHz

Comment :

Increasing CIN, from 4pF to 12pF reduces the feedback factor (beta), which directly lowers the DC Loop Gain. Consequently, the loop's unity-gain frequency also decreases, reflecting the system's reduced closed-loop bandwidth.

Compare between the results you obtained here and the results in Part 1 in a table.

Parameter	CIN	Part 1 Result (Behavioral)	Part 2 Result (Real OTA)
DC Loop Gain (dB)	4 pF	29.26 dB	28.61 dB
	12 pF	23.24 dB	22.8 dB
Loop GBW (MHz)	4 pF	5.02 MHz	3.53 MHz
	12 pF	2.51 MHz	1.54 MHz

The table shows that the **DC Loop Gain** is very similar in both cases, indicating the behavioral model was a good approximation of the real OTA's DC performance. However, the **Loop GBW** is significantly lower for the real OTA in Part 2, which reflects the reduced closed-loop bandwidth caused by the loading effect of the feedback network on the real amplifier's output.

notice that the unity gain frequency is much smaller than Part 1. Why? Comment.

The **unity gain frequency (UGF)** is smaller in Part 2 because the real OTA has parasitic capacitances and high-frequency poles that reduce bandwidth, unlike the ideal OTA in Part 1. This shows the practical limitations of real circuits compared to ideal models.

Comment :

The smaller UGF in Part 2 reflects the practical limitations of the real circuit. It shows that ideal models overestimate the frequency performance, while real devices have finite speed due to internal parasitics and non-idealities.

Gain Desensitization :

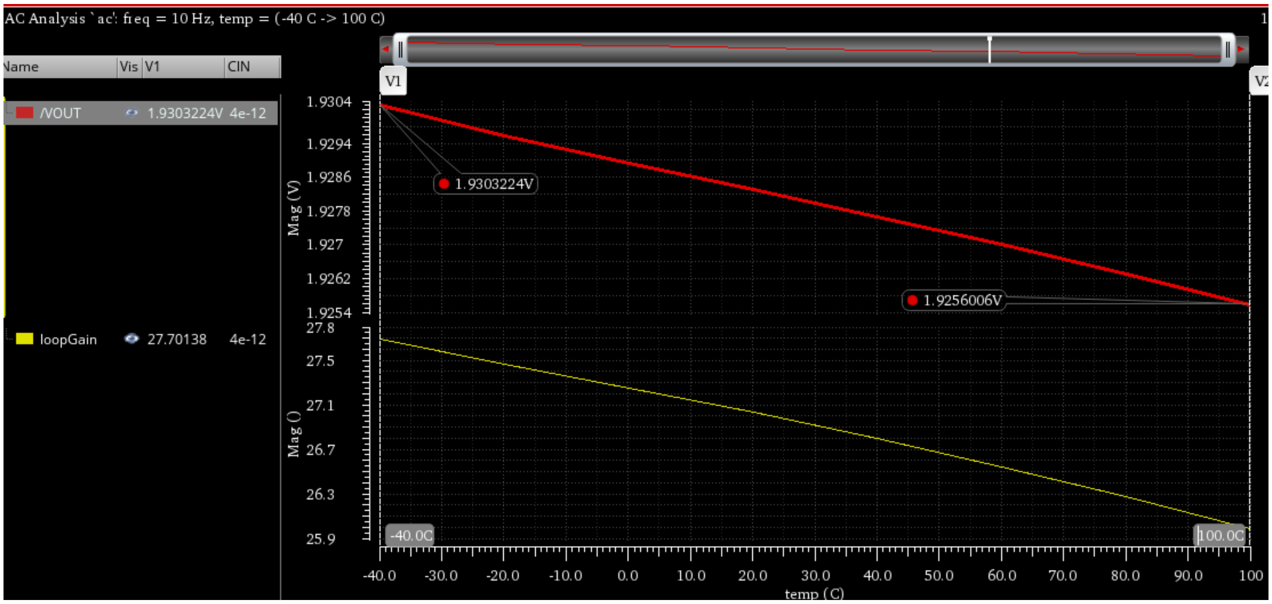

Figure 13 : Closed-loop and loop gain variation with temperature.

1. Closed-Loop Gain (Red Trace)

$$\text{Start Value} = 1.9303\,\text{V}, \quad \text{End Value} = 1.9256\,\text{V}$$

$$\%\Delta A_{\text{cl}} = \frac{1.9256 - 1.9303}{1.9303} \cdot 100 \approx -0.24\%$$

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2. Loop Gain (Yellow Trace)

$$\text{Start Value} = 27.70, \quad \text{End Value} = 26.00$$

$$\%\Delta LG_{\text{dc}} = \frac{26.00 - 27.70}{27.70} \cdot 100 \approx -6.14\%$$

Parameter	Percent Change from -40°C to 100°C
Closed-Loop Gain	**-0.24%**
Loop Gain	**-6.14%**

Comment :

Over the temperature extremes, the DC loop gain decreased by ≈6.5% due to the reduction in carrier mobility and transistor transconductance (gm) at higher temperatures, which lowers the intrinsic open-loop gain. In contrast, the DC closed-loop gain changed by only ≈0.245% — about 26× smaller. This clearly demonstrates how negative feedback desensitizes the overall gain to temperature-dependent variations in the active devices, making the circuit's performance stable and predictable across wide thermal ranges.

Transient analysis :

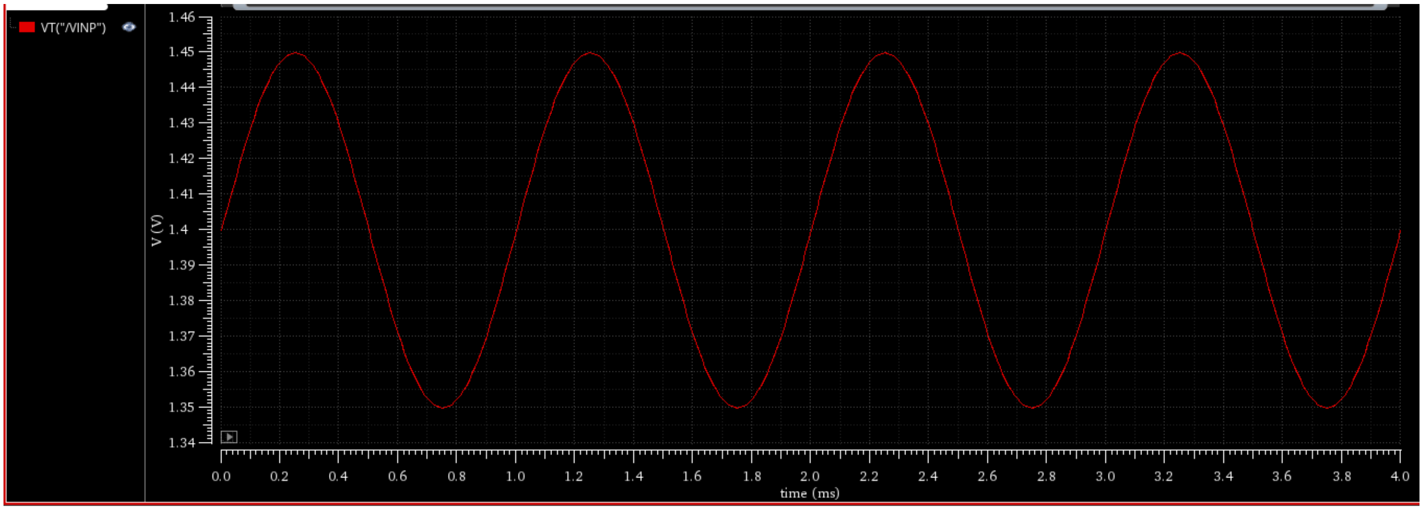

Figure 14 : Input signal (Vinp) vs. time for a 1 kHz sine wave.

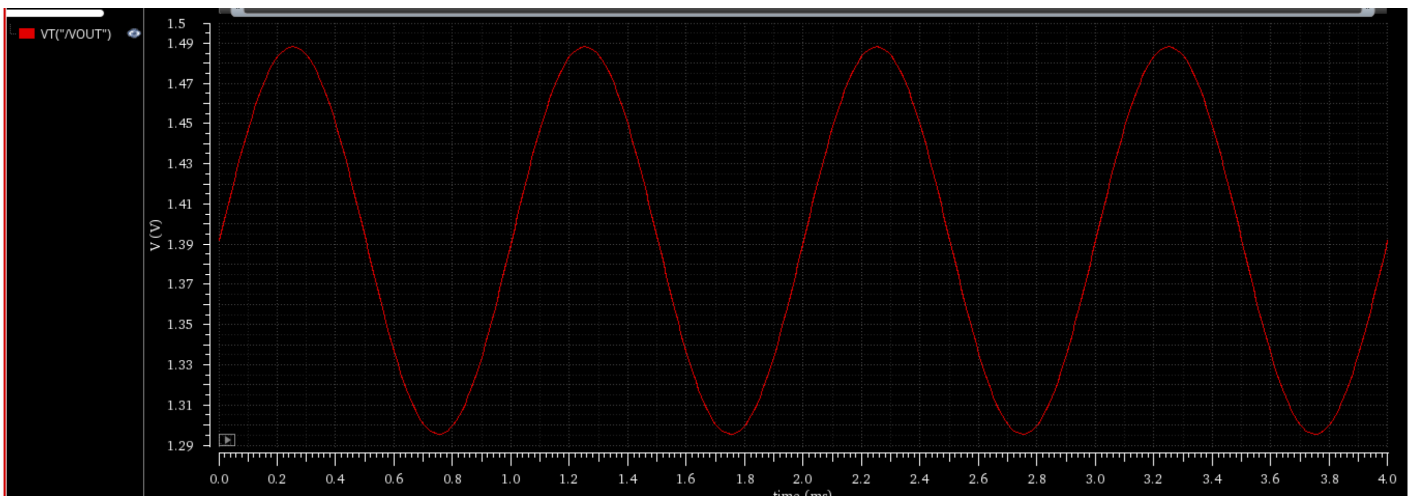

Figure 15 : Output signal (Vout) vs. time, showing a gain of 2.

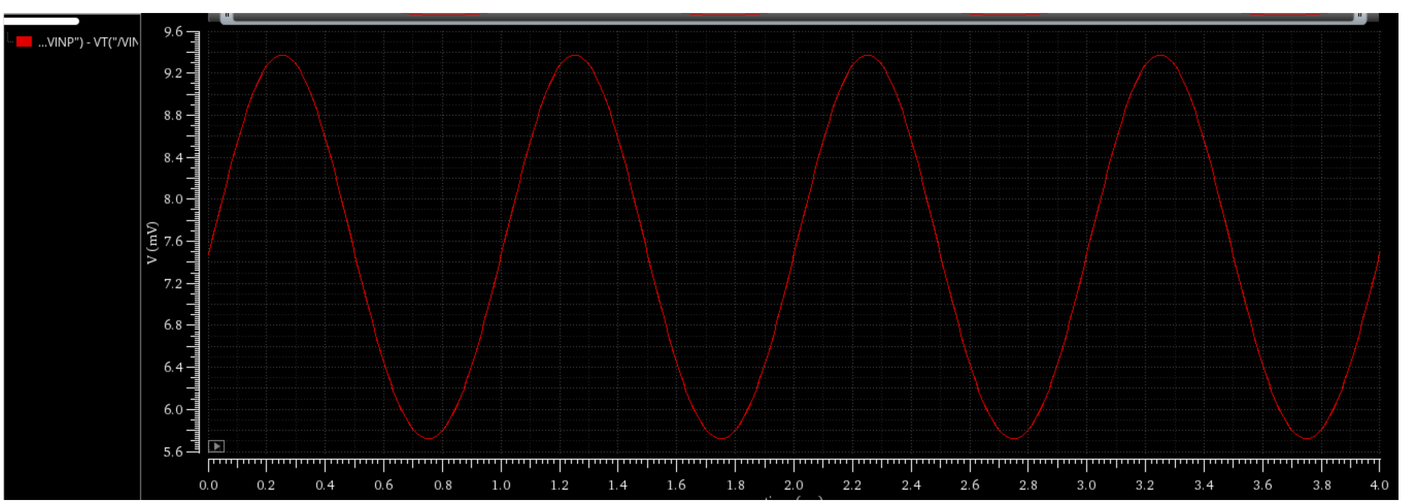

Figure 16: Differential input signal (Vp - Vn) vs. time.

Calculate the peak-to-peak voltage of the previous three signals. What is the relation between the output and (VP – VN)? Comment.

peakToPeak(VT("/VINP"))	100m
peakToPeak(VT("/VOUT"))	192.8m
peakToPeak((VT("/VINP") - VT("/VINN")))	3.65m

The OTA output is proportional to its **differential input** multiplied by the **open-loop gain**:

$$V_{\text{out}} = A_{\text{ol}} \cdot (V_P - V_N)$$

The Relationship and Commentary

The relationship between the output signal and the differential input signal (`VP - VN`) is the **Open-Loop Gain (A_OL)** of the OTA. We can calculate this from the peak-to-peak (Vpp) values you measured from the previous plots:

- **Vpp of Output Signal:** 192.8 mV
- **Vpp of Differential Input Signal:** 3.65 mV
- **Open-Loop Gain (Av_OL) = Vpp(Vout) / Vpp(Vp - Vn)**

  Av_OL = 53

Comment :

he transient analysis shows an open-loop gain of approximately **53**, which is close to the expected DC open-loop gain of ~**58** from the previous lab. This confirms that the relation

$$V_{\text{out}} = A_{\text{ol}} \cdot (V_P - V_N)$$

is valid, and it verifies the high-gain behavior of the designed OTA.

At FIN = BW_CL

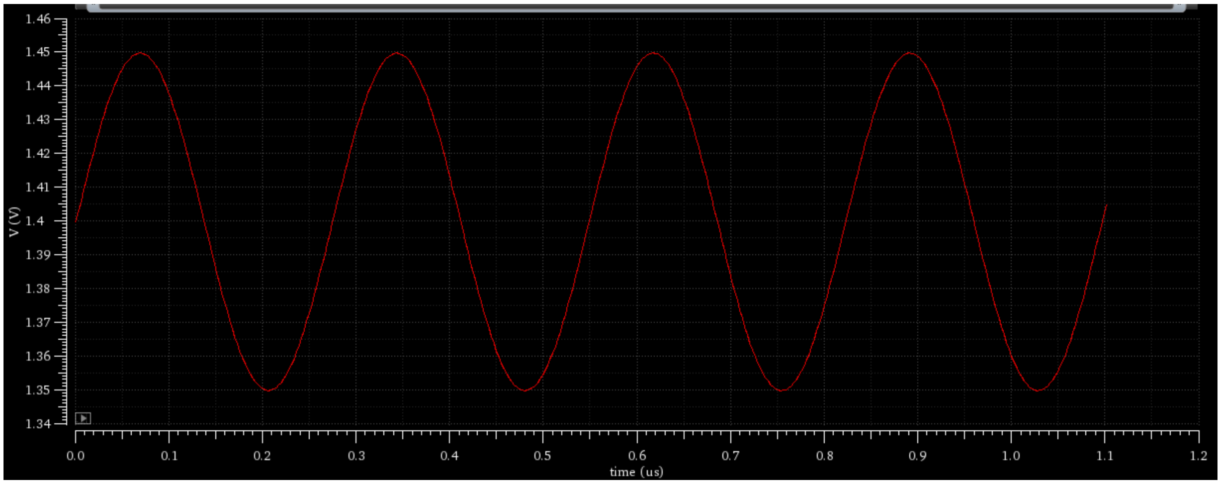

Figure 17 : Input signal (Vinp) vs. time for a BW_cl sine wave.

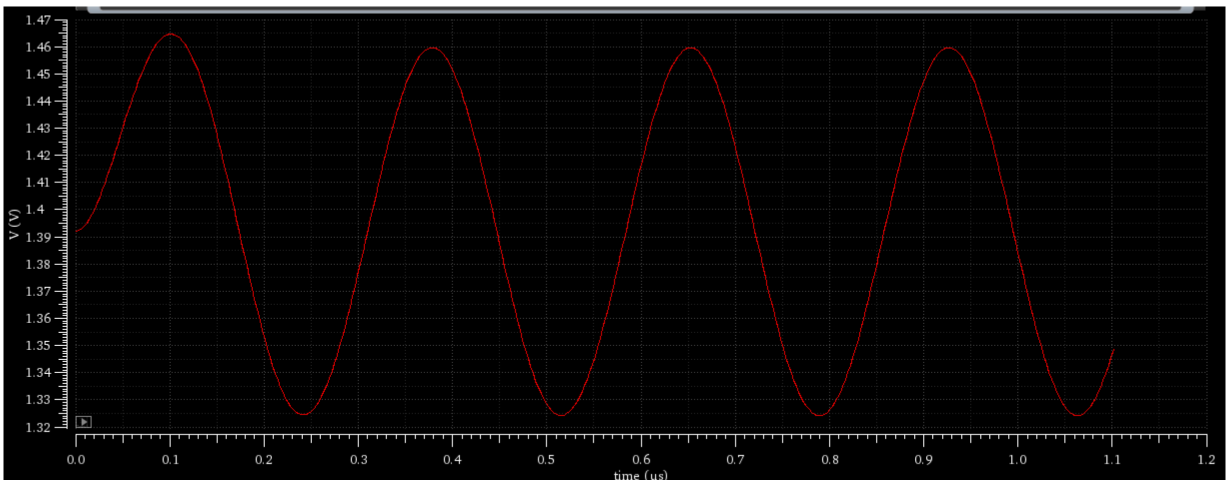

Figure 18 : : Output signal (Vout) vs. time, showing a gain of 2.

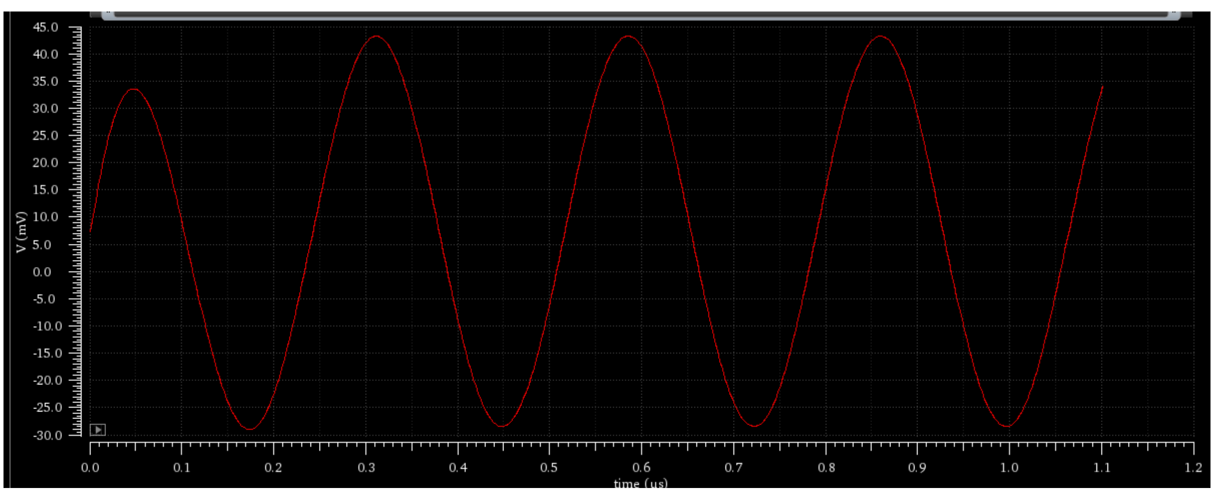

Figure 19 : Differential input signal (Vp - Vn) vs. time.

Calculate the peak-to-peak voltage of the previous three signals.

peakToPeak(VT("/VINP"))	100m
peakToPeak(VT("/VOUT"))	140.4m
peakToPeak((VT("/VINP") - VT("/VINN")))	72.24m

What is the relation between the output and the input signal? What is the relation between the output and (VP – VN)?

The OTA output is proportional to its **differential input** multiplied by the **open-loop gain**:

$$V_{\mathrm{out}} = A_{\mathrm{ol}} \cdot (V_P - V_N)$$

- **Vpp of Output Signal:** 140.4 mV
- **Vpp of Differential Input Signal:** 72.24 mV
- **Open-Loop Gain (Av_OL) = Vpp(Vout) / Vpp(Vp - Vn)**

  Av_OL = 1.94

This value is close to the measured closed-loop gain of 1.4, confirming the theory.

Comment :

The calculated open-loop gain at the bandwidth frequency is **1.94**. This value is on the same order of magnitude as the measured closed-loop gain of **1.4**. This confirms the theory hinted at in the lab manual: at high frequencies, the amplifier's intrinsic open-loop gain decreases significantly and approaches the closed-loop gain, demonstrating the limits of the feedback loop's effectiveness.

Compare between this case and the case of 1kHz input.

Signal	Vpp (from 1kHz sim)	Vpp (from BW_cl sim)
Input Signal (Vinp)	100 mV	100 mV
Output Signal (Vout)	192.8 mV	140.4 mV
Differential Input (Vp - Vn)	3.65 mV	72.24 mV

Observations:

1. **Output Gain:** At 1 kHz, the output is **192.8 mV**, but in the current case it drops **140.4 mV** due to the limited bandwidth.
2. **Differential Input:** The differential input increases dramatically from **3.65 mV** to **72.24 mV**, showing the OTA is less able to maintain the closed-loop gain at higher frequencies.
3. **Reason:** The current input frequency is closer to the OTA’s bandwidth limit, so the circuit can’t fully amplify the signal, causing reduced output and increased differential input.