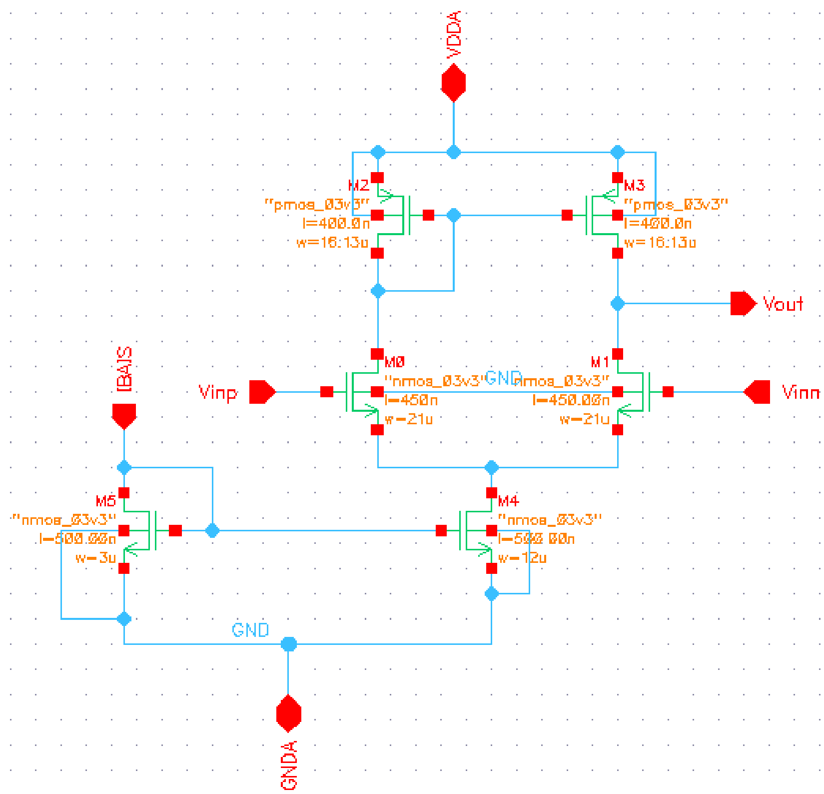
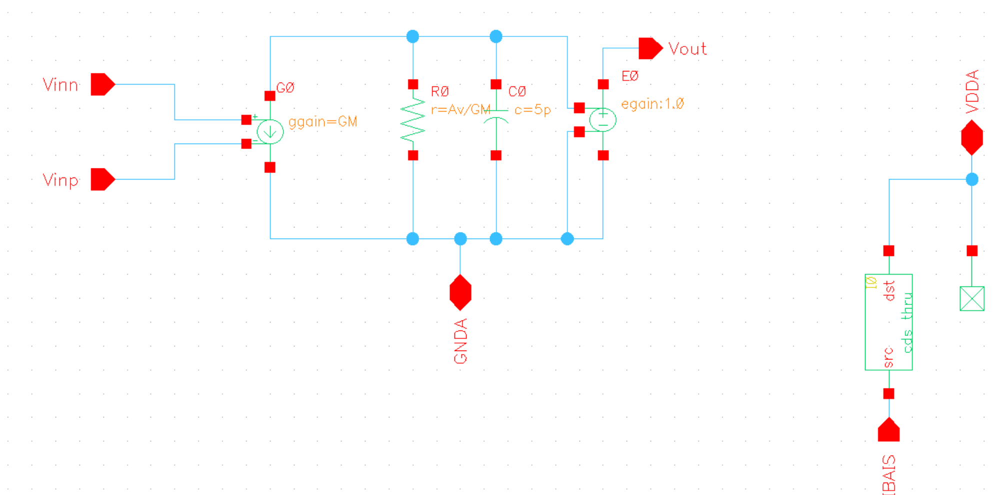
ITI CMOS Analog IC Design 2024
Lab 08
Negative Feedback

PART 1: Feedback with Behavioral OTA

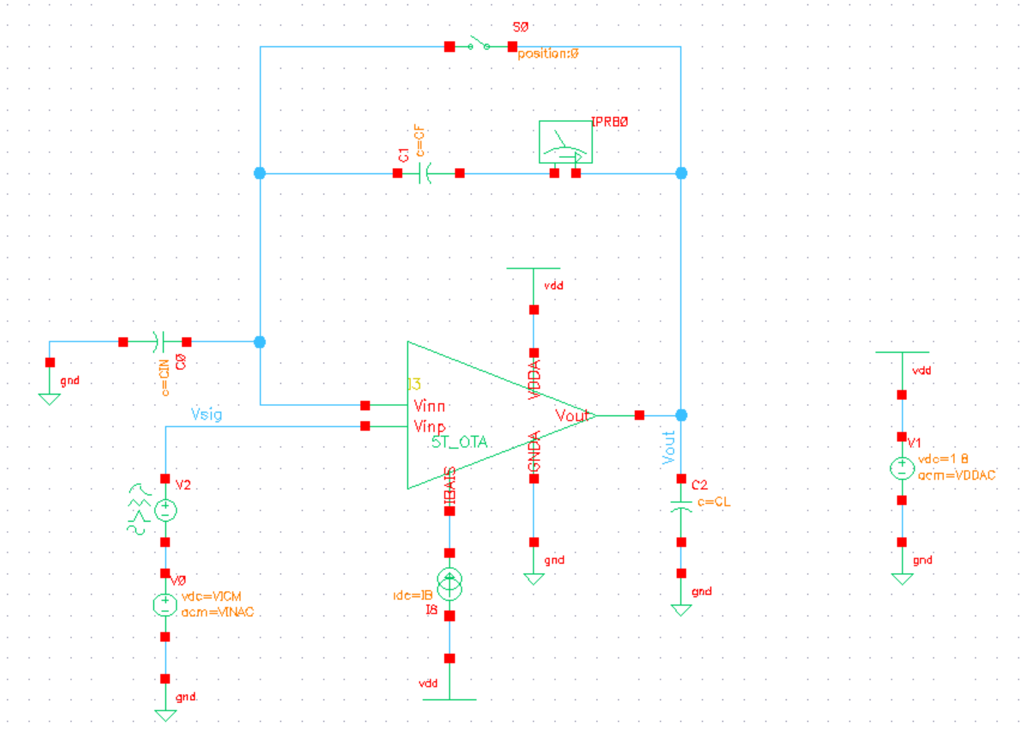
1. The schematic of 5T_OTA



2. The behavioral model of 5T_OTA

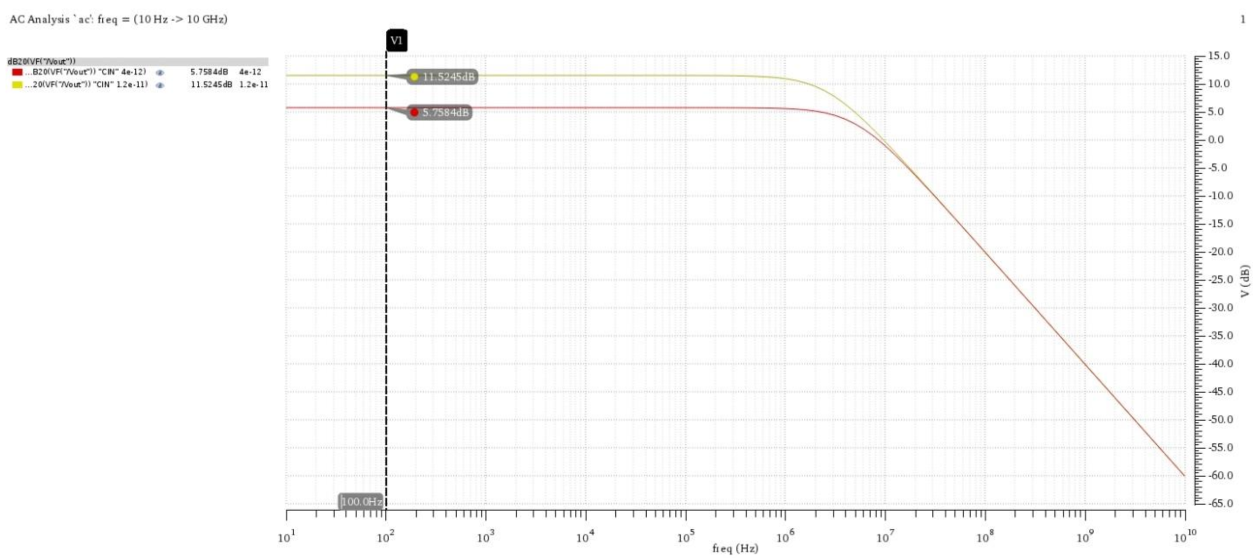


3. The 5T_OTA Test Bench



1. Closed loop gain vs frequency.

1. Plotting Vout in dB for the two values of CIN (4pF and 12pF)



2. Annotating the DC loop gain, the dominant pole, and the unity gain frequency

Parameters: CIN=4p			
1	ITI_Su2024:5T_OTA_tb:1	ACL	1.941
1	ITI_Su2024:5T_OTA_tb:1	ACL(DB)	5.758
1	ITI_Su2024:5T_OTA_tb:1	BW	5.164M
1	ITI_Su2024:5T_OTA_tb:1	UGF	8.658M
1	ITI_Su2024:5T_OTA_tb:1	GBW	10.05M
Parameters: CIN=12p			
2	ITI_Su2024:5T_OTA_tb:1	ACL	3.769
2	ITI_Su2024:5T_OTA_tb:1	ACL(DB)	11.52
2	ITI_Su2024:5T_OTA_tb:1	BW	2.661M
2	ITI_Su2024:5T_OTA_tb:1	UGF	9.72M
2	ITI_Su2024:5T_OTA_tb:1	GBW	10.06M

3. Hand analysis for gain and BW and GBW

$$A_{OL} = g_m * R_{out} = 315\mu S * 207K\Omega = 65.2$$

$$GBW = \frac{g_m}{2\pi * C_{out}} = \frac{315\mu S}{2\pi * 5pF} = 10.028MHz$$

$$BW_{OL} = \frac{1}{2\pi R_{out} C_{out}} = \frac{1}{2\pi 207k\Omega * 5pF} = 153.773kHz$$

- For Cin=4pF

$$\beta = \frac{C_F}{C_{IN} + C_F} = \frac{4pF}{4pF + 4pF} = \frac{1}{2} \; so \; A_{CL} = \frac{A_{OL}}{1 + \beta A_{CL}} = \frac{65.2}{1 + \frac{1}{2} * 65.2} = 1.94$$

$$BW = \frac{GBW}{A_{CL}} = \frac{10.028MHz}{1.92} = 5.223MHz$$

- For Cin=12pF

$$\beta = \frac{C_F}{C_{IN} + C_F} = \frac{4pF}{12pF + 4pF} = \frac{1}{4} \; so \; A_{CL} = \frac{A_{OL}}{1 + \beta A_{CL}} = \frac{65.2}{1 + \frac{1}{4} * 65.2} = 3.77$$

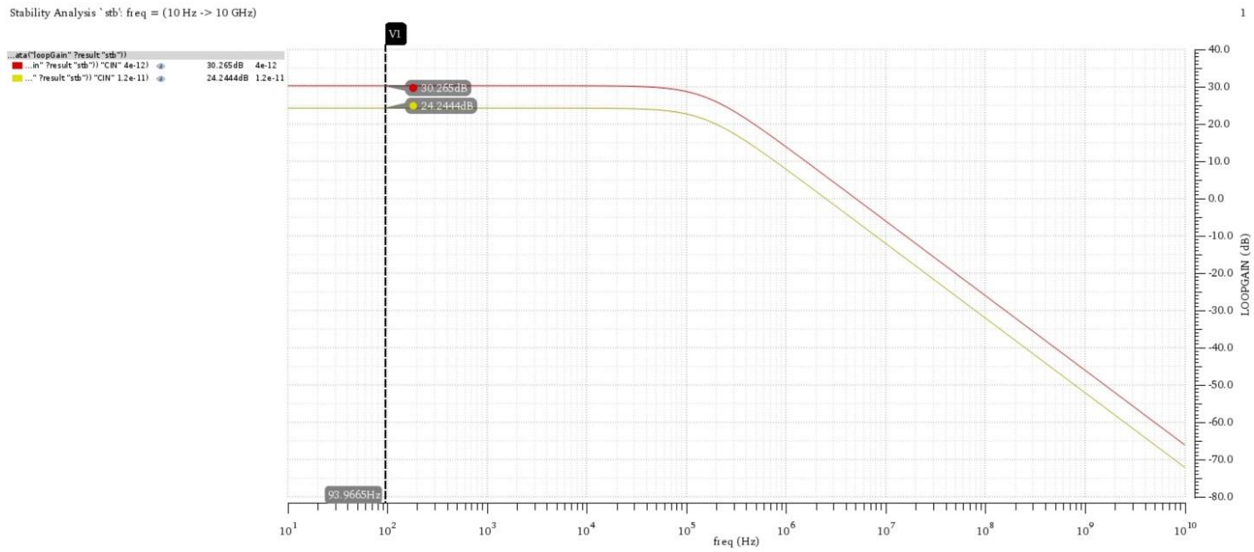
$$BW = \frac{GBW}{A_{CL}} = \frac{10.028MHz}{3.77} = 2.66\ MHz$$

	$C_{IN} = 4pF$		$C_{IN} = 12pF$	
	Simulation	**Analytical**	**Simulation**	**Analytical**
A_{CL}	$\mathbf{1.94}$	$\mathbf{1.94}$	$\mathbf{3.769}$	$\mathbf{3.77}$
BW	$\mathbf{5.164MHz}$	$\mathbf{5.223MHz}$	$\mathbf{2.662MHz}$	$\mathbf{2.666MHz}$
GBW	$\mathbf{10.05MHz}$	$\mathbf{10.028MHz}$	$\mathbf{10.06MHz}$	$\mathbf{10.028MHz}$

- As the last stage in behavioral model is buffer so the output capacitance CL and CF and Cin don't see Rout so they don't make a pole and don't affect the output pole in the 5T_OTA
- As Cin increase β decrease so the closed loop gain increase and the BW decrease as the GBW remain constant

2. Loop gain vs frequency.

1. Plotting loop gain in dB for the two values of CIN



2. Annotating the DC loop gain, the dominant pole, and the unity gain frequency.

Parameters: CIN=4p			
1	ITI_Su2024:5T_OTA_tb:1	LG	32.63
1	ITI_Su2024:5T_OTA_tb:1	LG(DB)	30.27
1	ITI_Su2024:5T_OTA_tb:1	BW	153.5k
1	ITI_Su2024:5T_OTA_tb:1	UGF	5.011M
1	ITI_Su2024:5T_OTA_tb:1	GBW	5.02M
1	ITI_Su2024:5T_OTA_tb:1	PM	-88.24
Parameters: CIN=12p			
2	ITI_Su2024:5T_OTA_tb:1	LG	16.31
2	ITI_Su2024:5T_OTA_tb:1	LG(DB)	24.25
2	ITI_Su2024:5T_OTA_tb:1	BW	153.5k
2	ITI_Su2024:5T_OTA_tb:1	UGF	2.504M
2	ITI_Su2024:5T_OTA_tb:1	GBW	2.51M
2	ITI_Su2024:5T_OTA_tb:1	PM	-86.48

3. Hand analysis for dc loop gain and BW

- For Cin=4pF

$$LG = \beta * A_{OL} = \frac{1}{2} * 65.2 = 32.6\,, BW_{LG} = BW_{OL}$$

$$GBW = \frac{1}{2\pi C_{out} R_{out}} * LG = \frac{1}{2\pi * 5pF * 207k\Omega} * 32.6 = 5.014MHz$$

- For Cin=12pF

$$LG = \beta * A_{OL} = \frac{1}{4} * 65.2 = 16.3\ , BW_{LG} = BW_{OL}$$

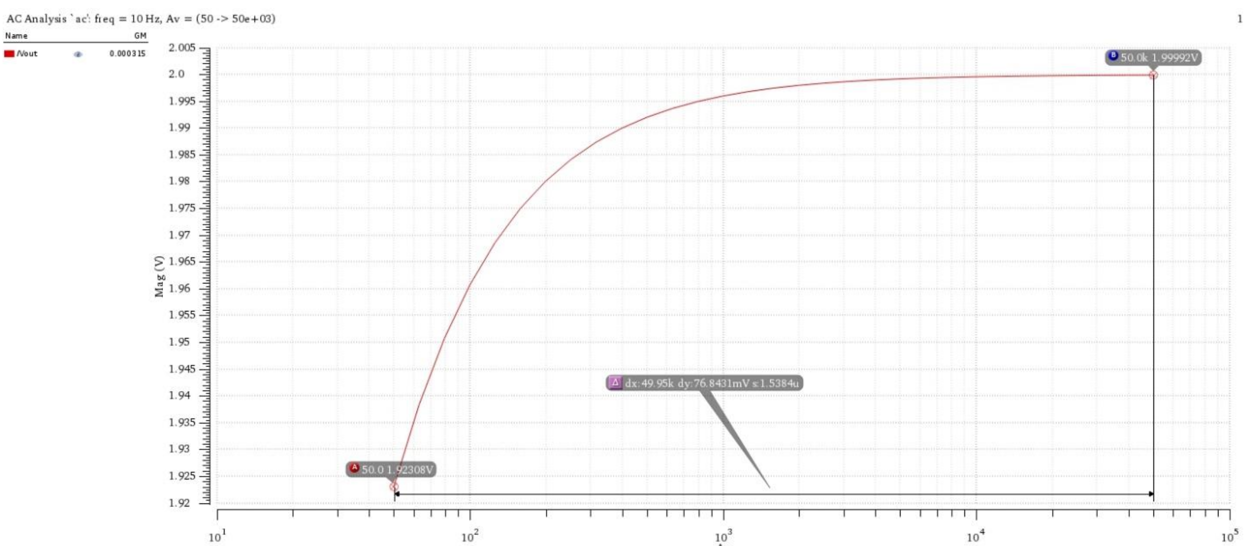
$$GBW = \frac{1}{2\pi C_{out} R_{out}} * LG = \frac{1}{2\pi * 5pF * 207k\Omega} * 16.3 = 2.507MHz$$

	$C_{IN} = 4pF$		$C_{IN} = 12pF$	
	Simulation	**Analytical**	**Simulation**	**Analytical**
LG	**32.63**	**32.6**	**16.31**	**16.3**
BW	$153.5kHz$	$153.773kHz$	$153.5kHz$	$153.773kHz$
GBW	$5.02MHz$	$5.014MHz$	$2.51MHz$	$2.507MHz$

- As Cin increase β decrease so the loop gain decrease and the BW remain constant, so GBW decrease
- The loading of the negative feedback canceled by the buffer

3. Gain Desensitization.

1. Plotting closed loop DC gain vs Av.

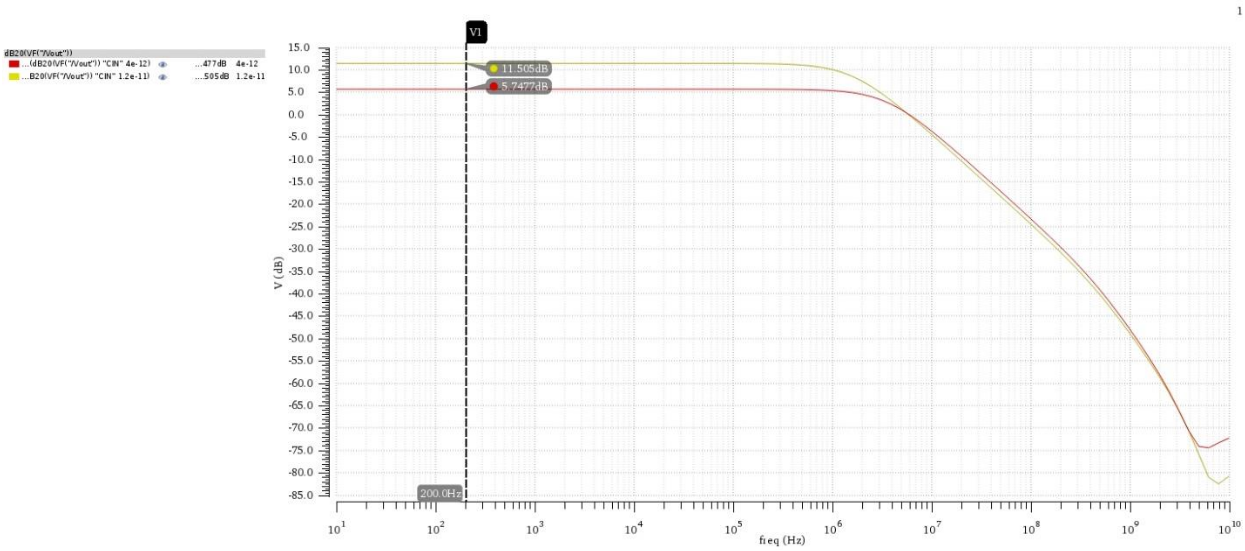


- We see from the graph the change in gain is around 76.84 mV and as the gain is 1.94V@Av=65.2 so the percentage of change in gain $\frac{\delta A_{CL}}{A_{CL}} = \frac{76.84mV}{1940mV} = 3.96\%$

PART 2: Feedback with Real 5T OTA

1. Closed loop gain vs frequency.

1. Plotting Vout in dB for the two values of CIN



2. Indicate the DC gain, the bandwidth, and the unity gain frequency

Parameters: CIN=4p			
1	ITI_Su2024:5T_OTA_tb:1	ACL	1.938
1	ITI_Su2024:5T_OTA_tb:1	ACL(DB)	5.748
1	ITI_Su2024:5T_OTA_tb:1	BW	3.655M
1	ITI_Su2024:5T_OTA_tb:1	UGF	6.09M
1	ITI_Su2024:5T_OTA_tb:1	GBW	7.101M
Parameters: CIN=12p			
2	ITI_Su2024:5T_OTA_tb:1	ACL	3.761
2	ITI_Su2024:5T_OTA_tb:1	ACL(DB)	11.5
2	ITI_Su2024:5T_OTA_tb:1	BW	1.645M
2	ITI_Su2024:5T_OTA_tb:1	UGF	6.014M
2	ITI_Su2024:5T_OTA_tb:1	GBW	6.202M

3. Hand analysis for gain and BW and GBW

$$A_{OL} = g_m * R_{out} = 315\mu S * 207K\Omega = 65.2$$

$$GBW_{OL} = \frac{g_m}{2\pi * C_{out}} = \frac{315\mu S}{2\pi * 5pF} = 10.028MHz$$

$$BW_{OL} = \frac{1}{2\pi R_{out} C_{out}} = \frac{1}{2\pi 207k\Omega * 5pF} = 153.773kHz$$

- For Cin=4pF

$$\beta = \frac{C_F}{C_{IN} + C_F} = \frac{4pF}{4pF + 4pF} = \frac{1}{2} \; so \; A_{CL} = \frac{A_{OL}}{1 + \beta A_{CL}} = \frac{65.2}{1 + \frac{1}{2} * 65.2} = 1.94$$

$$BW = \frac{1 + \beta A_{OL}}{2\pi R_{out} C_{out}} = \frac{1 + \frac{1}{2} * 65.2}{2\pi * 207k\Omega * (5pF + (4pF||4pF))} = 3.691MHz$$

$$GBW = A_{CL} * BW = 1.94 * 3.691MHz = 7.161MHz$$

- For Cin=12pF

$$\beta = \frac{C_F}{C_{IN} + C_F} = \frac{4pF}{12pF + 4pF} = \frac{1}{4} \; so \; A_{CL} = \frac{A_{OL}}{1 + \beta A_{CL}} = \frac{65.2}{1 + \frac{1}{4} * 65.2} = 3.77$$

$$BW = \frac{1 + \beta A_{OL}}{2\pi R_{out} C_{out}} = \frac{1 + \frac{1}{4} * 65.2}{2\pi * 207k\Omega * (5pF + (12pF||4pF))} = 1.663MHz$$

$$GBW = A_{CL} * BW = 3.77 * 1.663MHz = 6.27MHz$$

	$C_{IN} = 4pF$		$C_{IN} = 12pF$	
	Simulation	**Analytical**	**Simulation**	**Analytical**
A_{CL}	1.938	1.94	3.761	3.77
BW	$3.655MHz$	$3.691MHZ$	$1.645MHz$	$1.663MHz$
GBW	$7.101MHz$	$7.161MHz$	$6.202MHz$	$6.27MHz$

4. Comparing between the results obtained here and the results in Part 1

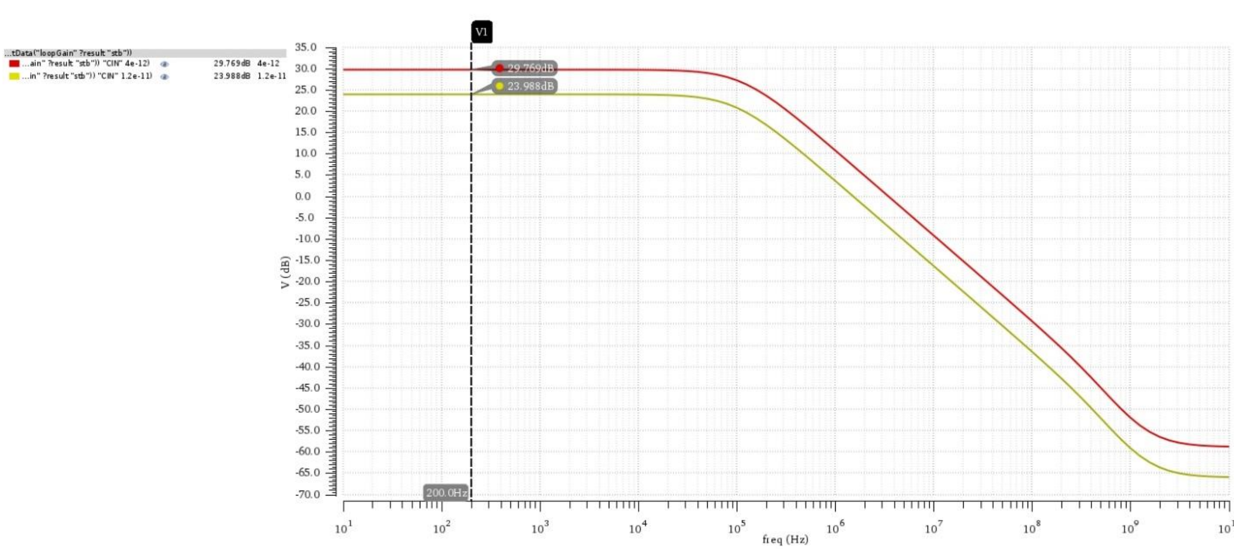
	$C_{IN} = 4pF$		$C_{IN} = 12pF$	
	Behavioral OTA	**Real OTA**	**Behavioral OTA**	**Real OTA**
A_{CL}	1.94	1.938	3.769	3.761
BW	$5.164MHz$	$3.655MHz$	$2.662MHz$	$1.645MHz$
GBW	$10.05MHz$	$7.101MHz$	$10.05MHz$	$6.202MHz$

5. As Cin increase β decrease so the closed loop gain increase and the BW decrease as the GBW remain constant

- As Cin increase β decrease and the capacitance of negative feedback increase Cout of the circuit and decrease the BW and GBW

2. Loop gain vs frequency.

1. Plotting loop gain in dB for the two values of CIN



2. Annotating the DC loop gain, the dominant pole, and the unity gain frequency

Parameters: CIN=4p			
1	ITI_Su2024:5T_OTA_tb:1	LG	30.79
1	ITI_Su2024:5T_OTA_tb:1	LG(DB)	29.77
1	ITI_Su2024:5T_OTA_tb:1	BW	114.4k
1	ITI_Su2024:5T_OTA_tb:1	UGF	3.566M
1	ITI_Su2024:5T_OTA_tb:1	GBW	3.532M
1	ITI_Su2024:5T_OTA_tb:1	PM	-88.39
Parameters: CIN=12p			
2	ITI_Su2024:5T_OTA_tb:1	LG	15.83
2	ITI_Su2024:5T_OTA_tb:1	LG(DB)	23.99
2	ITI_Su2024:5T_OTA_tb:1	BW	97.46k
2	ITI_Su2024:5T_OTA_tb:1	UGF	1.549M
2	ITI_Su2024:5T_OTA_tb:1	GBW	1.546M
2	ITI_Su2024:5T_OTA_tb:1	PM	-86.48

3. Hand analysis for dc loop gain and BW

- For Cin =4pF

$$LG = \beta * A_{OL} = \frac{1}{2} * 65.2 = 32.6$$

$$BW_{LG} = \frac{1}{2\pi R_{out} C_{out}} = \frac{1}{2\pi * 207k\Omega * (5pF + (4pF||4pF))} = 109.84kHz$$

$$GBW = BW_{LG} * LG = 109.84kHz * 32.6 = 3.58MHz$$

- For Cin=12pF

$$LG = \beta * A_{OL} = \frac{1}{4} * 65.2 = 16.3$$

$$BW = \frac{1}{2\pi R_{out} C_{out}} = \frac{1}{2\pi * 207k\Omega * (5pF + (12pF||4pF))} = 96.11kHz$$

$$GBW = BW_{LG} * LG = 96.11kHz * 16.3 = 1.567MHz$$

	$C_{IN} = 4pF$		$C_{IN} = 12pF$	
	Simulation	**Analytical**	**Simulation**	**Analytical**
LG	30.79	32.6	15.83	16.3
BW	$114.4kHz$	$109.84kHZ$	$97.46kHz$	$96.11Hz$
GBW	$3.532MHz$	$3.58MHz$	$1.546MHz$	$1.567MHz$

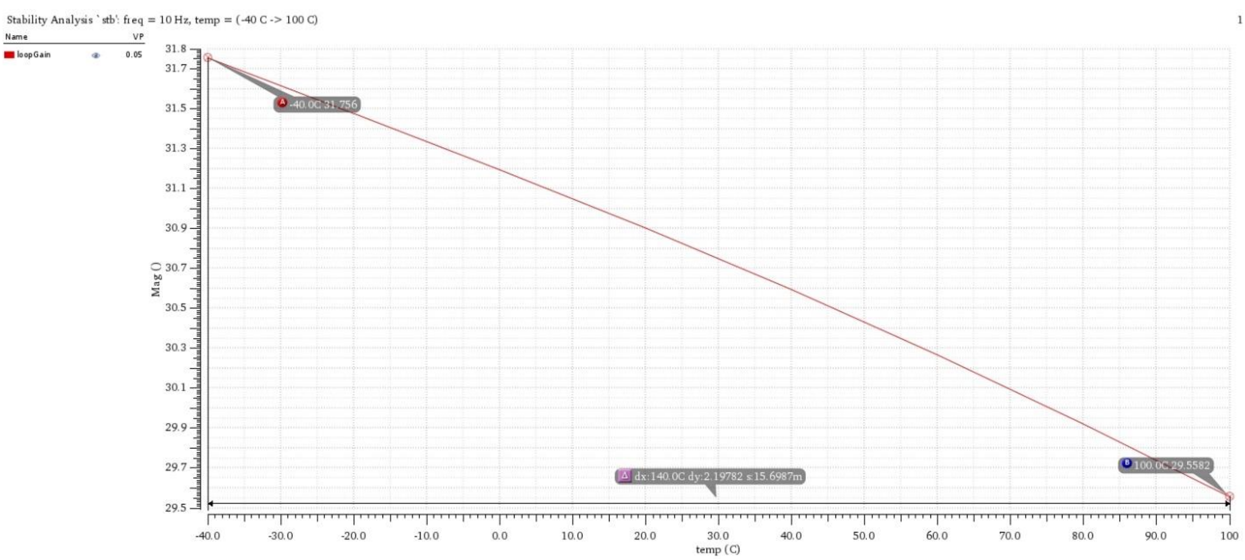
4. Comparing between the results obtained here and the results in Part 1

	$C_{IN} = 4pF$		$C_{IN} = 12pF$	
	Behavioral OTA	**Real OTA**	**Behavioral OTA**	**Real OTA**
LG	32.63	30.79	16.31	15.83
BW	$153.5kHz$	$114.4kHz$	$153.5kHz$	$97.46kHz$
GBW	$5.02MHz$	$3.532MHz$	$2.51MHz$	$1.546MHz$

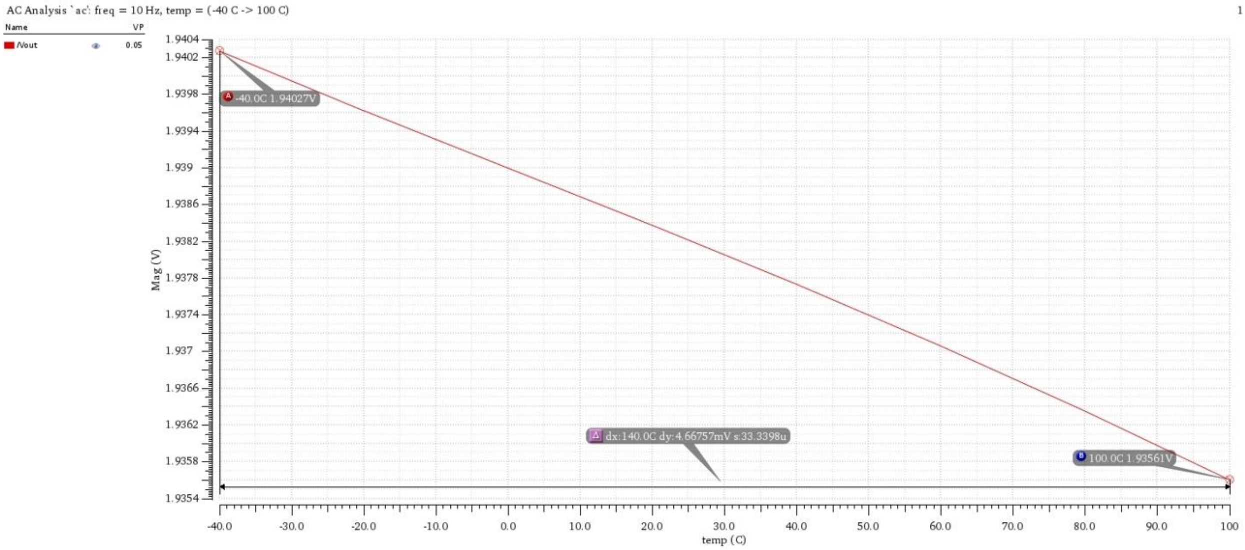
5. The β is independent of frequency but the feedback give some capacitance load on the output node and this reduces the BW so the UGF and GBW decrease

3. Gain Desensitization.

1. Plotting LG Vs Temperature



2. Plotting Vout Vs temperature

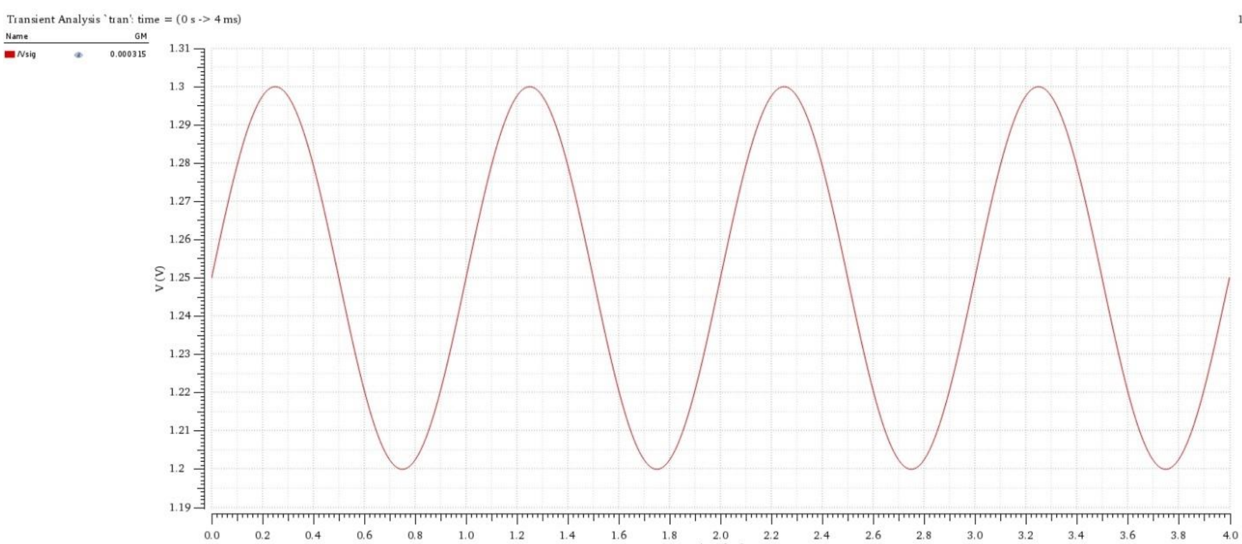


6. We see from the graph the change in gain is around 4.668mV and as the gain is 1.938V@T=27 so the percentage of change in gain $\frac{\delta A_{CL}}{A_{CL}} = \frac{4.668mV}{1938mV} = .24\%$

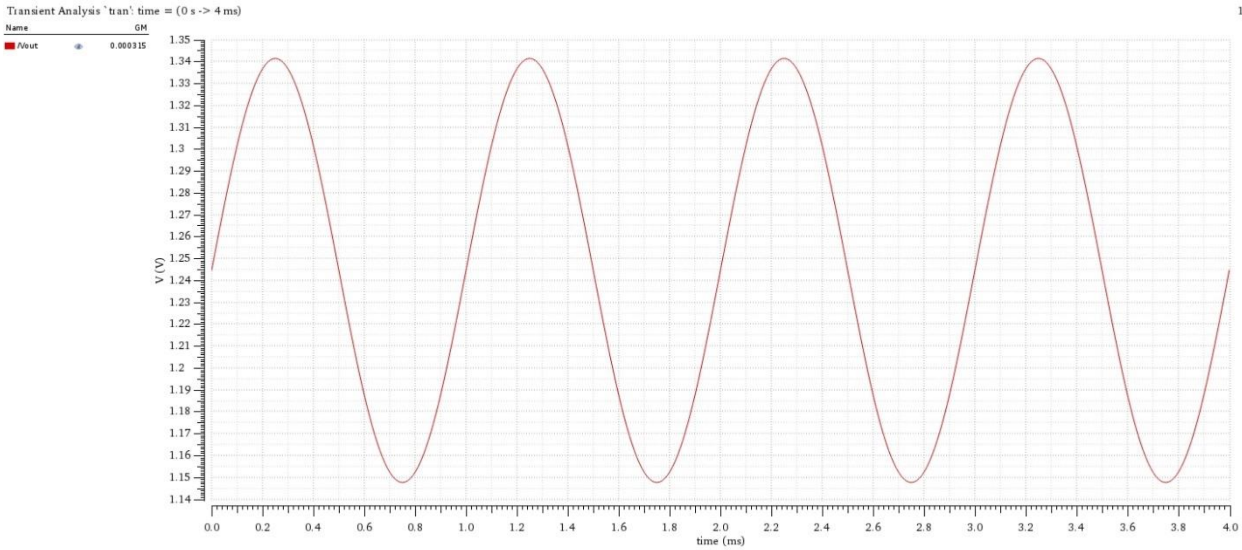
	Behavioral OTA	Real OTA
$\delta A_{CL}/A_{CL}$	**3.96**	**.24**

4. Transient analysis

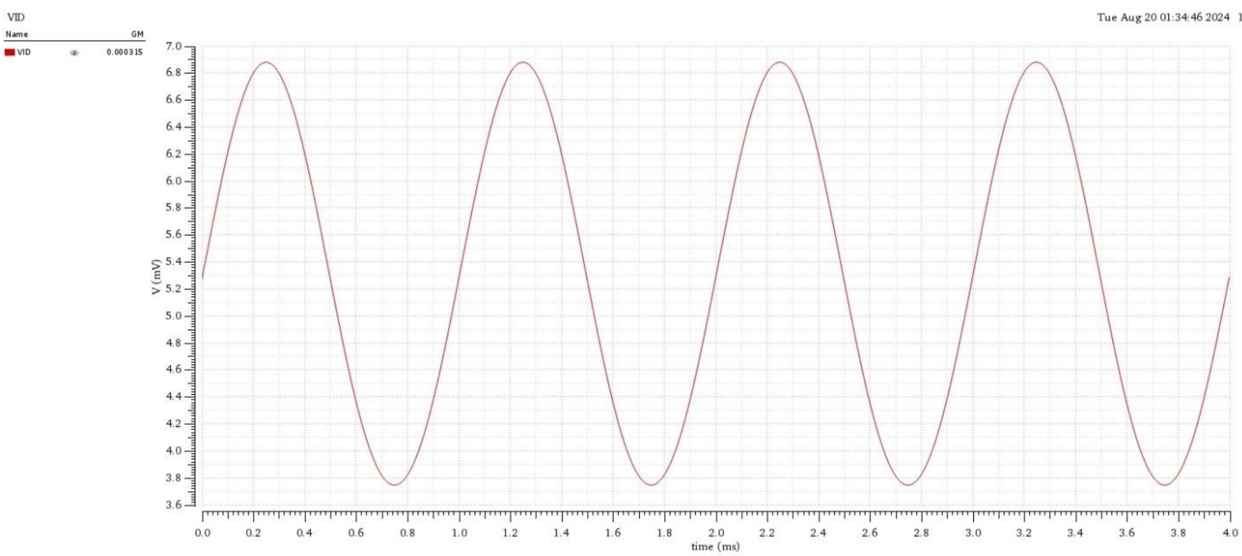
1. Plotting the input signal



2. Plotting the output signal



3. Plotting the differential input signal of the OTA (VP – VN)

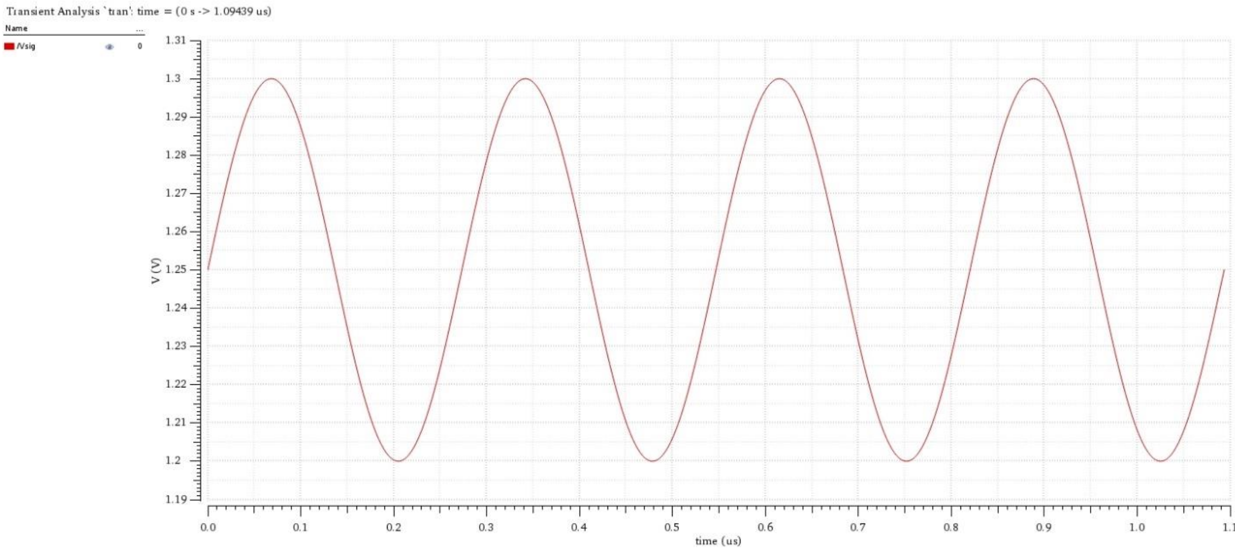


4. the relation between the output and (VP – VN)

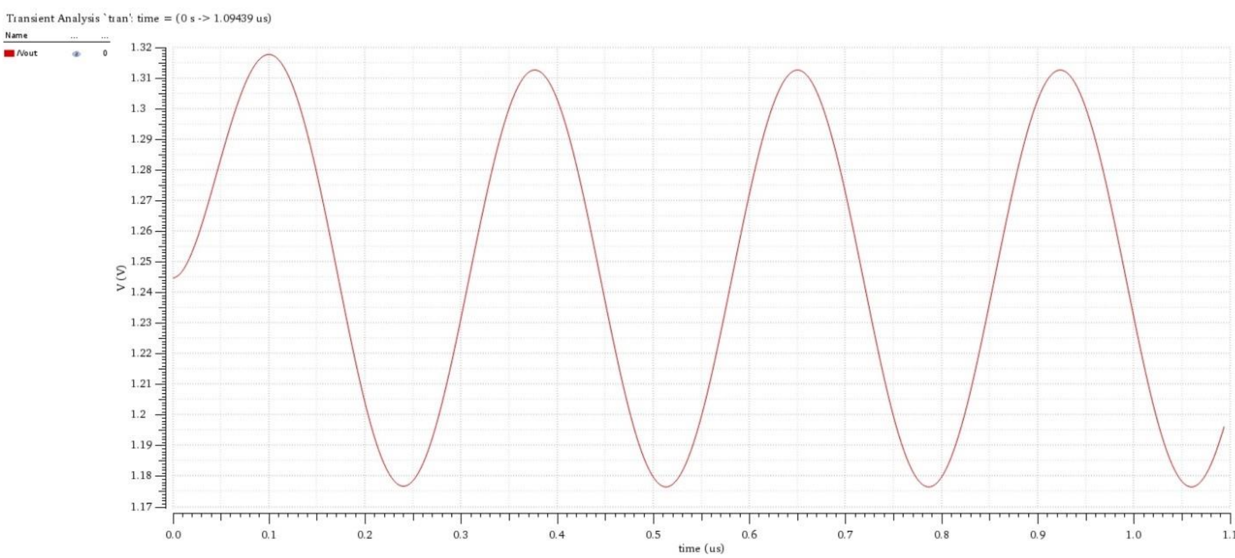
ITI_Su2024:5T_OTA_tb:1	VIDpp	3.135m
ITI_Su2024:5T_OTA_tb:1	Vsigpp	99.99m
ITI_Su2024:5T_OTA_tb:1	Voutpp	193.8m

7. As we see $\frac{V_{out}}{V_{ID}} = \frac{193.8}{3.135} = 61.81 \approx A_{OL}$ and we notice that the diffrence between the two input node is approximatly zero and will decrease more if we increase the open loop gain

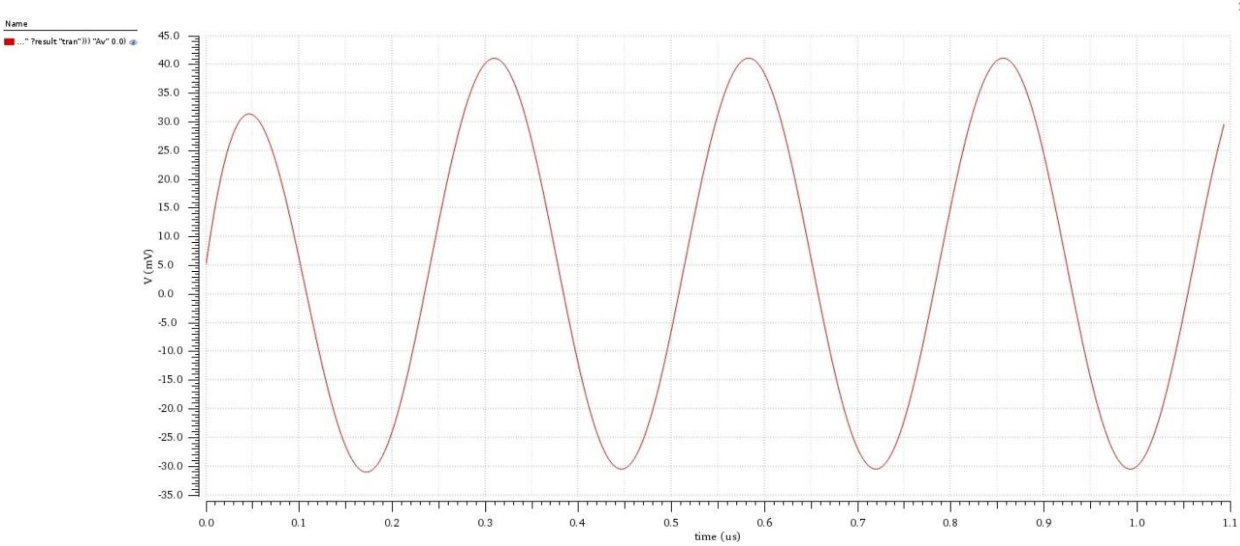
5. Plotting the input signal $@f = 3.655MHz$



6. Plotting the output signal$@f = 3.655MHz$



7. Plotting the differential input signal of the OTA (VP – VN) $@f = 3.655MHz$



8. the relation between the output and (VP – VN)

ITI_Su2024:5T_OTA_tb:1	VIDpp	72.12m
ITI_Su2024:5T_OTA_tb:1	Vsigpp	99.99m
ITI_Su2024:5T_OTA_tb:1	Voutpp	141.1m

8. As we see $\frac{V_{out}}{V_{ID}} = \frac{141.1}{72.12} = 1.96 \approx A_{CL}$ as the open-loop and closed-loop asymptotes coincide at this high frequency. And as GBW remain constant so the gain of open-loop at this high frequency equal the gain of closed-loop