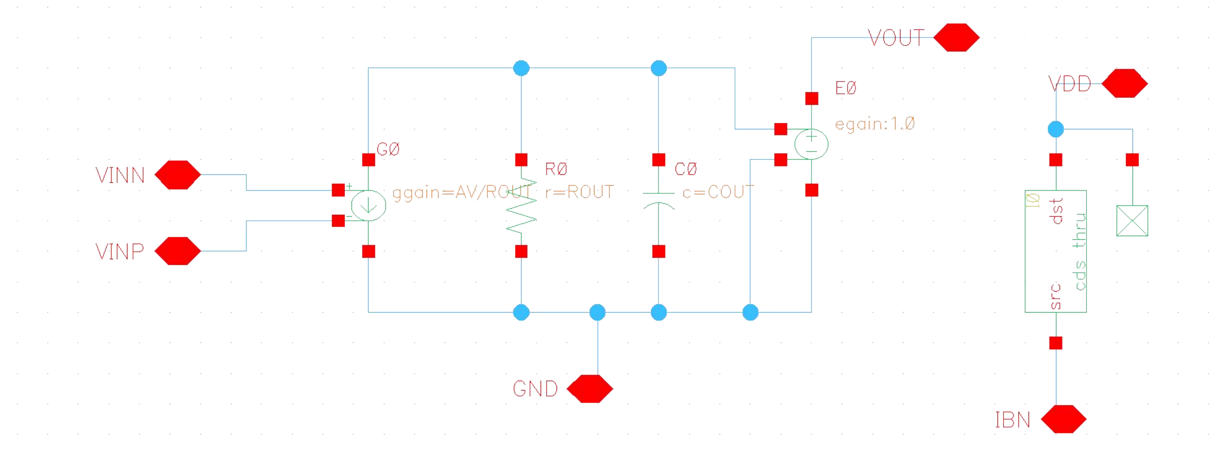
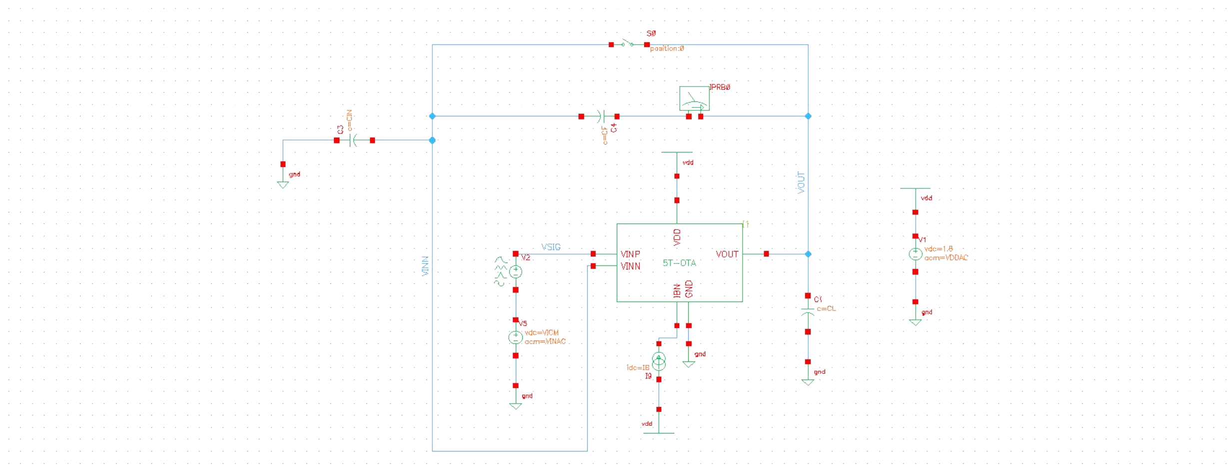
Lab 08

PART 1: Feedback with Behavioral OTA:

Behavioral schematic:

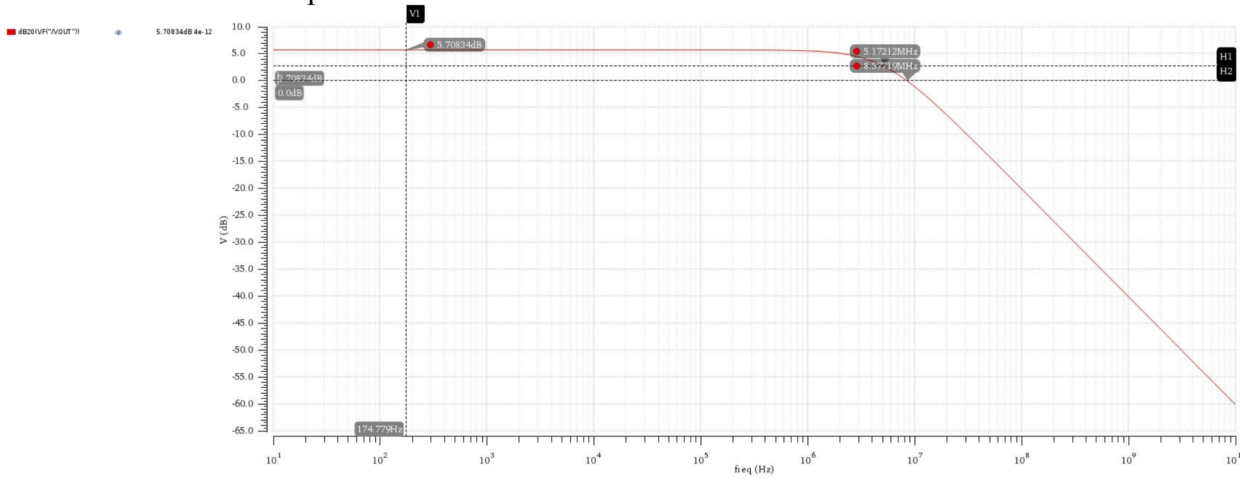


Testbench schematic:

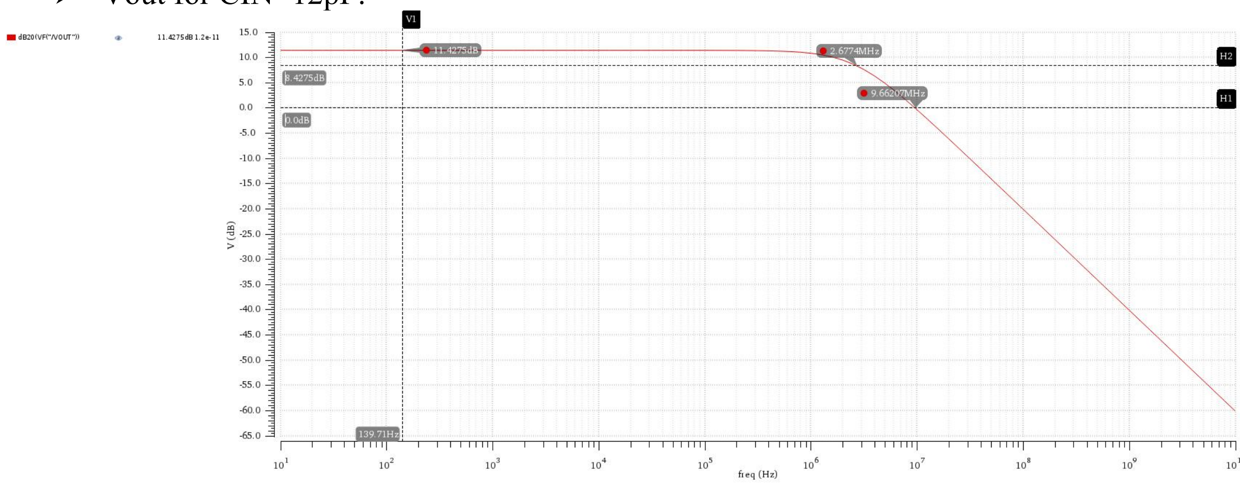


1) Closed loop gain vs frequency:

- **Plot Vout in dB for the two values of CIN (4pF and 12pF). Indicate the DC gain, the bandwidth, and the unity gain frequency in the plot.**
  - ➢ Vout for CIN=4pF:



  - ➢ Vout for CIN=12pF:



  - ➢ Results:

Point	Test	Output	Nominal	Spec	Weight	Pass/Fail
Parameters: CIN=4p						
1	ITI_Labs:Lab8_teastbench:1	dB20(VF("/VOUT"))				
1	ITI_Labs:Lab8_teastbench:1	ymax(dB20(VF("/VOUT")))	5.708			
1	ITI_Labs:Lab8_teastbench:1	bandwidth(VF("/VOUT") 3 "lo...	5.181M			
1	ITI_Labs:Lab8_teastbench:1	gainBwProd(VF("/VOUT"))	10.02M			
1	ITI_Labs:Lab8_teastbench:1	ymax(mag(VF("/VOUT")))	1.929			
Parameters: CIN=12p						
2	ITI_Labs:Lab8_teastbench:1	dB20(VF("/VOUT"))				
2	ITI_Labs:Lab8_teastbench:1	ymax(dB20(VF("/VOUT")))	11.43			
2	ITI_Labs:Lab8_teastbench:1	bandwidth(VF("/VOUT") 3 "lo...	2.685M			
2	ITI_Labs:Lab8_teastbench:1	gainBwProd(VF("/VOUT"))	10.03M			
2	ITI_Labs:Lab8_teastbench:1	ymax(mag(VF("/VOUT")))	3.727			

• Compare the DC gain, BW, and GBW with hand analysis in a table.

DC gain:

for CIN=4pF: $A = 1 + \frac{CIN}{CF} = 2.$

for CIN=12pF: $A = 1 + \frac{CIN}{CF} = 4.$

Bandwidth:

for CIN=4pF: $BW = \frac{1}{2\pi * Rout * Cout}(1 + \beta * AOL) = \frac{(1+0.5*54.638)}{2\pi*167860*5.18*10^{-12}} = 5.183MHz.$

for CIN=12pF: $BW = \frac{1}{2\pi * Rout * Cout}(1 + \beta * AOL) = \frac{(1+0.25*54.638)}{2\pi*167860*5.18*10^{-12}} = 2.683MHz.$

GBW:

for CIN=4pF: $GBW = A * BW = 10.366MHz.$

for CIN=12pF: $GBW = A * BW = 10.732MHz.$

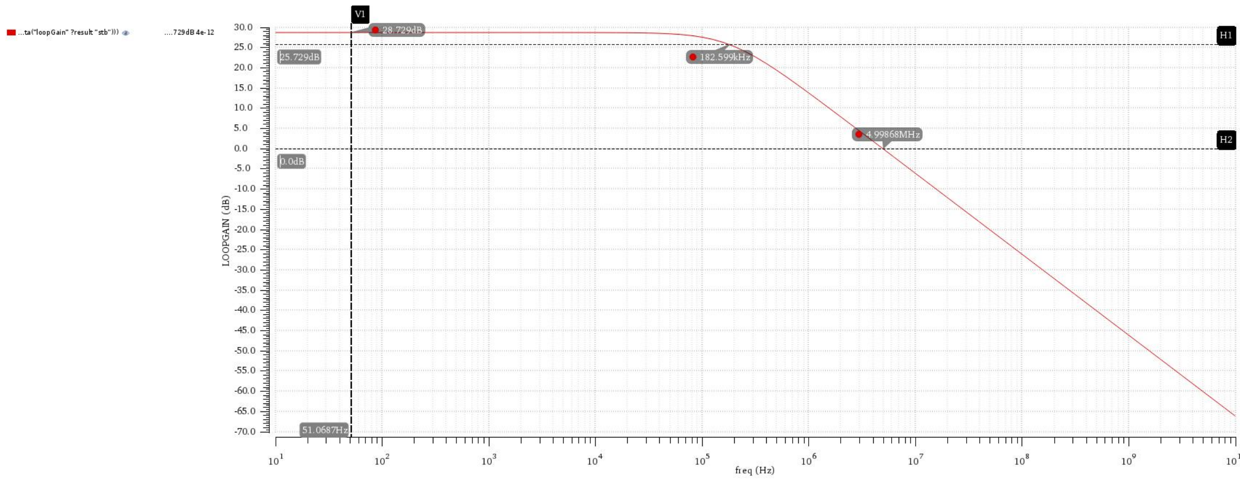
	CP=4pF		CP=12pF	
	Hand Analysis	Simulation	Hand Analysis	Simulation
Gain	2	1.929	4	3.727
BW	$5.183MHz$	$5.181MHz$	$2.683MHz$	$2.685MHz$
GBW	$10.366MHz$	$10.02MHz$	$10.732MHz$	$10.03MHz$

- **Comment on the difference between the results for the two values of CIN.**
  - The difference between the results is that when we increase CIN the gain increases but BW decreases with the same ratio as GBW is constant and GBW is constant as the output is the dominant pole as we can see when we changed CIN from 4pF to 12pF the gain doubled but BW decreased to half.
  - The gain in simulation is less because when we calculate the ACL analytically, we use the approximation of $\beta * AOL \gg 1$ so $ACL = \frac{1}{\beta}$ but in real $ACl = \frac{AOL}{1+\beta*AOL}$.
  - Note if we used the exact expression for ACL the hand analysis will be a lot more accurate.

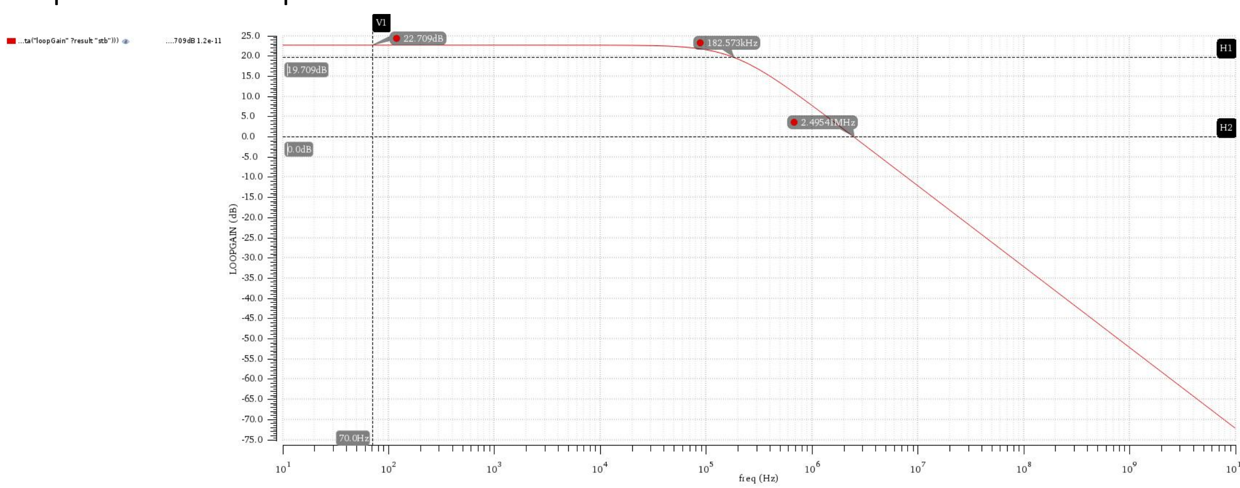
2) Loop gain vs frequency:

- **Plot loop gain in dB for the two values of CIN. Annotate the DC loop gain, the dominant pole, and the unity gain frequency in the plot.**

➢ Loop Gain for CIN=4pF:



➢ Loop Gain for CIN=12pF:



➢ Results:

Point	Test	Output	Nominal	Spec	Weight	Pass/Fail
Parameters: CIN=4p						
1	ITI_Labs:Lab8_teastbench:1	unityGainFreq(mag(getData(...	5M			
1	ITI_Labs:Lab8_teastbench:1	ymax(mag(getData("loopGai...	27.32			
1	ITI_Labs:Lab8_teastbench:1	dB20(mag(getData("loopGai...				
1	ITI_Labs:Lab8_teastbench:1	ymax(dB20(mag(getData("lo...	28.73			
Parameters: CIN=12p						
2	ITI_Labs:Lab8_teastbench:1	unityGainFreq(mag(getData(...	2.497M			
2	ITI_Labs:Lab8_teastbench:1	ymax(mag(getData("loopGai...	13.66			
2	ITI_Labs:Lab8_teastbench:1	dB20(mag(getData("loopGai...				
2	ITI_Labs:Lab8_teastbench:1	ymax(dB20(mag(getData("lo...	22.71			

- **Compare DC LG and GBW with hand analysis in a table.**

DC Loop Gain:

For CIN=4pF: $LG = \beta * AOL = 0.5 * 54.638 = 27.319 = 28.739dB$.

For CIN=12pF: $LG = \beta * AOL = 0.25 * 54.638 = 13.6595 = 22.7dB$.

GBW:

For CIN=4pF: $GBW = \beta * GBWol = 0.5 * 10MHz = 5MHz$.

For CIN=12pF: $GBW = \beta * GBWol = 0.25 * 10MHz = 2.5MHz$.

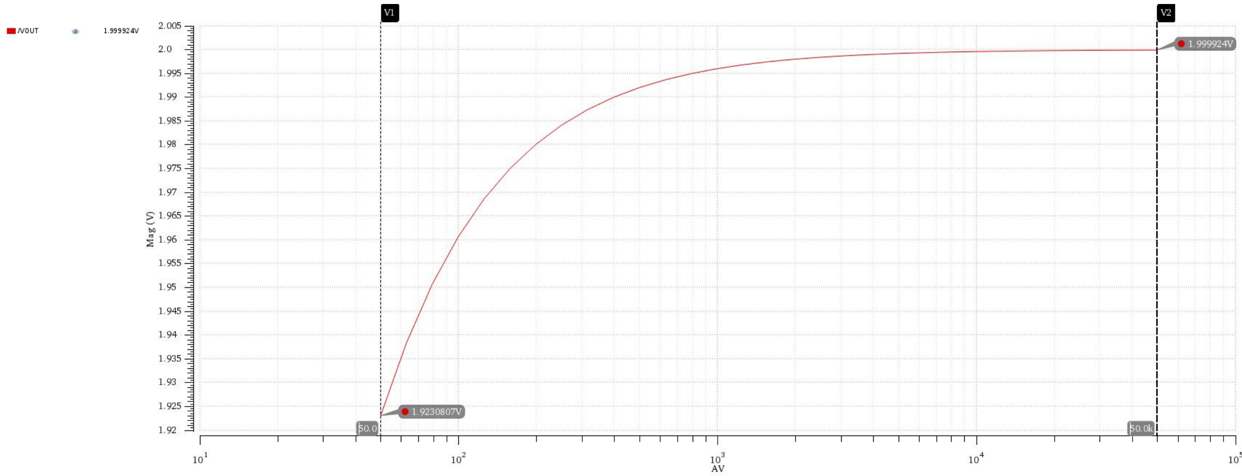
	CP=4pF		CP=12pF	
	Hand Analysis	Simulation	Hand Analysis	Simulation
Gain	$28.739dB$	$28.73dB$	$22.7dB$	$22.71dB$
GBW	$5MHz$	$5MHz$	$2.5MHz$	$2.497MHz$

- **Comment on the differences between the results for the two values of CIN.**

➢ When we increase CIN beta decreases as $\beta = \frac{CF}{CF+CIN}$ then the loop gain decreases as $LG = \beta * AOL$ then the UGF (and GBW) decreases as $GBW = \beta * AOL * BWol = \beta * GBWol$

3) Gain Desensitization:

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



• **Calculate the percent change in closed loop gain (magnitude, not dB). Note that open loop gain (Av) changes by three orders of magnitude (60 dB). Comment.**

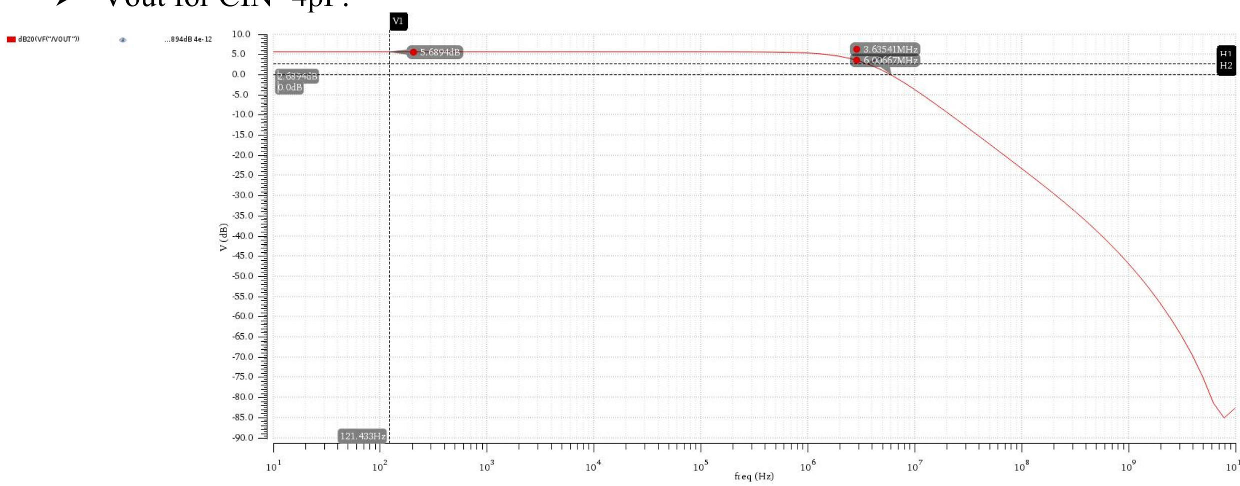
$$percentage = \frac{1.999924 - 1.9230807}{1.9230807} * 100 = 3.99\% \approx 4\%$$

Comment: the closed loop gain is not affected by the change in AOL which was a huge change by three order of magnitude (60dB) but the closed loop gain only changed a small change so the circuit became more linear (doesn't depend on input) and more stable to PVT changes.

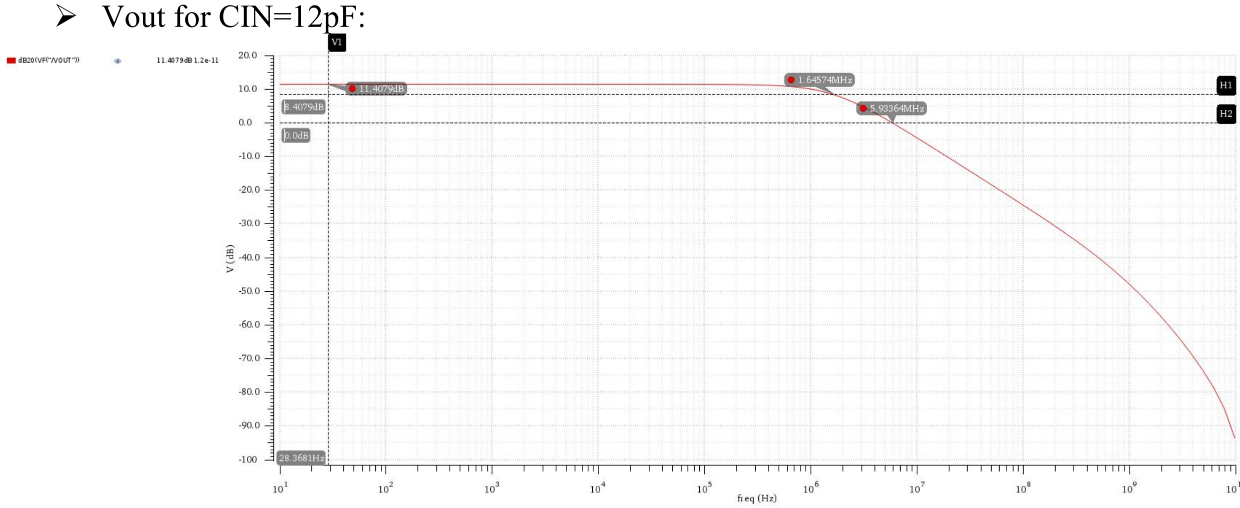
PART 2: Feedback with Real 5T OTA:

1. Closed loop gain vs frequency:

- **Plot Vout in dB for the two values of CIN (4pF and 12pF). Indicate the DC gain, the bandwidth, and the unity gain frequency in the plot.**
    - ➢ Vout for CIN=4pF:



- ➢ Vout for CIN=12pF:



- Results:

Point	Test	Output	Nominal	Spec	Weight	Pass/Fail
Parameters: CIN=4p						
1	ITI_Labs:Lab8_teastbench:1	dB20(VF("/VOUT"))				
1	ITI_Labs:Lab8_teastbench:1	ymax(dB20(VF("/VOUT")))	5.689			
1	ITI_Labs:Lab8_teastbench:1	ymax(mag(VF("/VOUT")))	1.925			
1	ITI_Labs:Lab8_teastbench:1	bandwidth(VF("/VOUT") 3 "lo...	3.647M			
1	ITI_Labs:Lab8_teastbench:1	gainBwProd(VF("/VOUT"))	7.037M			
Parameters: CIN=12p						
2	ITI_Labs:Lab8_teastbench:1	dB20(VF("/VOUT"))				
2	ITI_Labs:Lab8_teastbench:1	ymax(dB20(VF("/VOUT")))	11.41			
2	ITI_Labs:Lab8_teastbench:1	ymax(mag(VF("/VOUT")))	3.719			
2	ITI_Labs:Lab8_teastbench:1	bandwidth(VF("/VOUT") 3 "lo...	1.649M			
2	ITI_Labs:Lab8_teastbench:1	gainBwProd(VF("/VOUT"))	6.147M			

• Compare the DC gain, BW, and GBW with hand analysis in a table.

DC gain:

for CIN=4pF: $A = 1 + \frac{CIN}{CF} = 2.$

for CIN=12pF: $A = 1 + \frac{CIN}{CF} = 4.$

Bandwidth:

$Rout = (ron//rop) = 169.3k\Omega$

for CIN=4pF: $cout = (CF//CIN) + CL = 7pF$

$$BW = \frac{1}{2\pi * Rout * Cout}(1 + \beta * AOL) = \frac{(1 + 0.5 * 54.638)}{2\pi * 169300 * 7 * 10^{-12}} = 3.8MHz.$$

for CIN=12pF: $cout = (CF//CIN) + CL = 8pF$

$$BW = \frac{1}{2\pi * Rout * Cout}(1 + \beta * AOL) = \frac{(1 + 0.25 * 54.638)}{2\pi * 169300 * 8 * 10^{-12}} = 1.723MHz.$$

GBW:

for CIN=4pF: $GBW = A * BW = 7.6MHz.$

for CIN=12pF: $GBW = A * BW = 6.892MHz.$

	CP=4pF		CP=12pF	
	Hand Analysis	Simulation	Hand Analysis	Simulation
Gain	2	1.925	4	3.719
BW	$3.8MHz$	$3.647MHz$	$1.723MHz$	$1.649MHz$
GBW	$7.6MHz$	$7.037MHz$	$6.892MHz$	$6.147MHz$

- **Comment on the difference between the results for the two values of CIN.**
  - The difference between the results is that when we increase CIN the gain increases. On the other hand cout increases which decreases the BW than what we expected so GBW decreases.

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

	CP=4pF		CP=12pF	
	Part1	Part2	Part1	Part2
Gain	1.929	1.925	3.727	3.719
BW	$5.181MHz$	$3.647MHz$	$2.685MHz$	$1.649MHz$
GBW	$10.02MHz$	$7.037MHz$	$10.03MHz$	$6.147MHz$

- **You will notice that the bandwidth, and consequently the GBW are much smaller than Part1. Why? Comment.**

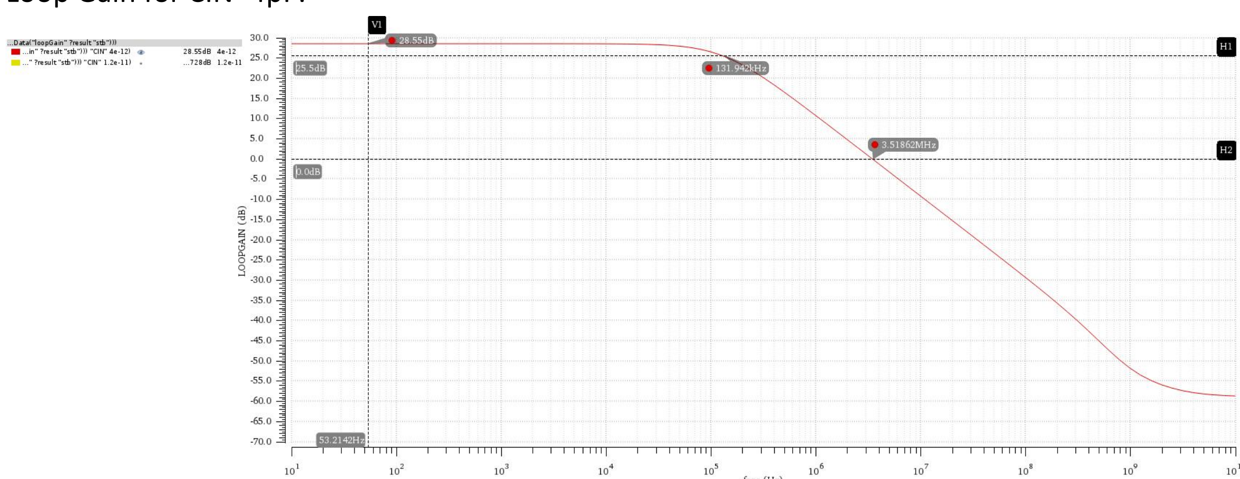
The BW and GBW are smaller because of the loading effect of the feedback network on the load capacitance which increased the capacitance and decreased the BW and GBW.

Comment: if the network has capacitances, it is always expected to have less BW because of the loading effect.

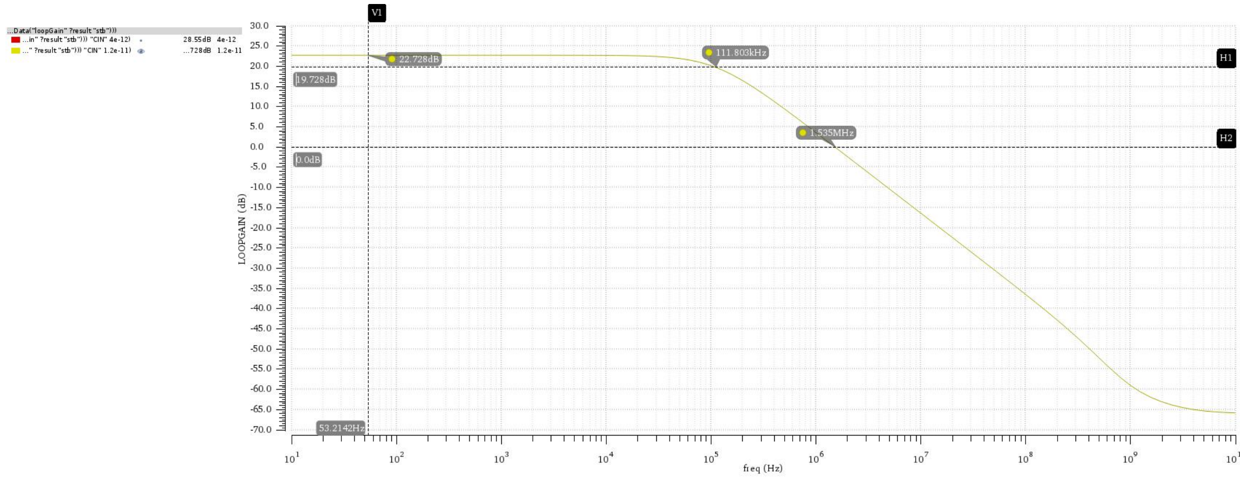
2. Loop gain vs frequency:

- **Plot loop gain in dB for the two values of CIN. Annotate the DC loop gain, the dominant pole, and the unity gain frequency in the plot.**

- Loop Gain for CIN=4pF:



- Loop Gain for CIN=12pF:



- Results:

Point	Test	Output	Nominal	Spec	Weight	Pass/Fail
Parameters: CIN=4p						
1	ITI_Labs:Lab8_teastbench:1	dB20(mag(getData("loopGai...				
1	ITI_Labs:Lab8_teastbench:1	ymax(dB20(mag(getData("lo...	28.55			
1	ITI_Labs:Lab8_teastbench:1	ymax(mag(getData("loopGai...	26.76			
1	ITI_Labs:Lab8_teastbench:1	unityGainFreq(mag(getData(...	3.542M			
Parameters: CIN=12p						
2	ITI_Labs:Lab8_teastbench:1	dB20(mag(getData("loopGai...				
2	ITI_Labs:Lab8_teastbench:1	ymax(dB20(mag(getData("lo...	22.73			
2	ITI_Labs:Lab8_teastbench:1	ymax(mag(getData("loopGai...	13.69			
2	ITI_Labs:Lab8_teastbench:1	unityGainFreq(mag(getData(...	1.54M			

- **Compare DC LG and GBW with hand analysis in a table.**

DC Loop Gain:

For CIN=4pF: $LG = \beta * AOL = 0.5 * 54.638 = 27.319 = 28.739dB$.

For CIN=12pF: $LG = \beta * AOL = 0.25 * 54.638 = 13.6595 = 22.7dB$.

GBW:

For CIN=4pF: $GBW = \beta * GBWol = 0.5 * 7.6MHz = 3.6MHz$.

For CIN=12pF: $GBW = \beta * GBWol = 0.25 * 6.892MHz = 1.723MHz$.

Note: I used the analytical GBW I got for the closed loop as it equals GBW for open loop and also note that if we used the exact expression for ACL when calculating GBWcl we will get more accurate results.

	CP=4pF		CP=12pF	
	Hand Analysis	Simulation	Hand Analysis	Simulation
Gain	$28.739dB$	$28.55dB$	$22.7dB$	$22.73dB$
GBW	$3.6MHz$	$3.542MHz$	$1.723MHz$	$1.54MHz$

- **Comment on the differences between the results for the two values of CIN.**

➢ When we increase CIN beta decreases as $\beta = \frac{CF}{CF+CIN}$ then the loop gain decreases as $LG = \beta * AOL$ then the UGF (and GBW) decreases as $GBW = \beta * AOL * BWol = \beta * GBWol$

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

	CP=4pF		CP=12pF	
	Part1	Part2	Part1	Part2
LG	$28.73dB$	$28.55dB$	$22.71dB$	$22.73dB$
GBW	$5MHz$	$3.542MHz$	$2.497MHz$	$1.54MHz$

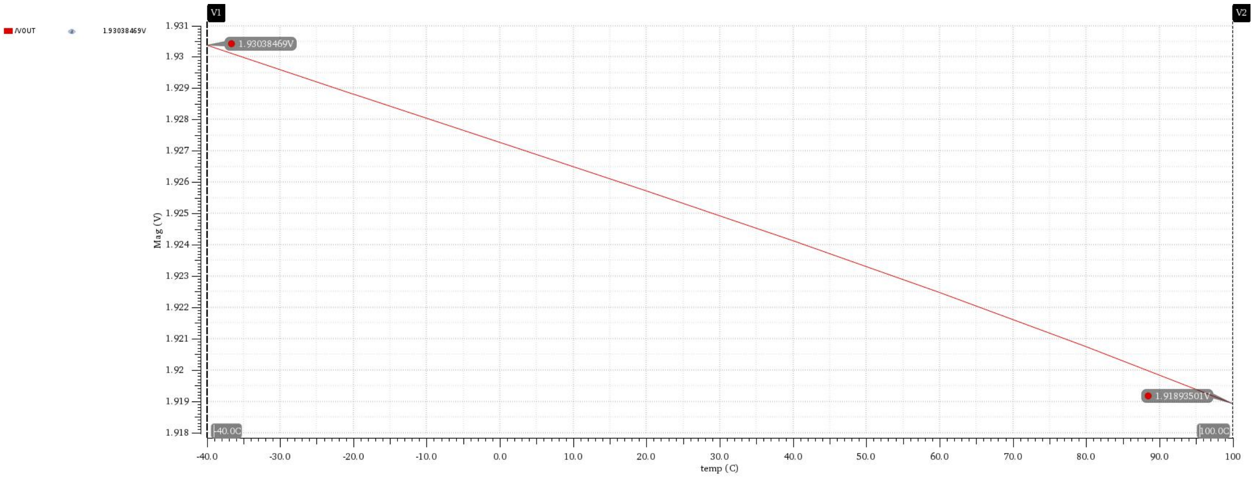
- **You will notice that the unity gain frequency is much smaller than Part 1. Why? Comment.**

The UGF(GBW) is smaller because of the loading effect of the feedback network on the load capacitance which increased the capacitance cout and decreased the BW and GBW.

Comment: if the network has capacitances, it is always expected to have less BW because of the loading effect.

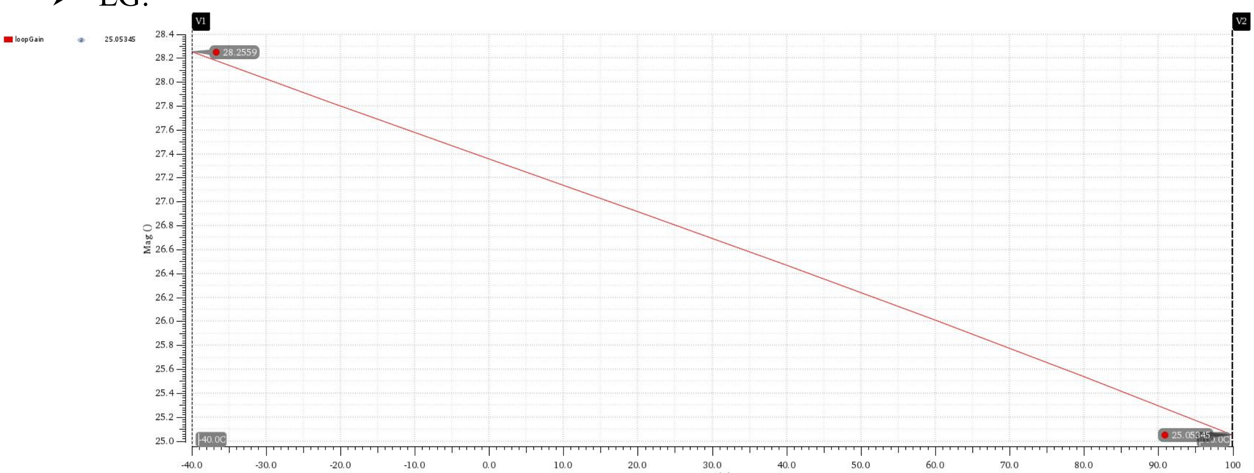
3. Gain Desensitization:

- **Compare the percent change in the DC loop gain (from STB) and the DC closed loop gain (from AC) across temperature extremes. Do NOT use dB when calculating percent change. Comment.**
  - ACL:



$$percentage = \left|\frac{1.91893501 - 1.93038469}{1.93038469}\right| * 100 = 0.593\%$$

- LG:



$$percentage = \left|\frac{25.05345 - 28.2559}{28.2559}\right| * 100 = 11.3\%$$

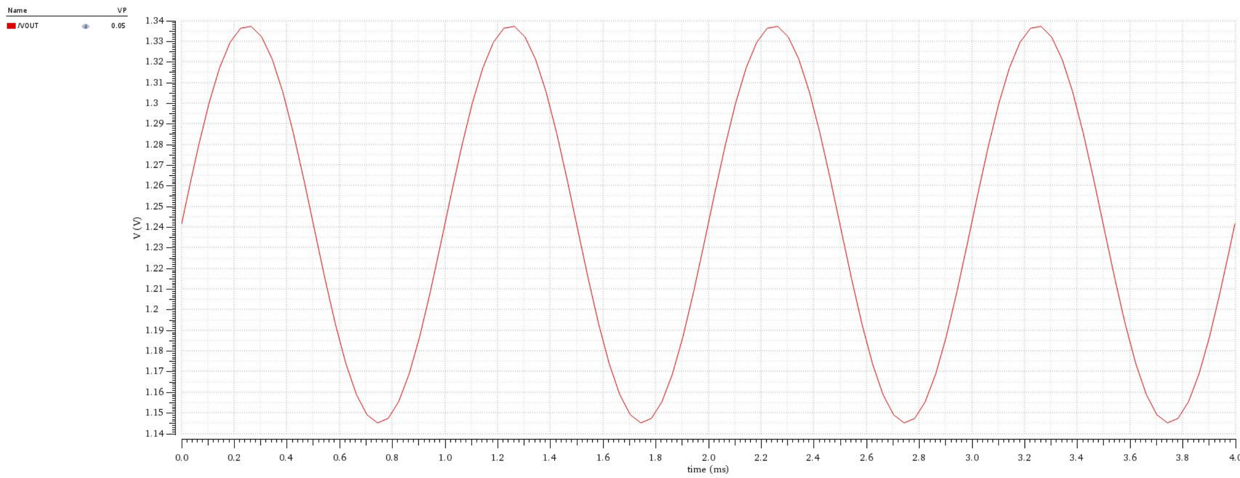
Comment:

The closed loop gain doesn’t change a lot with the variation of temperature even this variation changed the loop gain and open loop gain by more than 10% the closed loop gain didn’t change approximately so the gain became stable against PVT variations and this is the idea of gain desensitization which we get as an advantage of feedback.

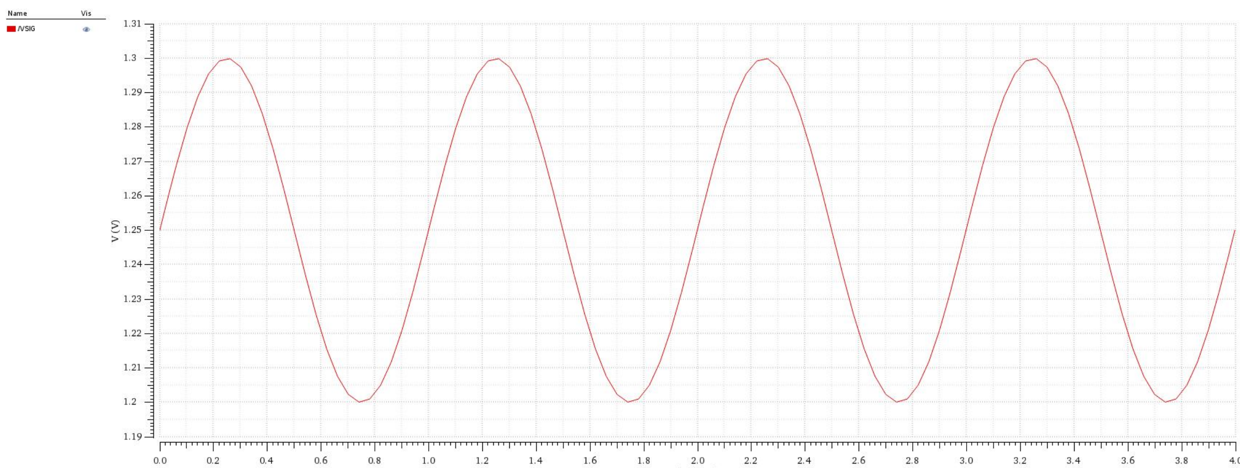
4. Transient analysis:

- **Plot the input signal, the output signal, and the differential input signal (VP –VN).**

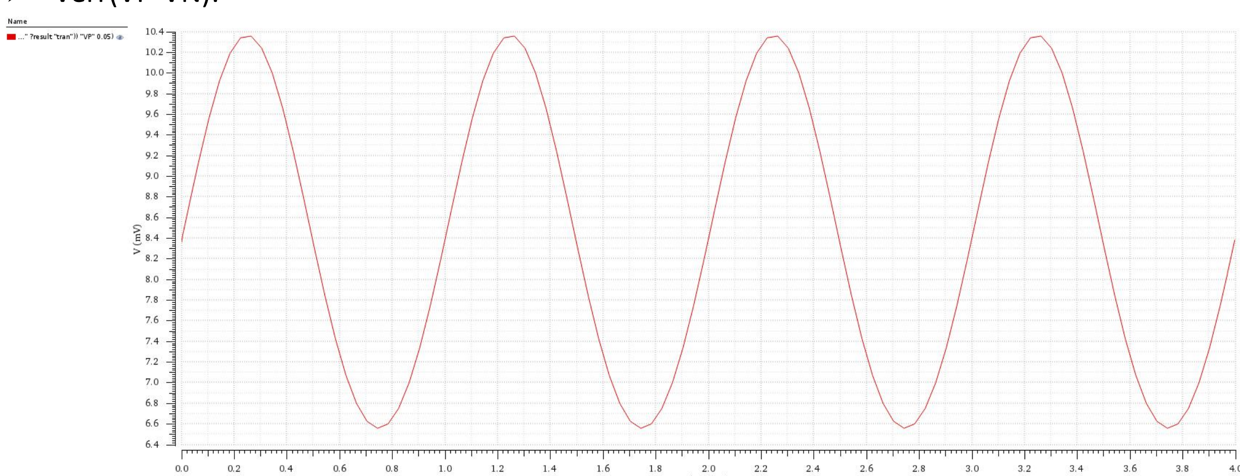
  - Vout:



  - Vin:

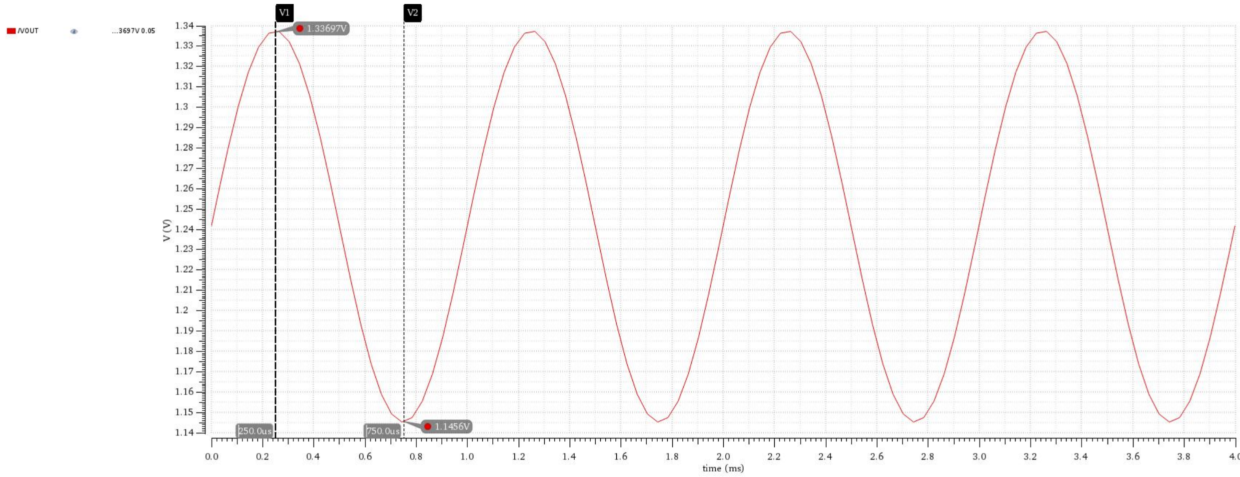


  - Verr(VP-VN):



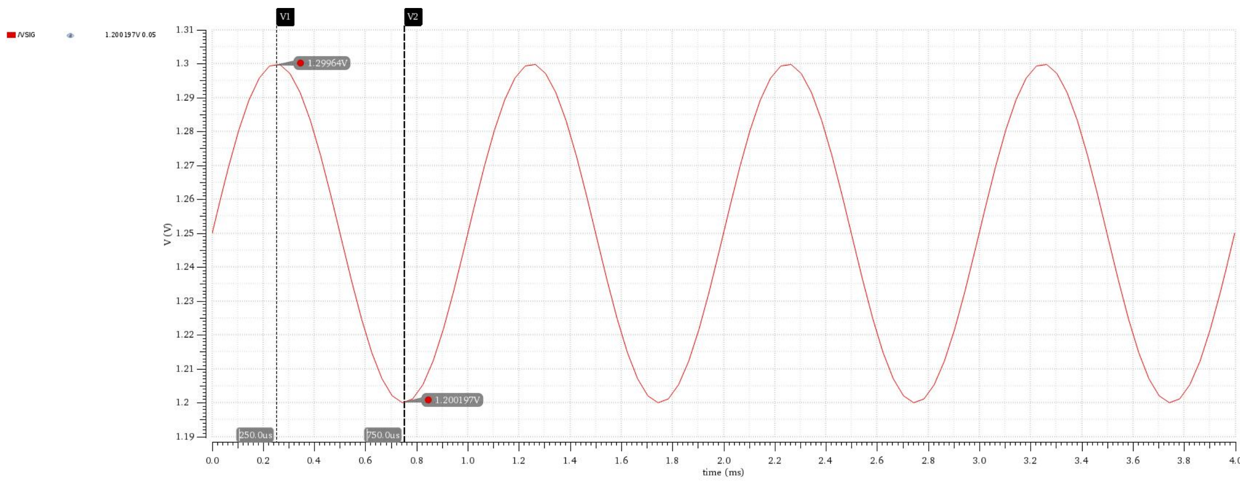
• Calculate the peak-to-peak voltage of the previous three signals. What is the relation between the output and (VP – VN)? Comment.

- Vout:



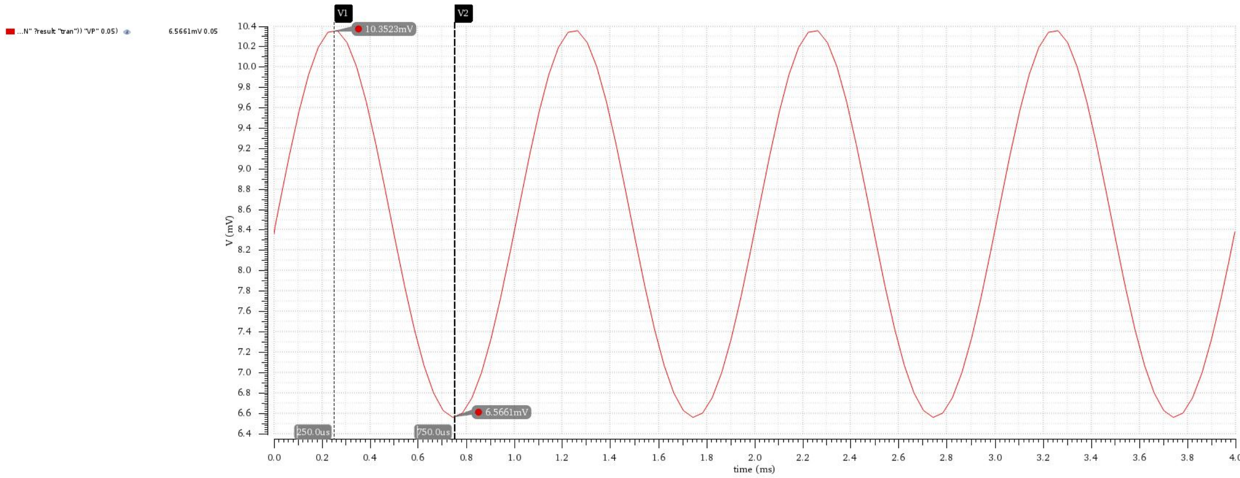
$$Vptp = 1.33697 - 1.1456 = 191.37mV$$

- Vin:



$$Vptp = 1.29964 - 1.200197 = 99.44mV$$

➢ Verr(VP-VN):



$$Vptp = 10.3523 - 6.5661 = 3.7862mV$$

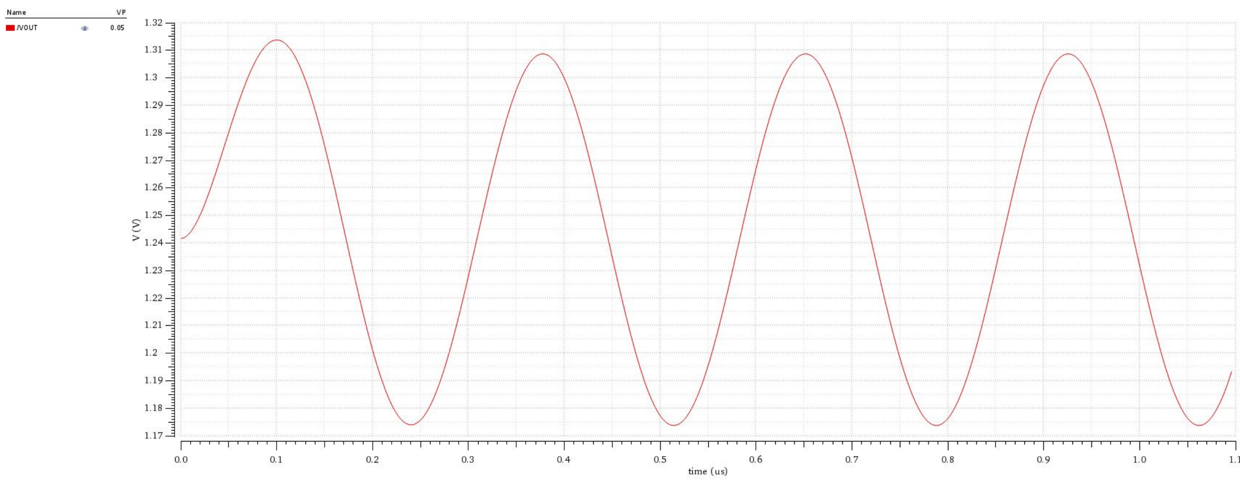
Comment:

➢ $\frac{Vout}{Verr} = \frac{191.37}{3.7862} = 50.544 \approx AOL$. the relation between Vout and the differential signal is the open loop gain.

➢ $\frac{Vout}{Vin} = \frac{191.37}{99.44} = 1.9244$. the relation between the Vout and Vin is the closed loop gain.

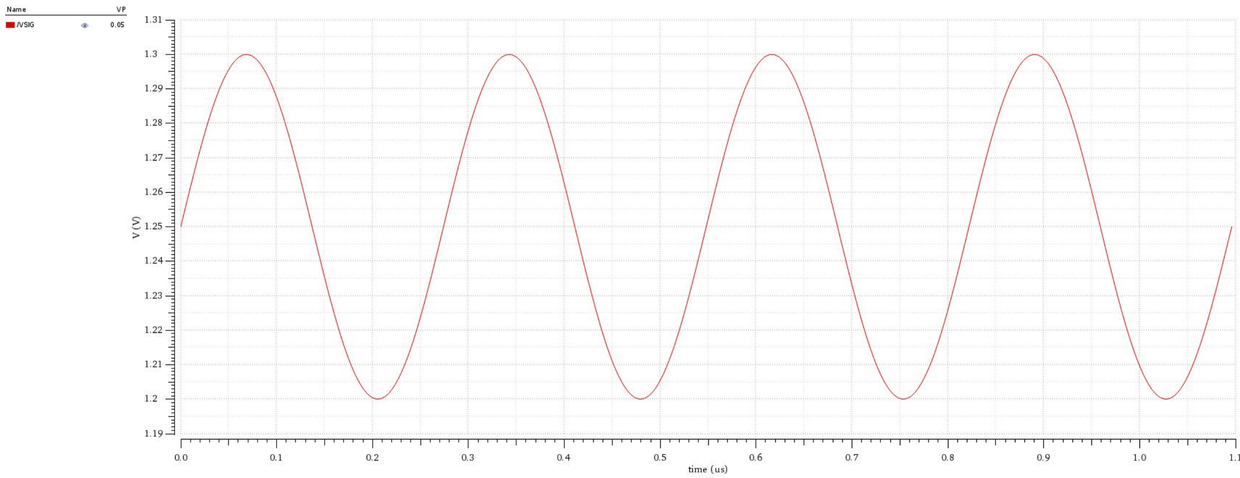
- **Repeat the transient analysis with FIN exactly equal to the closed loop bandwidth. Plot the input signal, the output signal, and the differential input signal of the OTA (VP – VN).**

➢ Vout:

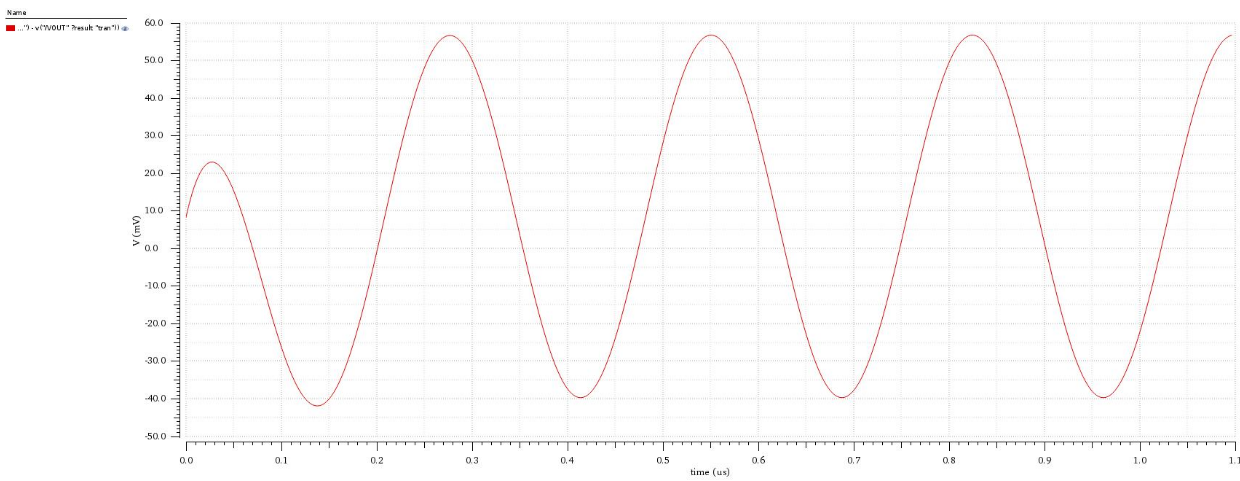


Note: this phase shift happens because we use F=BWcl which makes -45 shift in the output phase.

➢ Vin:

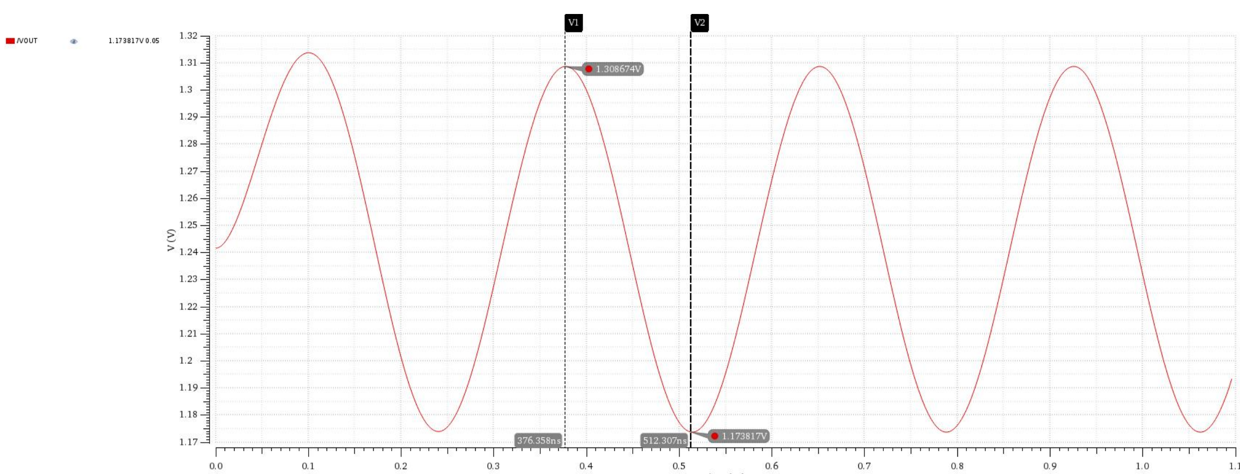


➢ Verr(VP-VN):



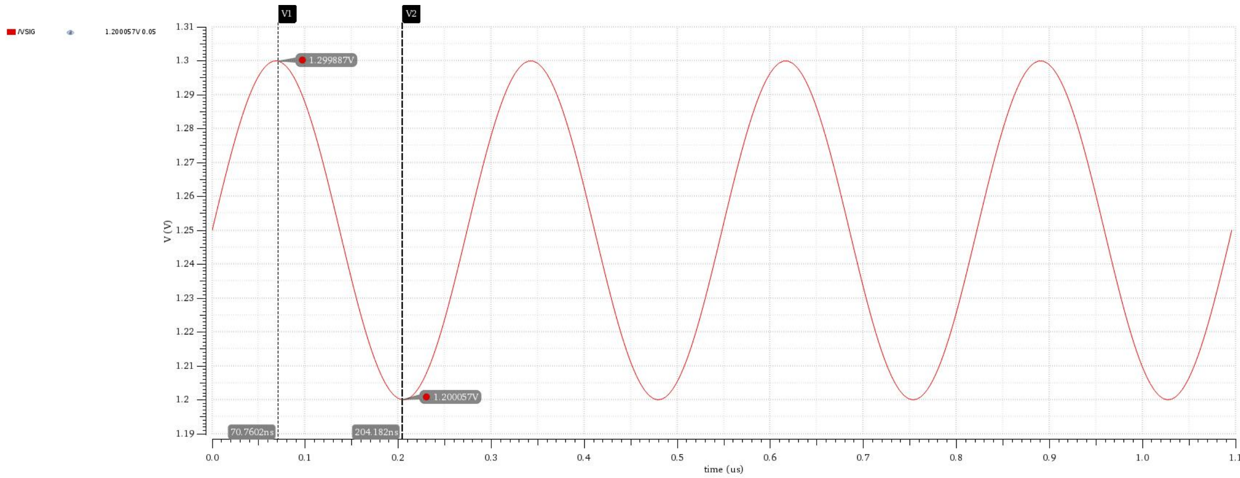
• Calculate the peak-to-peak voltage of the previous three signals. What is the relation between the output and the input signal? What is the relation between the output and (VP – VN)? Compare between this case and the case of 1kHz input.

➢ Vout:



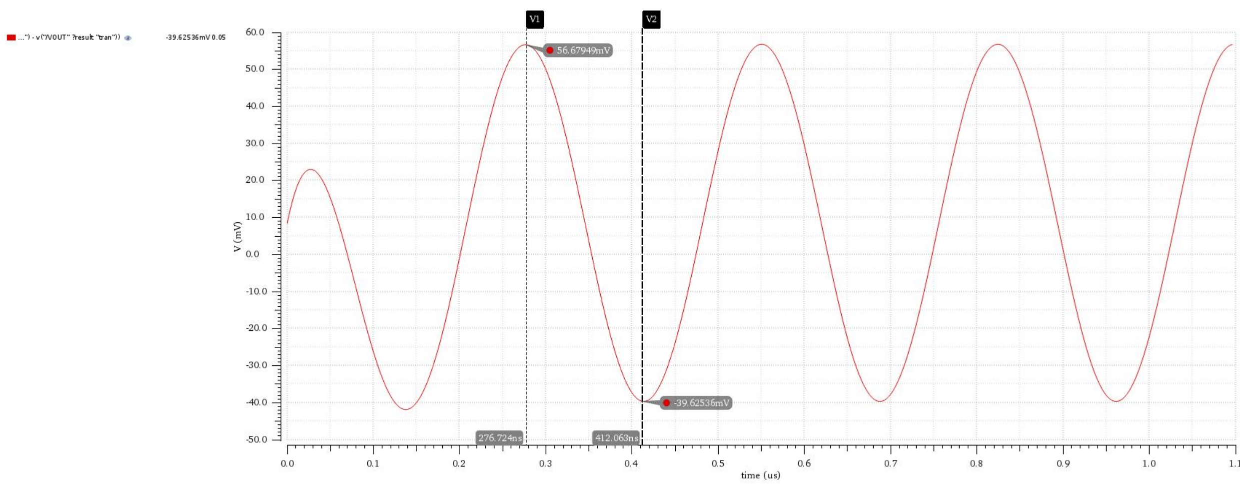
$Vptp = 1.308674 - 1.173817 = 134.857mV$

- Vin:



$Vptp = 1.299887 - 1.200057 = 99.83mV$

- Verr(VP-VN):



$Vptp = 56.67949 - (-39.62536) = 96.3mV$

$\frac{Vout}{Vin} = \frac{134.857}{99.83} = 1.35 \approx 1.41$ which is closed loop gain magnitude at frequency=BWcl.

$\frac{Vout}{Verr} = \frac{134.857}{96.3} = 1.4$ which is open loop gain magnitude at frequency=BWcl and analytically AOL should equal 1.92 at frequency=BWcl. Another explanation is that it is obvious from the Bode plot of the open loop gain and closed loop gain that they are almost equal at high frequencies.

	$F = 1KHz$	$F = BWcl$
$\frac{Vout}{Vin}$	1.924	1.35
$\frac{Vout}{Verr}$	50.544	1.4