Cairo University

Cairo University, Faculty of Engineering
Electronics and Electrical Communications
Department (EECE)

IC Project

Amplifier Design & Waveform Generator

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Figures

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Part 1:

Initial Design for main circuit:

- $gain = 90\ dB = 32.623\ K$
- $BW = 1\ MHz$
- $GBW = 32.623\ GHz$
- $GBW = \frac{gm}{2\pi * CL} = 32.623\ GMz$
- Assume $CL = 100 + 200 = 300\ fF$
- $gm = 62\ mS$ and we will take margin: $gm = 70\ mS$
- And for $\frac{gm}{ID} = 20$ for input pair:
- So, $ID = 3.5\ mA$
- $gain = gm_1 * gm_2 * ro_1 * ro_2 * A$
- we will design that ota gain : $A = 70$
- Let $ro_1 = ro_2 = 1000\ \Omega$
- So, $gm_2 = 6.5\ mS$

For input pair:

- $\frac{gm}{ID} = 20$
- $ID = 3.5\ mA$
- $\frac{gm}{gds} = 70 * 1 = 70$
- Sizing:

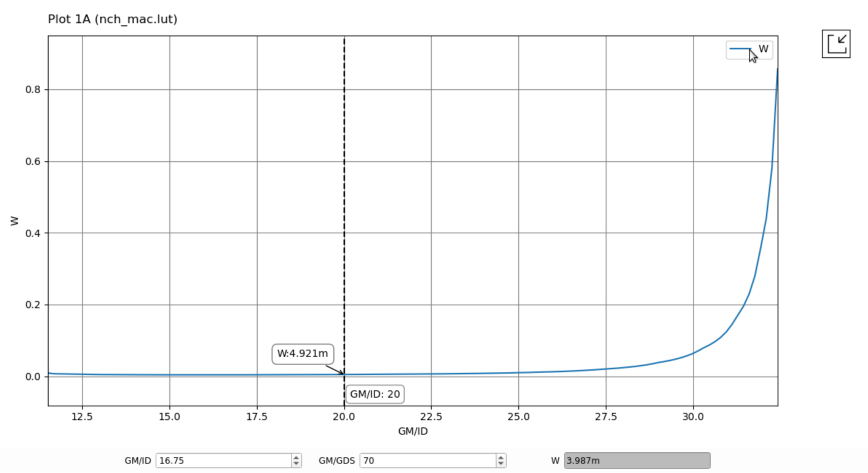


Figure 1:Width of input pair

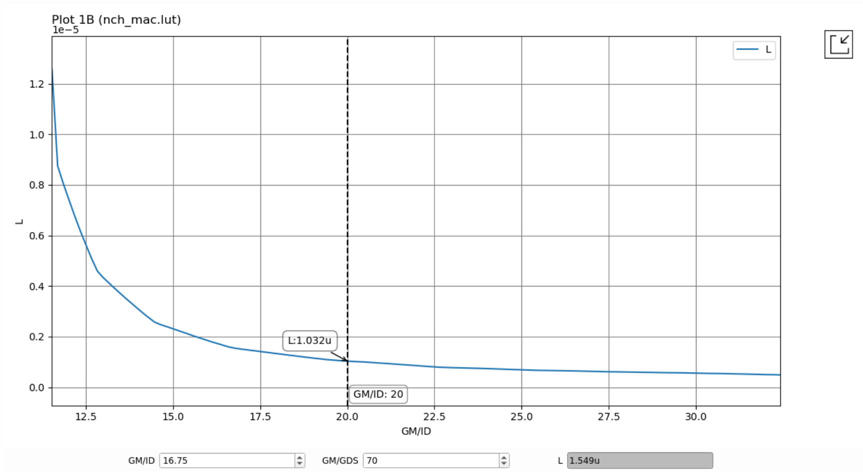


Figure 2:Lenght of input pair

For NMOS cascode:

- $\frac{gm}{ID} = 15$
- $ID = 3.5\ mA$
- $gds = 1\ mS$
- Sizing:

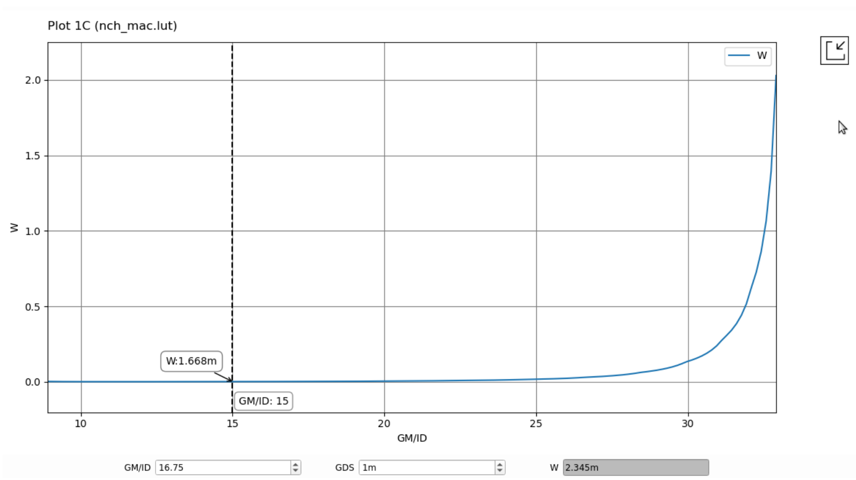


Figure 3:Width of nmos cascode

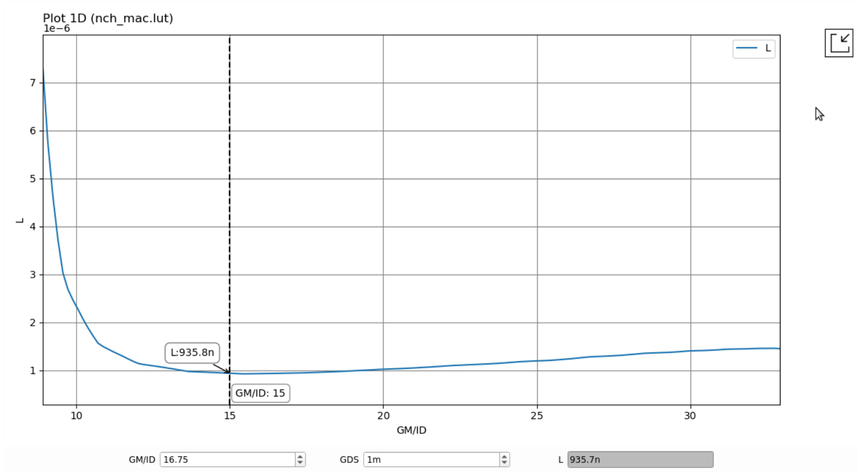


Figure 4:Length of nmos cascode

For PMOS cascode:

- $\frac{gm}{ID} = 15$
- $ID = 3.5\ mA$
- $gds = 1\ mS$
- Sizing:

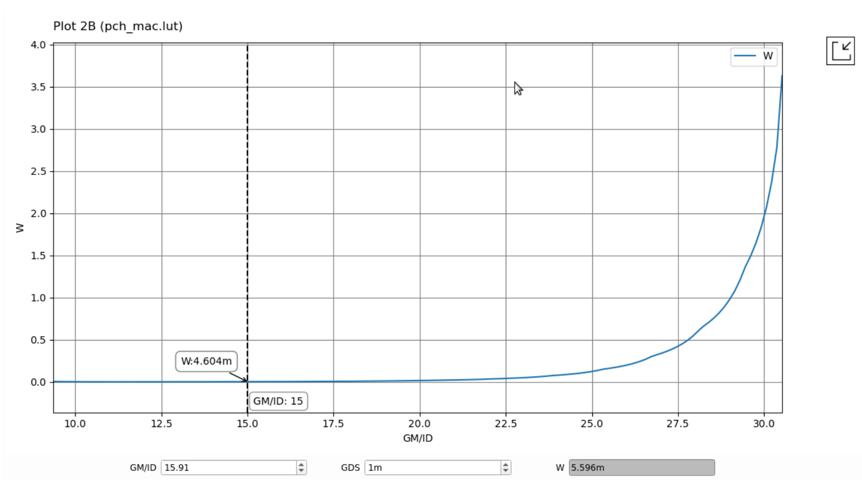


Figure 5:Width of pmos cascode

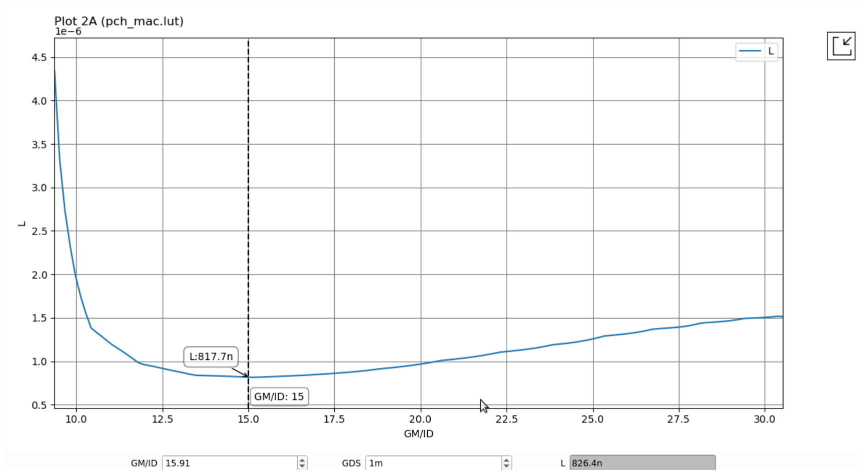


Figure 6:Length of pmos cascode

For PMOS load:

- $\frac{gm}{ID} = 10$
- $ID = 3.5\ mA$
- $gds = 1\ mS$
- Sizing:

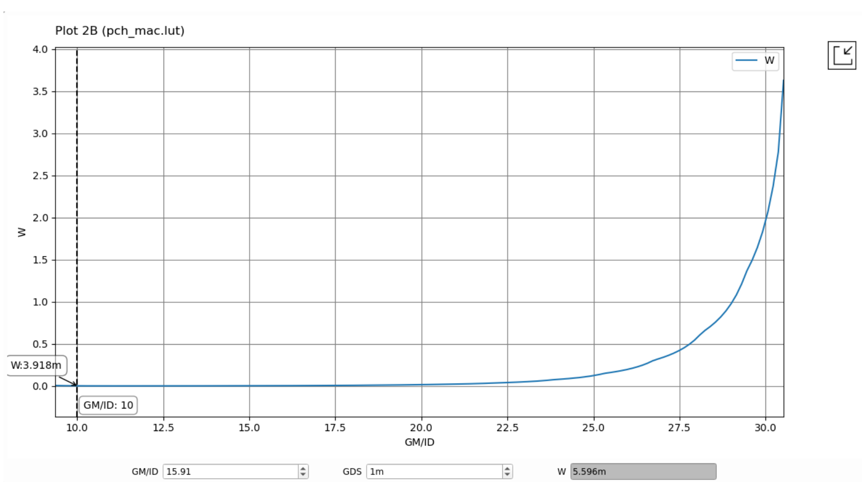


Figure 7:Width of pmos load

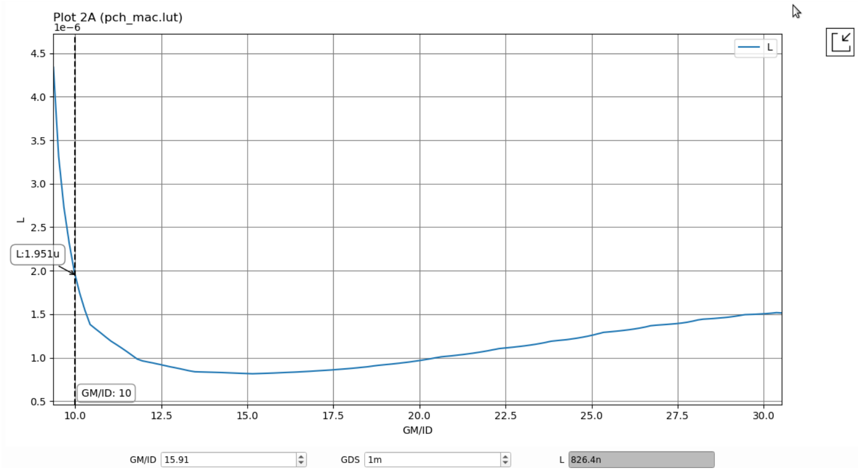


Figure 8:Length of pmos load

For NMOS tail:

- $\frac{gm}{ID} = 10$
- $ID = 7\ mA$
- Assume that: $L = 1\ um$
- Sizing:

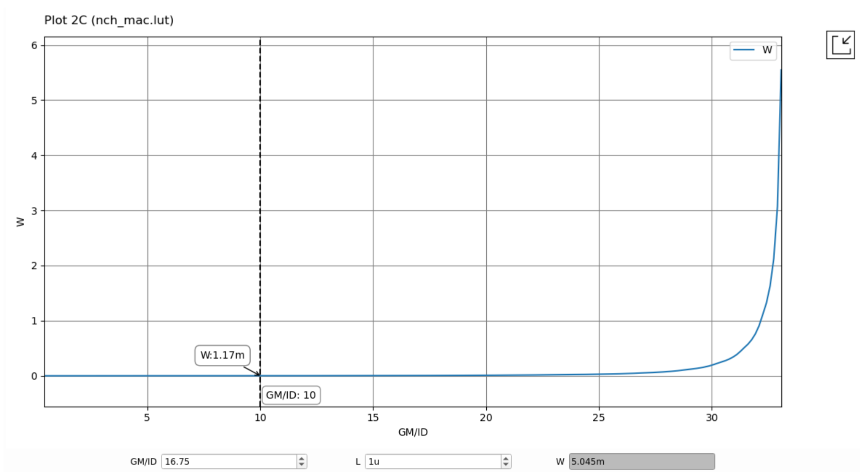


Figure 9:Width of nmos tail current source

Tuning:

- Using these values with ideal OTA, we found that the gain is smaller than 90 dB and the BW is larger than 1 MHz. so we run DC analysis and found that gm is smaller than the specified value (70 mS) so we increased the width of the input pair mosfets by using multipliers to increase the gm. The gain increased and the BW decreased.

- We found that the Cdd of the cascode mosfets is large so we decreased the length of the mosfets and the current (from 3.5 mA to 3.26 mA): $GBW = \frac{gm}{2\pi * CL} = \frac{2 * ID}{2\pi * CL * Vov}$ for the same GBW. The BW increased but the gain decreased because we decreased the output resistance and the current.

- We found that gds of the input pair is large so we increased the length of it. So, the gain increased

- After some parametric sweep, we reach the required specs

Initial design for the OTA:

- $gain = 70$
- $assume\ a\ large\ BW: BW = 20\ MHz$
- $GBW = 1.4\ GHz$
- $GBW = \frac{gm}{2\pi * CL}$
- Assume that the total capacitance seen by the output: $C_{tot} = 400\ fF$
- $gm = 4\ mS$ and I will take margin: $gm = 5\ mS$
- And for $\frac{gm}{ID} = 20$ for input pair:
- So, $ID = 250\ uA$
- $gain = gm_1 * ro_1 // ro_2$
- Let $ro_1 = ro_2$
- So, $\frac{gm}{gds} = 140$
- $gds = 35\ uS$

For input pair:

- $\frac{gm}{ID} = 20$
- $ID = 250\ uA$
- $\frac{gm}{gds} = 140$
- Sizing: $L = 2.2\ um$ and $W = 455\ um$

For Load:

- $\frac{gm}{ID} = 15$
- $ID = 250\ uA$
- $gds = 35\ uS$
- Sizing: $L = 1.1\ um$ and $W = 230\ um$

For NMOS tail:

- $\frac{gm}{ID} = 10$
- $ID = 500\ uA$
- Assume that: $L = 1\ um$
- Sizing: $L = 1\ um$ and $W = 100\ um$

Tuning:

- In the design we decreased the current to improve the BW and we did small changes on width and length of each mosfet.
- After some parametric sweep, we reach the required specs

OTA:

Schematic:

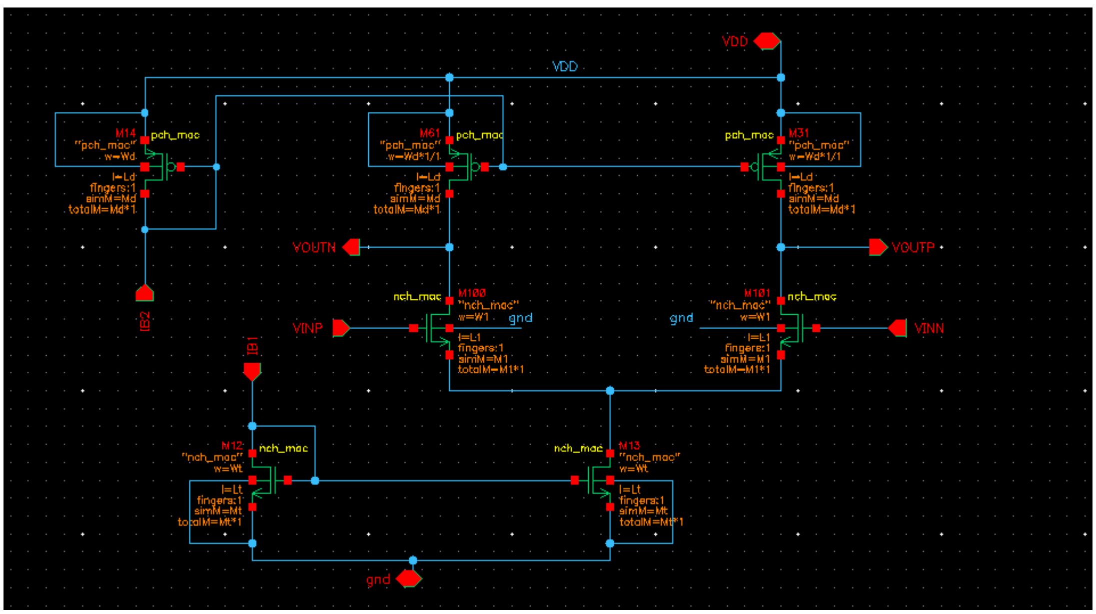


Figure 10:Schematic of OTA

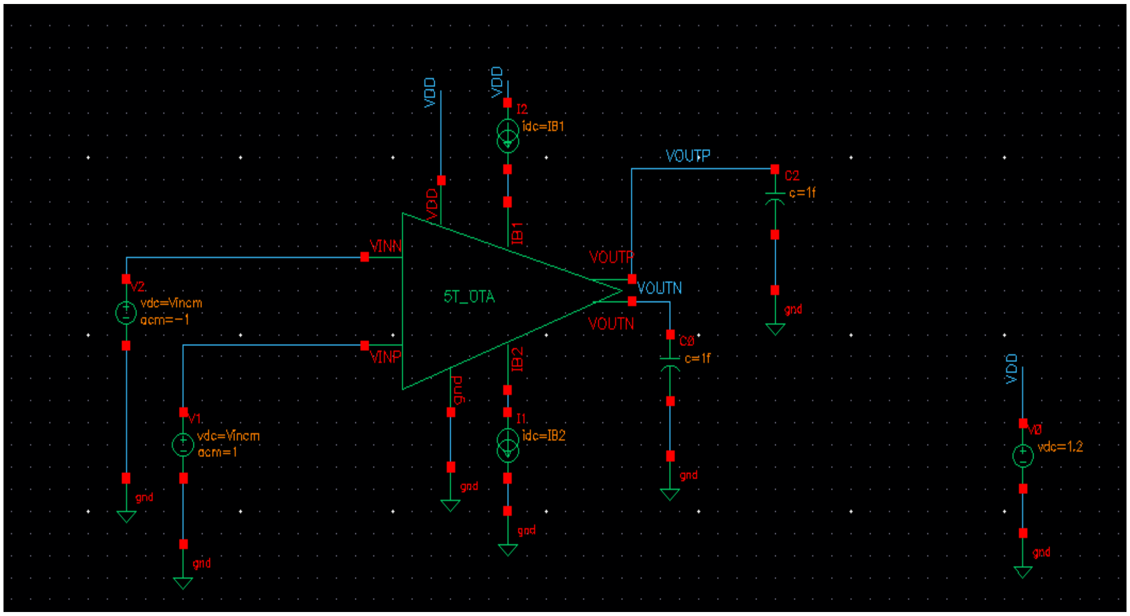


Figure 11:Schematic of OTA testbench

DIFF gain:

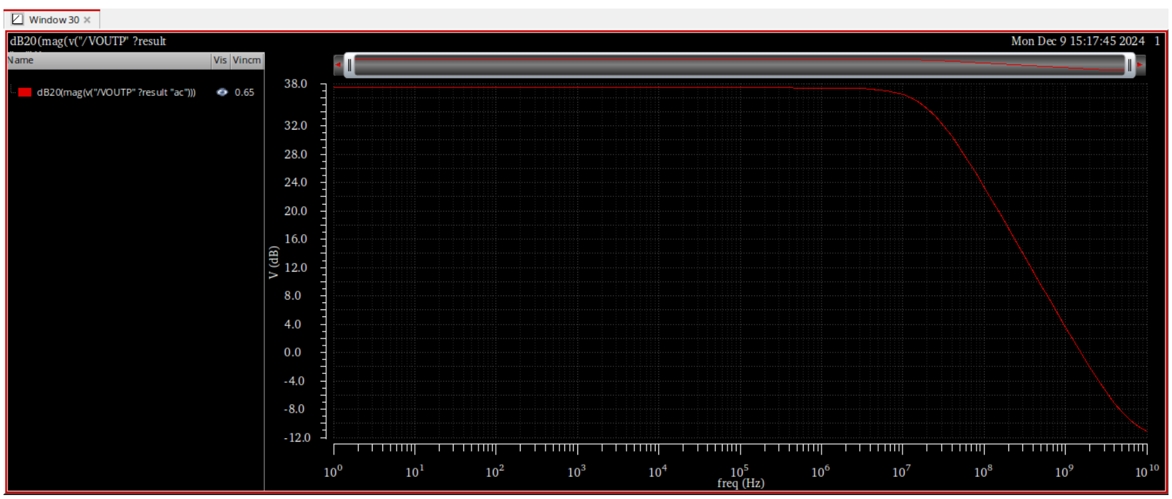


Figure 12:OTA Gain in db

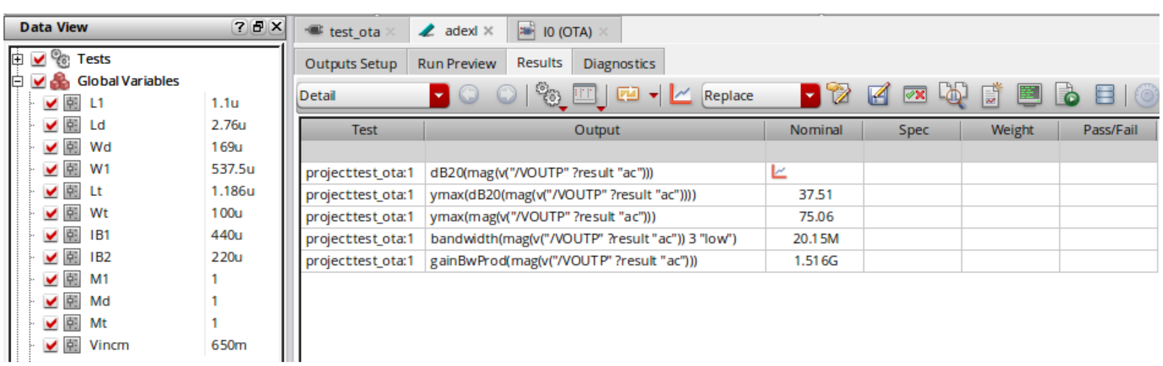


Figure 13:OTA Results

The operating point and the sizing:

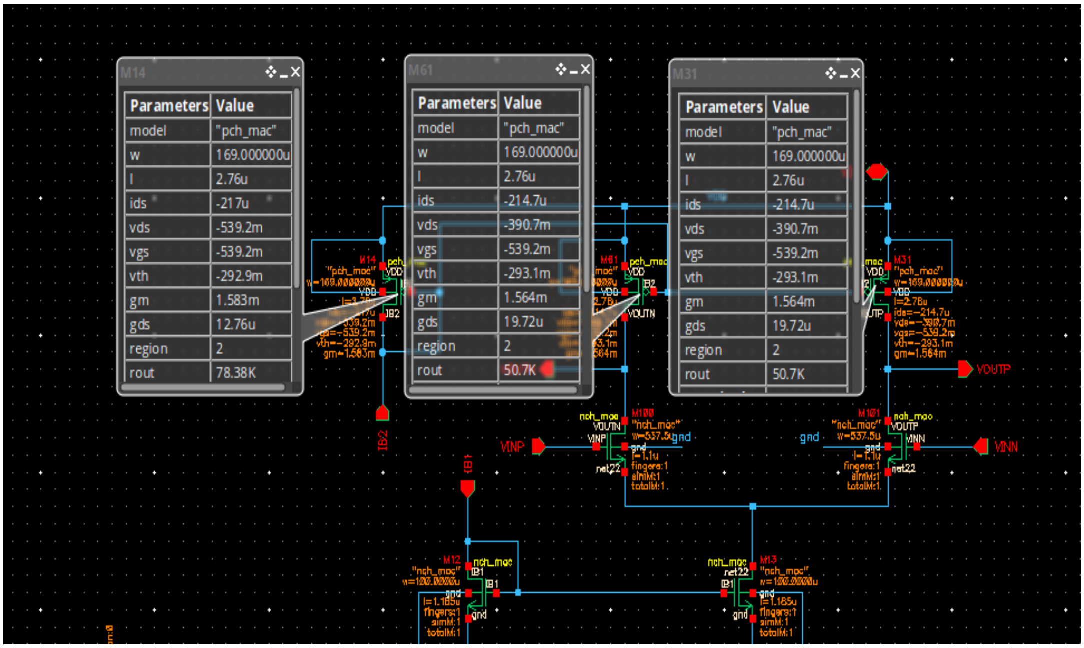


Figure 14:PMOS OTA devices op

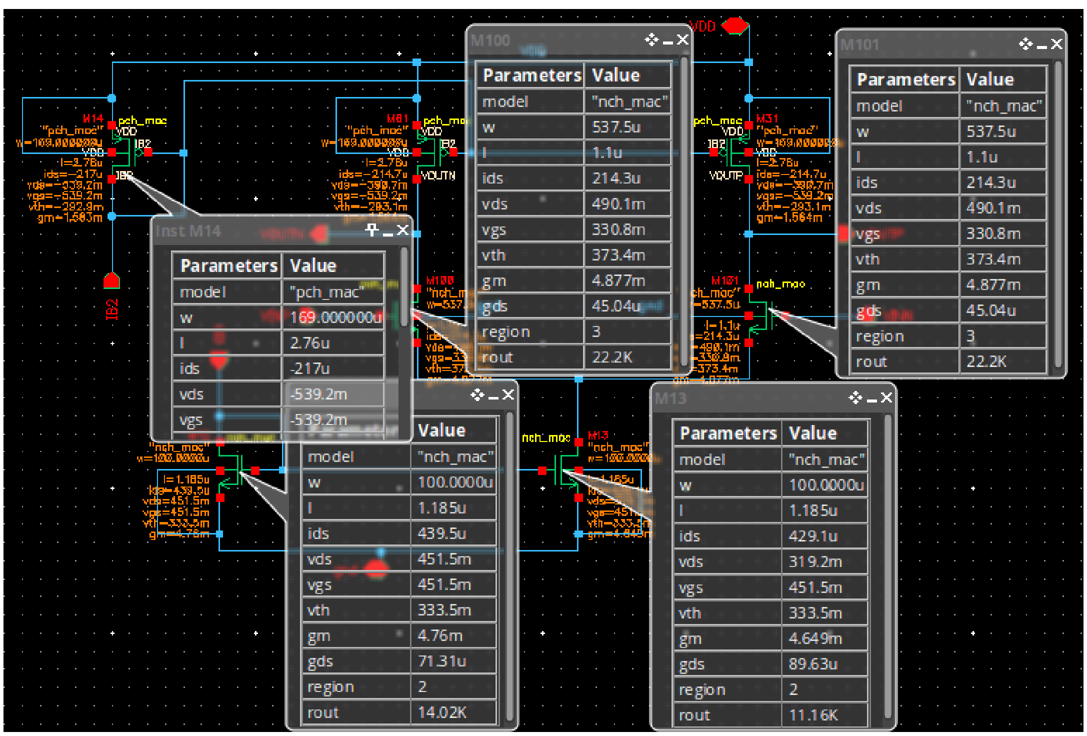


Figure 15:NMOS OTA devices op

Main Circuit with ideal OTA:

Schematic:

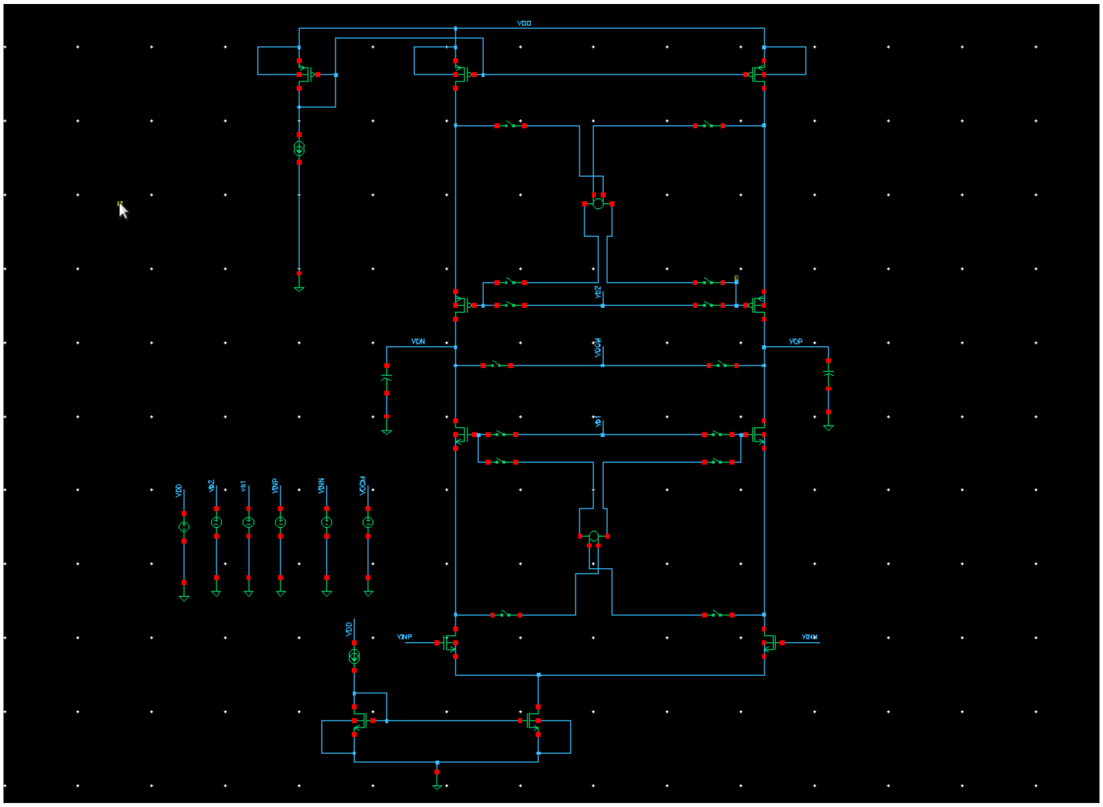


Figure 16:Amplifier Schematic with ideal OTA

DIFF gain:

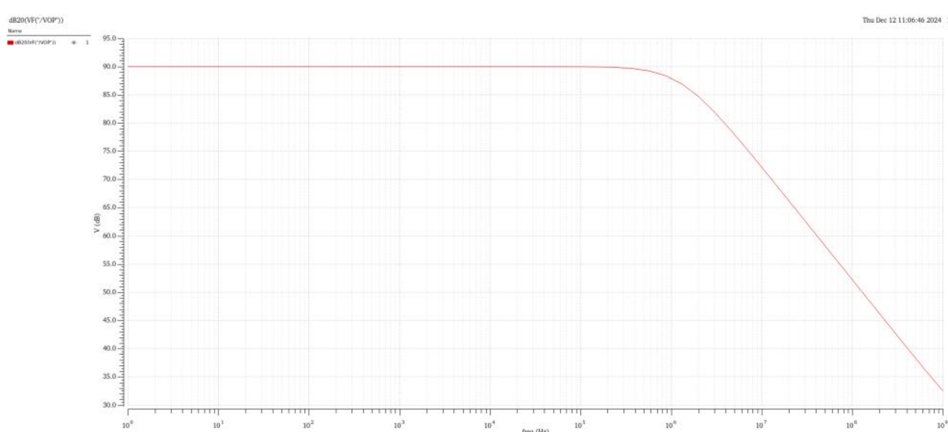


Figure 17:Amplifier gain in db with ideal OTA

Test	Output	Nominal	Spec	Weight	Pass/Fail
Final:Telescopic_with_ideal_op_amp:1	bandwidth(VF("/VOP") 3 "low")	1.3M			
Final:Telescopic_with_ideal_op_amp:1	ymax(dB20(VF("/VOP")))	90.04			
Final:Telescopic_with_ideal_op_amp:1	gainBwProd(VF("/VOP"))	41.39G			
Final:Telescopic_with_ideal_op_amp:1	dB20(VF("/VOP"))				

Figure 18:Amplifier results with ideal OTA

Main Circuit with actual OTA:

Schematic:

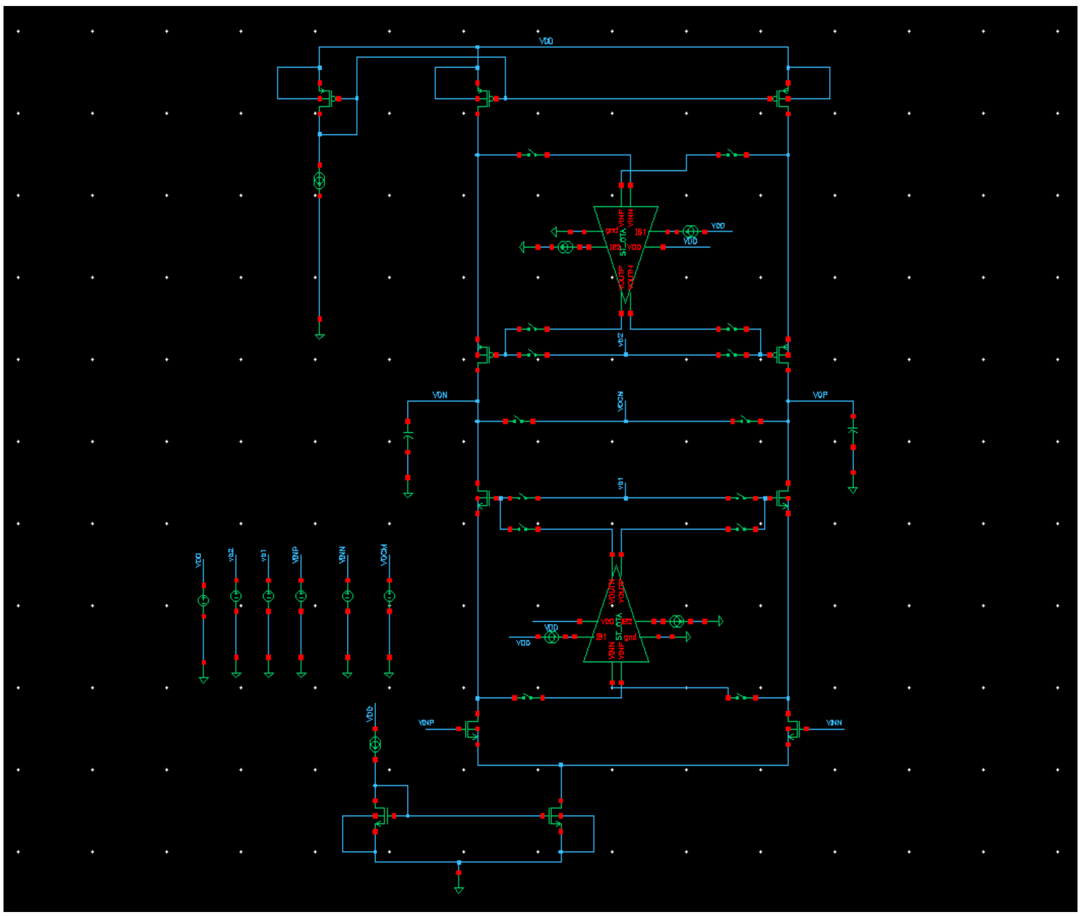


Figure 19:Schematic of Amplifier with real OTA

DIFF gain:

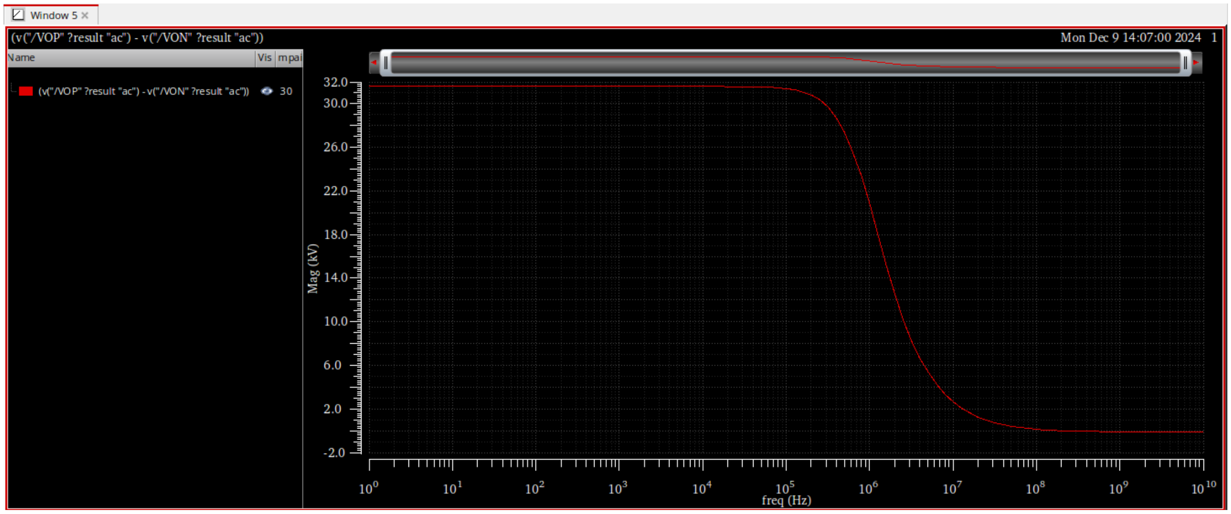


Figure 20:Amplifier gain magntiude with real OTA

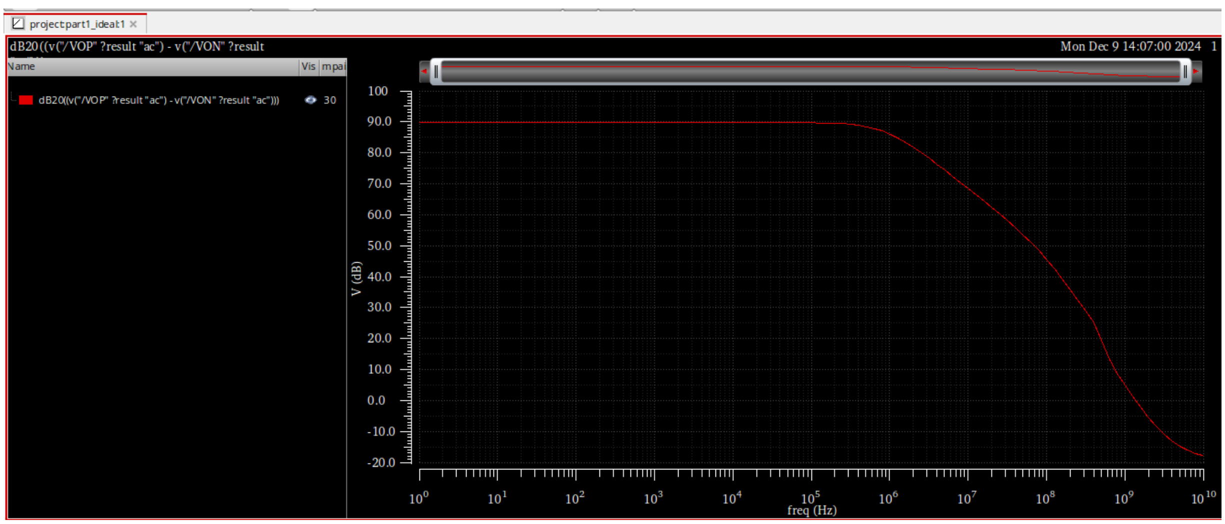


Figure 21::Amplifier gain in db with real OTA

Test	Output	Nominal	Spec	Weight	Pass/Fail
projectpart1_ideal1	dB20((v("/VOP" ?result "ac") - v("/VON" ?result "ac")))				
projectpart1_ideal1	ymax(dB20((v("/VOP" ?result "ac") - v("/VON" ?result "ac"))))	90.01			
projectpart1_ideal1	bandwidth((v("/VOP" ?result "ac") - v("/VON" ?result "ac")) 3 "low")	865k			
projectpart1_ideal1	gainBwProd((v("/VOP" ?result "ac") - v("/VON" ?result "ac")))	27.46G			

Figure 22::Amplifier results with real OTA

Note :

the desired bandwidth which is 1M couldn't be fully reached because of the limited bandwidth of the OTA added in this circuit, leading to have a bandwidth which is the parallel combination of both bandwidths of the OTA and the telescopic.

The operating point:

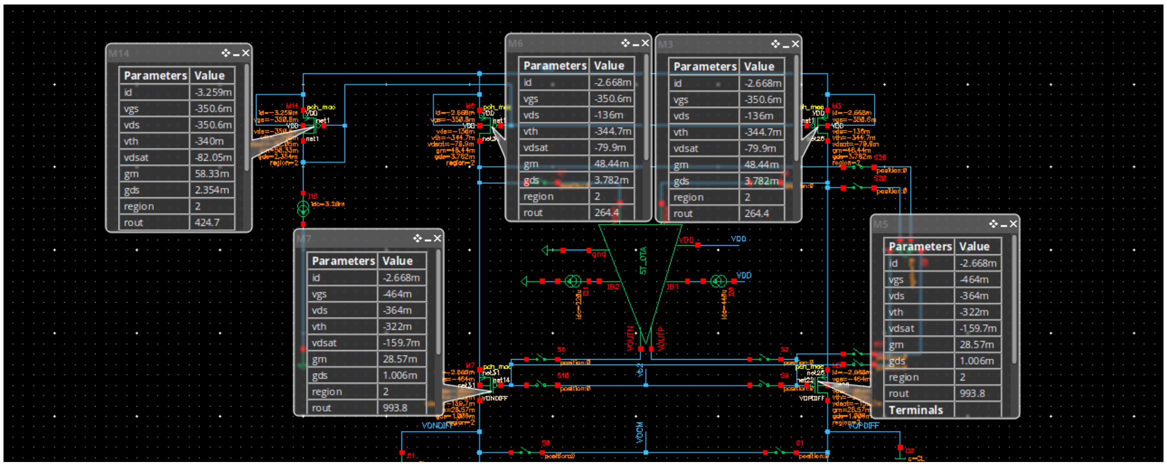


Figure 23:Main amplifier pmos devices op

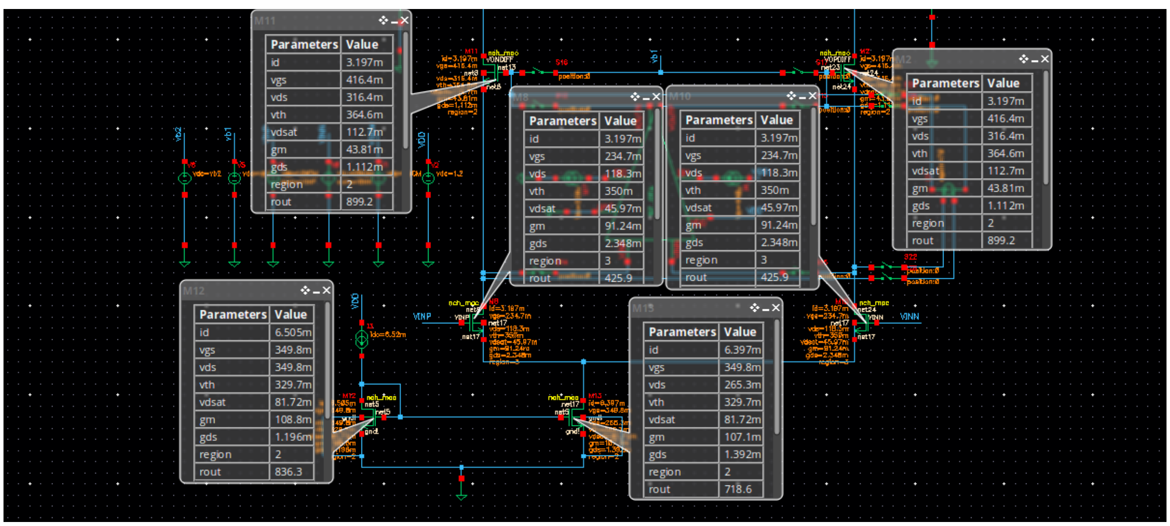


Figure 24::Main amplifier nmos devices op

The sizing:

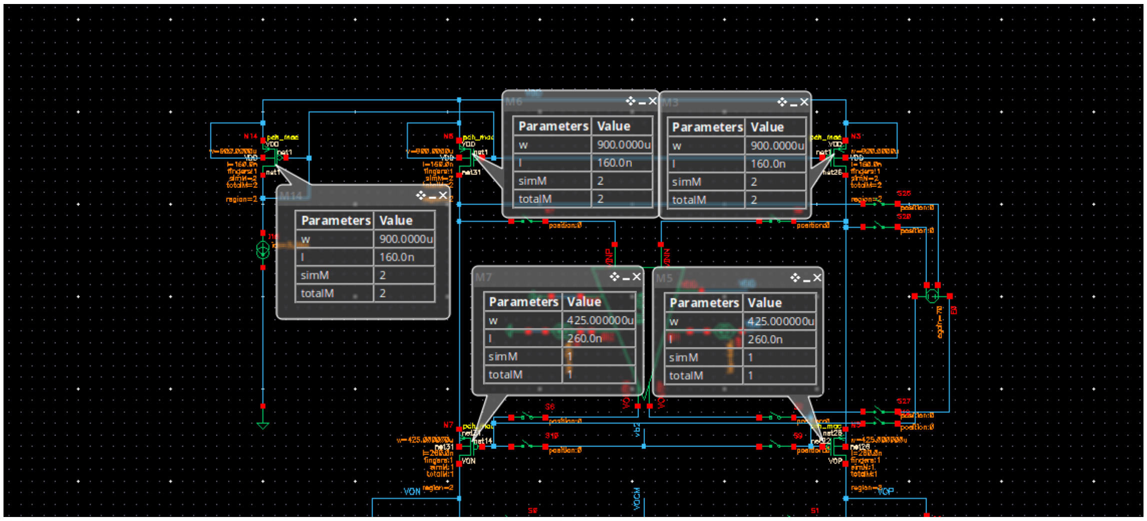


Figure 25::Main amplifier pmos devices sizing

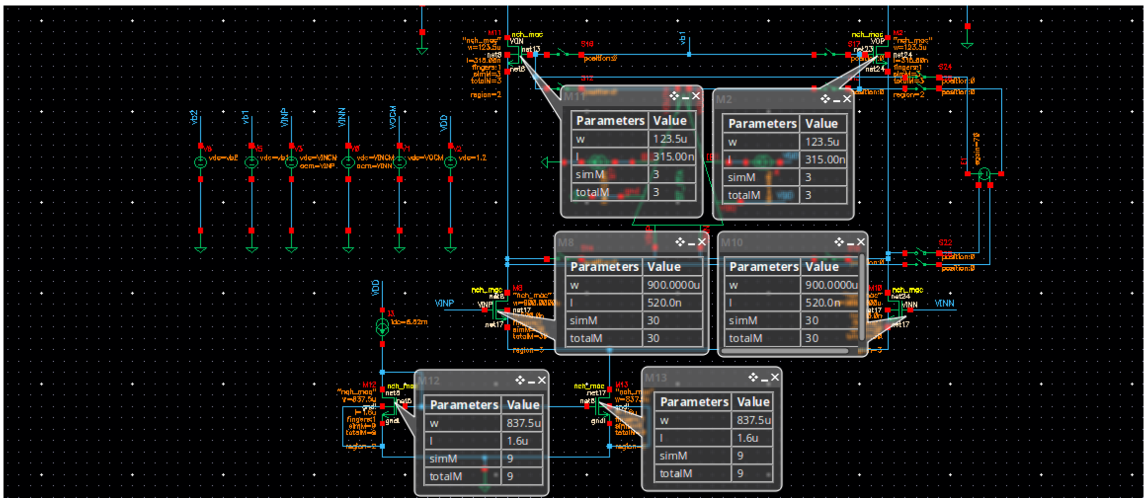


Figure 26::Main amplifier nmos devices sizing

The dissipated power:

- $OTA\ total\ current = 440 * 2 + 220 = 1.1\ mA$
- $The\ ideal\ circuit\ total\ current = 6.52 * 2 + 3.26 = 16.3\ mA$
- $Total\ current = 1.1 + 16.3 = 17.4\ mA$
- $the\ dissipated\ power = 17.4 * 1.2 = 20.88\ mW$

Comparison of analytic gain and simulation gain:

$$|A0| = gm1 * (Routup\ //Routdown)$$

$$|A0| \approx (gm * ro)^3$$

$$|Ao| = gm_1 * gm_2 * ro_1 * ro_2 * A$$

$$A0 = 91.24 * 43.81 * 10^{-6} * 993.8 * 899.2 * (4.877 * 22.2) = 386740.4075$$

$$Ao\ in\ db = 111$$

method	hand analysis	simulation
gain in db	111	90.01

the deviation between hand analysis and simulation is due to approximations taken in hand analysis method

Bonus Part:

Different gains:

DIFF gain:(Add)

- Already calculated above.

CM gain:(Acc)

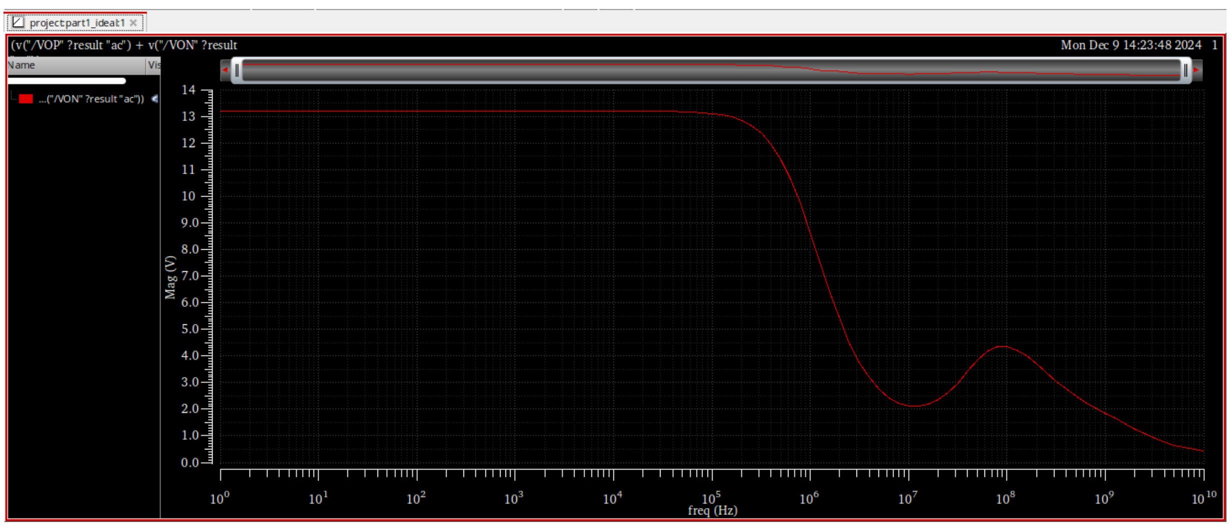


Figure 27:Common mode to common mode gain

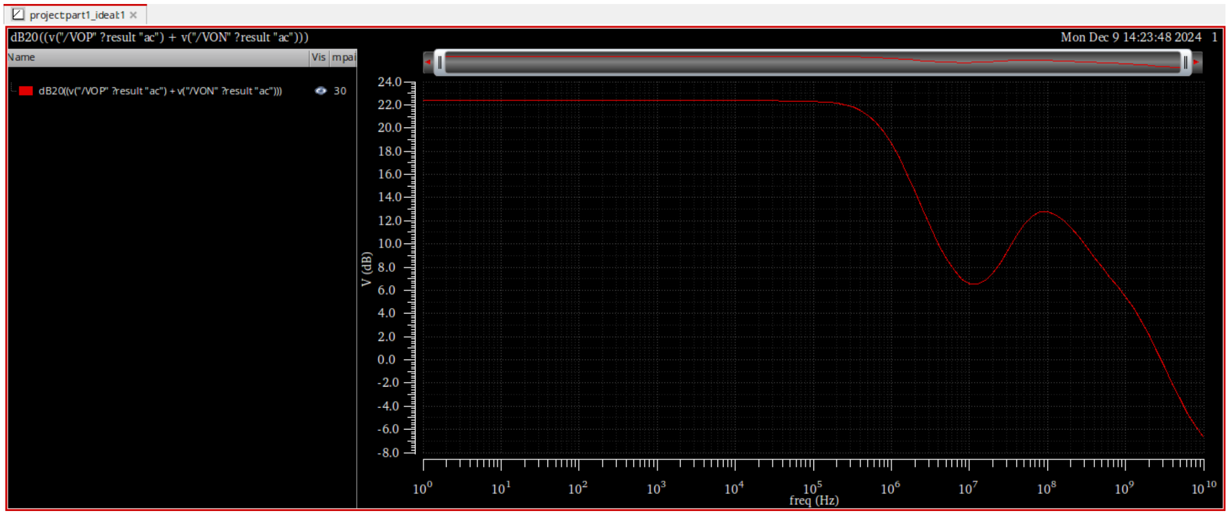


Figure 28:Common mode to common mode gain in db

Test	Output	Nominal	Spec	Weight	Pass/Fail
projectpart1_ideal:1	dB20((v("/VOP" ?result "ac") + v("/VON" ?result "ac")))				
projectpart1_ideal:1	(v("/VOP" ?result "ac") + v("/VON" ?result "ac"))				
projectpart1_ideal:1	ymax(dB20((v("/VOP" ?result "ac") + v("/VON" ?result "ac"))))	22.43			
projectpart1_ideal:1	ymax(mag((v("/VOP" ?result "ac") + v("/VON" ?result "ac"))))	13.23			
projectpart1_ideal:1	bandwidth((v("/VOP" ?result "ac") + v("/VON" ?result "ac")) 3 "low")	859.9k			
projectpart1_ideal:1	gainBwProd((v("/VOP" ?result "ac") + v("/VON" ?result "ac")))	11.4M			

Figure 29:Common mode to common mode gain results

Diff to CM gain:(Adc)

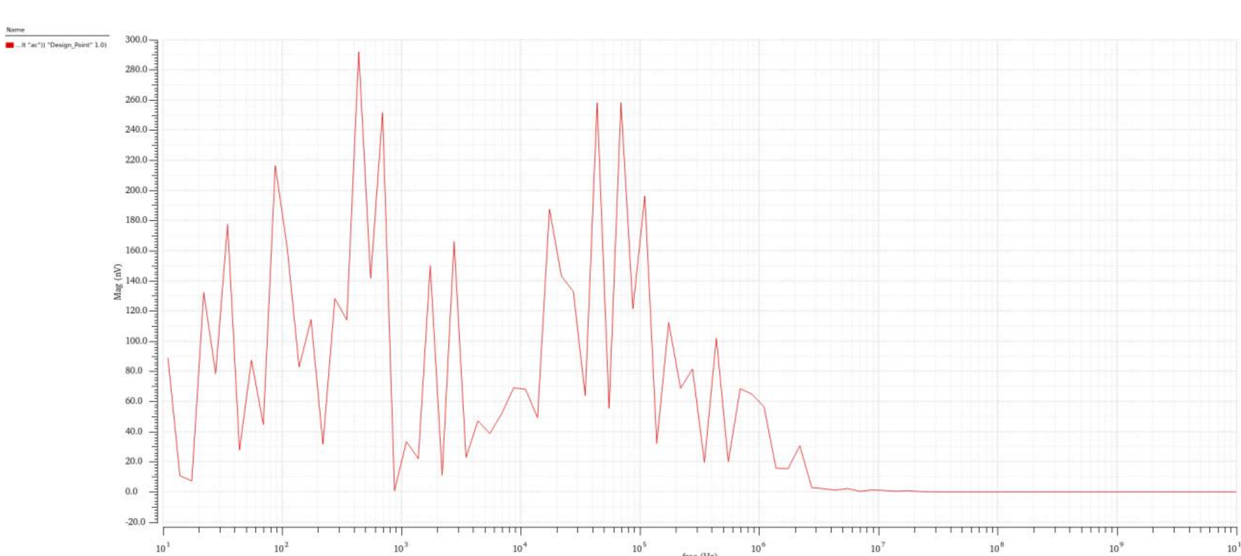


Figure 30:diffirential to common mode gain in db

Test	Ou Click to go forward	Nominal	Spec	Weight	Pass/Fail
Final:gains:1	ymax(mag((v("/VOP" ?result "ac"...	146.1n			

Figure 31:diffirential to common mode gain results

CM to Diff gain:(Acd)

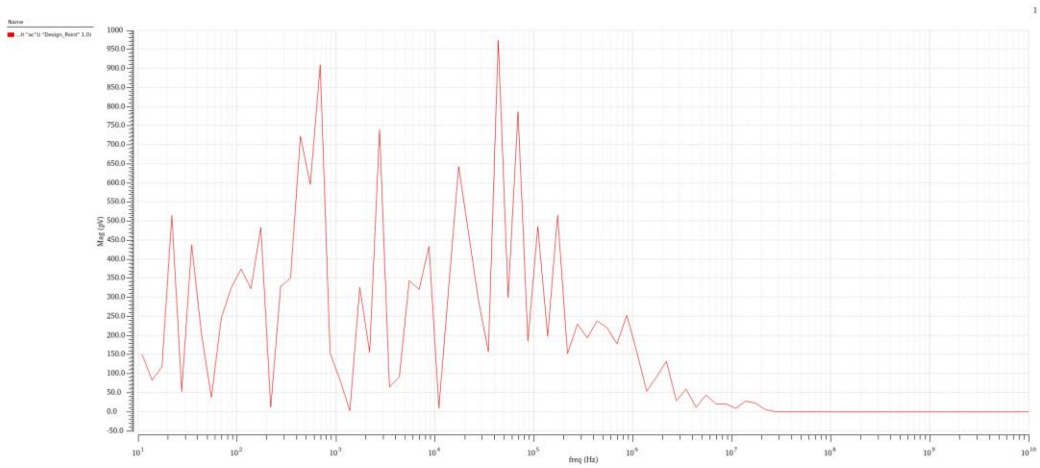


Figure 32:common mode to diffirential gain in db

Test	Output	Nominal	Spec	Weight	Pass/Fail
Final:gains:1	ymax(mag((v("/VOP" ?result "ac"...	974.3p			

Figure 33:common mode to diffirential gain results

CMRR:

Method:

- The equation:$CMRR = \frac{Adiff}{Acc}$
- We repeated the circuit and we used one to get the diff gain and the other for the CM gain and this is the schematic:

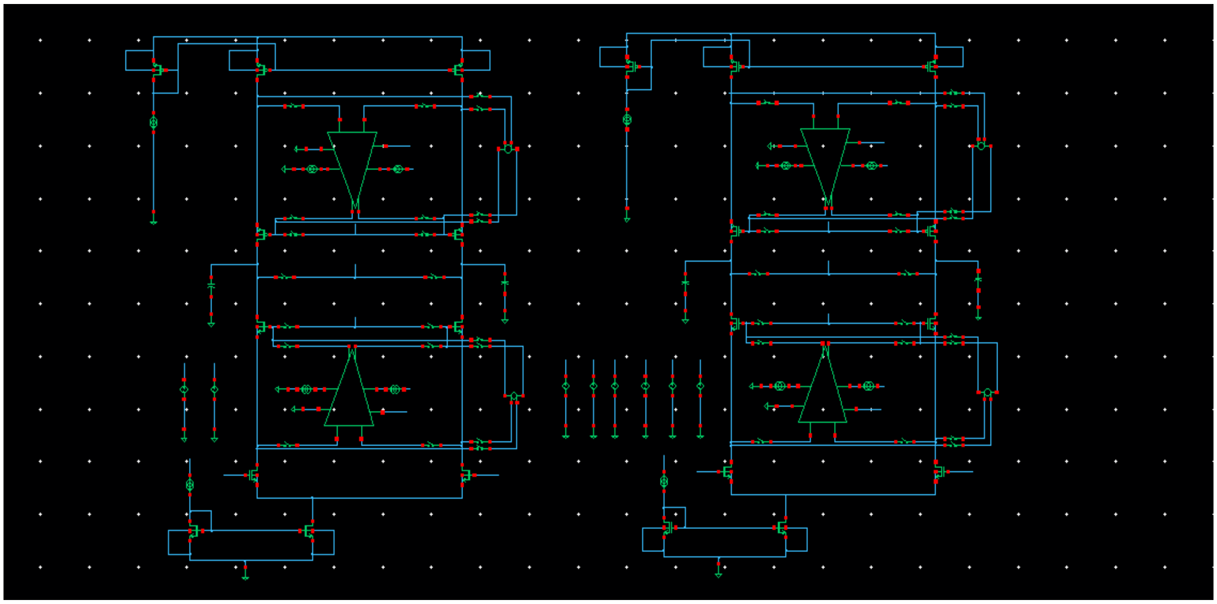


Figure 34:CMRR schematic

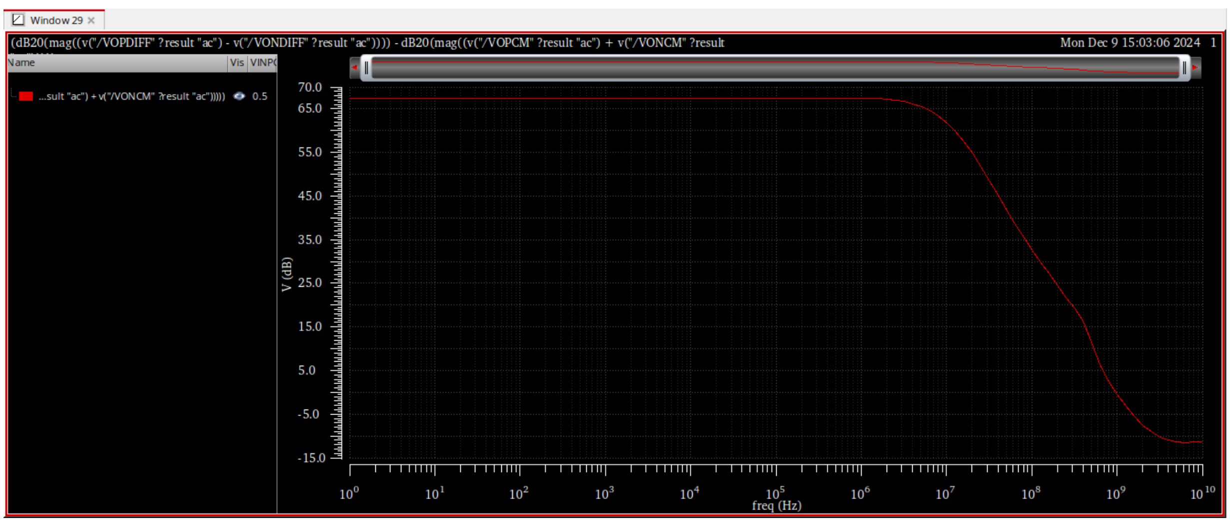


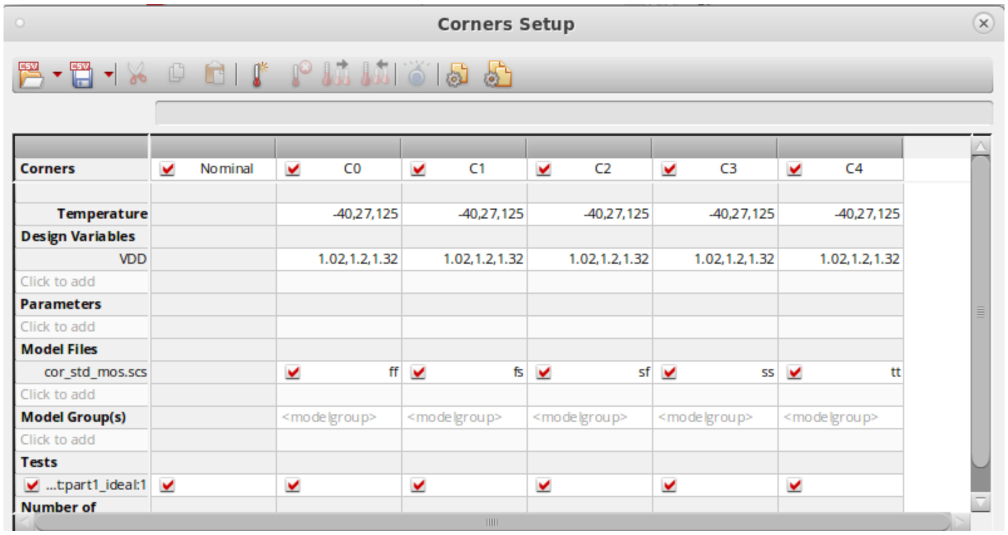
Figure 35:CMRR in db

Test	Output	Nominal
projectpart1_ideal:1	(dB20(mag((v("/VOPDIFF" ?result "ac") - v("/VONDIFF" ?result "ac")))) - dB20(mag((v("/VOPCM" ?result "ac") + v("/VONCM" ?result "ac")))))	
projectpart1_ideal:1	ymax((dB20(mag((v("/VOPDIFF" ?result "ac") - v("/VONDIFF" ?result "ac")))) - dB20(mag((v("/VOPCM" ?result "ac") + v("/VONCM" ?result "ac"))))))	67.61

Figure 36:CMRR results

2-Corners:

Corner setup:



Corners	Nominal	C0	C1	C2	C3	C4
Temperature		-40,27,125	-40,27,125	-40,27,125	-40,27,125	-40,27,125
Design Variables						
VDD		1.02,1.2,1.32	1.02,1.2,1.32	1.02,1.2,1.32	1.02,1.2,1.32	1.02,1.2,1.32
Click to add						
Parameters						
Click to add						
Model Files						
cor_std_mos.scs		ff	fs	sf	ss	tt
Click to add						
Model Group(s)		<modelgroup>	<modelgroup>	<modelgroup>	<modelgroup>	<modelgroup>
Click to add						
Tests						
...t:part1_ideal:1						
Number of						

Figure 37:Corners setup

The corners:

	Parameter	Nominal						C0_0	C0_1	C0_2	C0_3	C0_4	C0_5
	VDD	1.2						1.02	1.02	1.02	1.2	1.2	1.2
	cor_std_mos.scs							ff	ff	ff	ff	ff	ff
	crn65gplus_2d5_lk_v1d0.scs	tt_lvt						nom	nom	nom	nom	nom	nom

Test	Output	Nominal	Spec	Weight	Pass/Fail	Min	Max	C0_0	C0_1	C0_2	C0_3	C0_4	C0_5
project:part1_ideal:1	bandwidth(mag(v("/VOP" ?result...	865k				815.9k	22.49M	815.9k	1.776M	22.49M	815.9k	1.776M	22.49M
project:part1_ideal:1	dB20(ymax(mag(v("/VOP" ?resul...	90.01				49.7	92.27	92.27	83.27	49.7	92.27	83.27	49.7

Figure 38:Corners part#1

C0_6	C0_7	C0_8	C1_0	C1_1	C1_2	C1_3	C1_4	C1_5	C1_6	C1_7	C1_8	C2_0	C2_1	C2_2	C2_3	C2_4	C2_5
1.32	1.32	1.32	1.02	1.02	1.02	1.2	1.2	1.2	1.32	1.32	1.32	1.02	1.02	1.02	1.2	1.2	1.2
ff	ff	ff	fs	fs	fs	fs	fs	fs	fs	fs	fs	sf	sf	sf	sf	sf	sf
nom	nom	nom	nom	nom	nom	nom	nom	nom	nom	nom	nom	nom	nom	nom	nom	nom	nom

C0_6	C0_7	C0_8	C1_0	C1_1	C1_2	C1_3	C1_4	C1_5	C1_6	C1_7	C1_8	C2_0	C2_1	C2_2	C2_3	C2_4	C2_5
815.9k	1.776M	22.49M	907.3k	942.7k	6.976M	907.3k	942.7k	6.976M	907.3k	942.7k	6.976M	1.175M	1.029M	1.428M	1.175M	1.029M	1.428M
92.27	83.27	49.7	90.49	89.05	65.61	90.49	89.05	65.61	90.49	89.05	65.61	88.8	88.41	80.78	88.8	88.41	80.78

Figure 39:Corners part#2

C2_6	C2_7	C2_8	C3_0	C3_1	C3_2	C3_3	C3_4	C3_5	C3_6	C3_7	C3_8	C4_0	C4_1	C4_2	C4_3	C4_4	C4_5
1.32	1.32	1.32	1.02	1.02	1.02	1.2	1.2	1.2	1.32	1.32	1.32	1.02	1.02	1.02	1.2	1.2	1.2
sf	sf	sf	ss	ss	ss	ss	ss	ss	ss	ss	ss	tt	tt	tt	tt	tt	tt
nom	nom	nom	nom	nom	nom	nom	nom	nom	nom	nom	nom	nom	nom	nom	nom	nom	nom

C2_6	C2_7	C2_8	C3_0	C3_1	C3_2	C3_3	C3_4	C3_5	C3_6	C3_7	C3_8	C4_0	C4_1	C4_2	C4_3	C4_4	C4_5
1.175M	1.029M	1.428M	2.001M	1.449M	1.567M	2.001M	1.449M	1.567M	2.001M	1.449M	1.567M	918k	865k	1.419M	918k	865k	1.419M
88.8	88.41	80.78	82.32	84.8	80.11	82.32	84.8	80.11	82.32	84.8	80.11	90.91	90.01	80.93	90.91	90.01	80.93

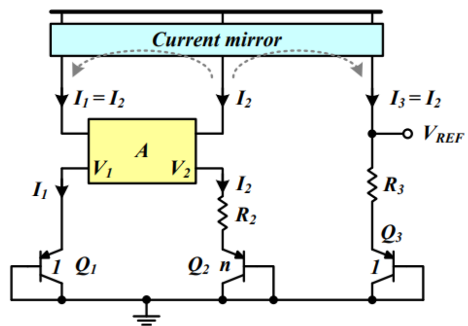
Figure 40:Corners part#3

3-Band gap circuit:(BGR)

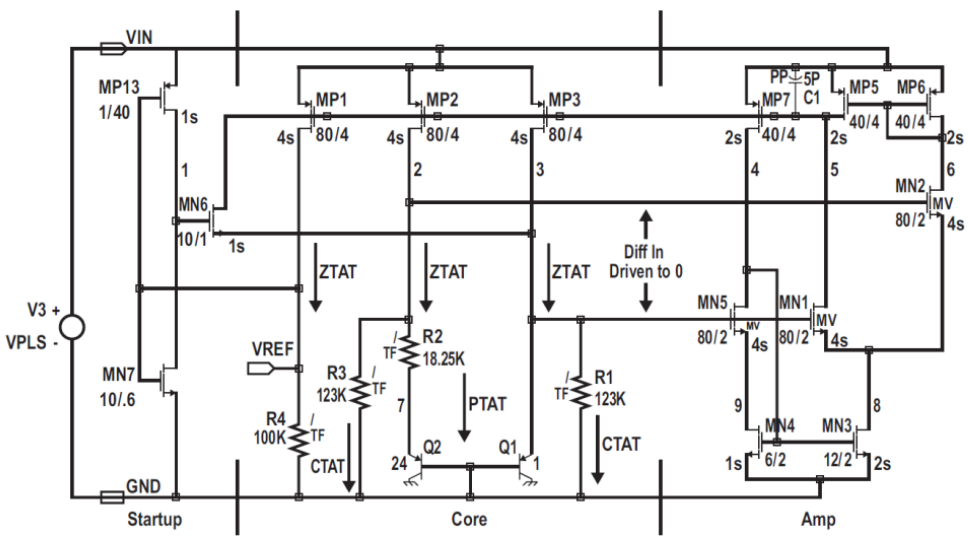
- Stable DC voltage and DC current generation

- little dependence on process (P) and supply (V)
- Well-defined dependence on temperature (T)

- Temperature dependence
  - Positive temperature coefficient (+ve TC): Proportional to absolute temperature (PTAT)
  - Negative temperature coefficient (-ve TC): Complementary to absolute temperature (CTAT)
  - Temperature independent (Zero-TC): ZTAT = PTAT + CTAT
- Most process parameters vary with temperature
  - If we achieve a temperature independent reference it will also be process independent.



We will take this circuit [Brokaw, IDT, 2011] as a reference design point and tuning the transistor parameters to give us the required VDD that equals 1.2V:



Schematic:

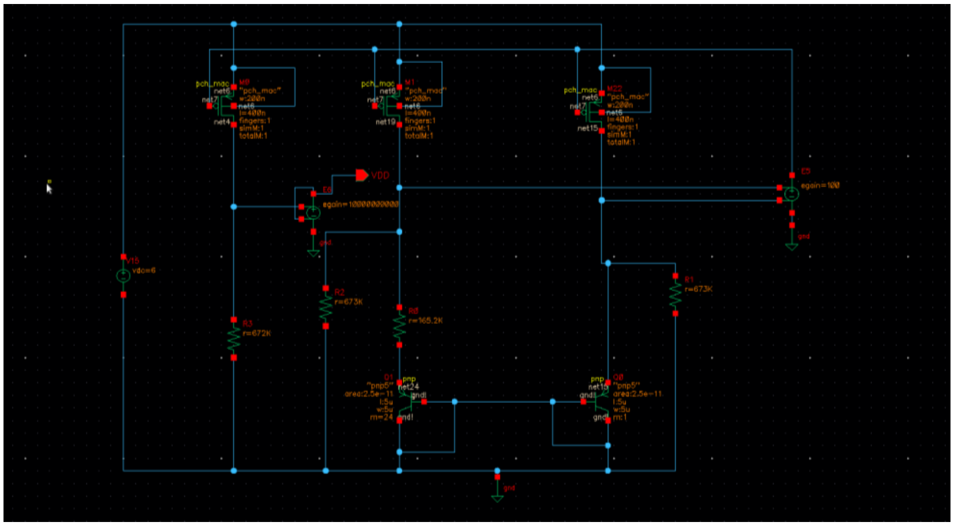


Figure 41:Schematic of BGR

Test	Output	Nominal	Spec	Weight	Pass/Fail
Final:BGR_LBOSA:1	VDC("/VDD")	1.2			

Figure 42:Output voltage of BGR

Main circuit with BGR:

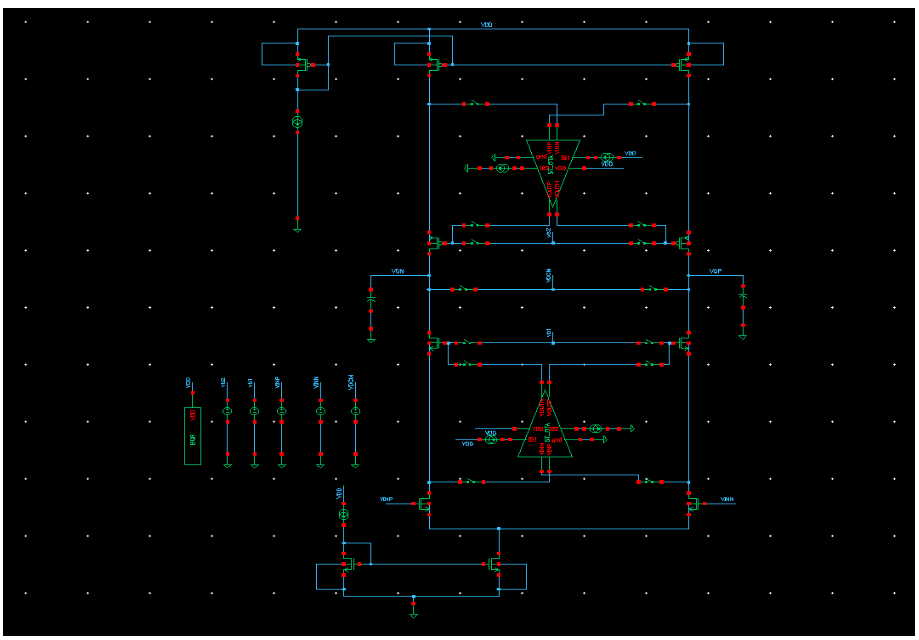


Figure 43:Main circuit with BGR

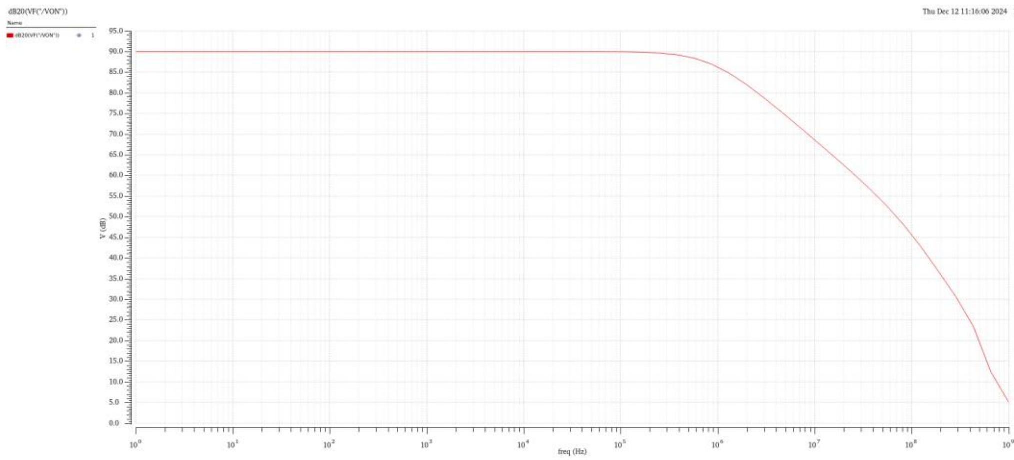


Figure 44:gain with bgr circuit

Test	Output	Nominal	Spec	Weight	Pass/Fail
Final:Telescopic_with_5T_OTA_and_BGR:1	ymax(dB20(VF("/VOP")))	90.04			
Final:Telescopic_with_5T_OTA_and_BGR:1	bandwidth(VF("/VOP") 3 "low")	863k			
Final:Telescopic_with_5T_OTA_and_BGR:1	dB20(VF("/VON"))				
Final:Telescopic_with_5T_OTA_and_BGR:1	gainBwProd(VF("/VON"))	27.47G			

Figure 45:results with bgr circuit

Part 2:

1. Determine the values of the passive elements (resistors and capacitors) to generate output frequencies from 100kHz up to 10MHz. (show your analysis and design choices)

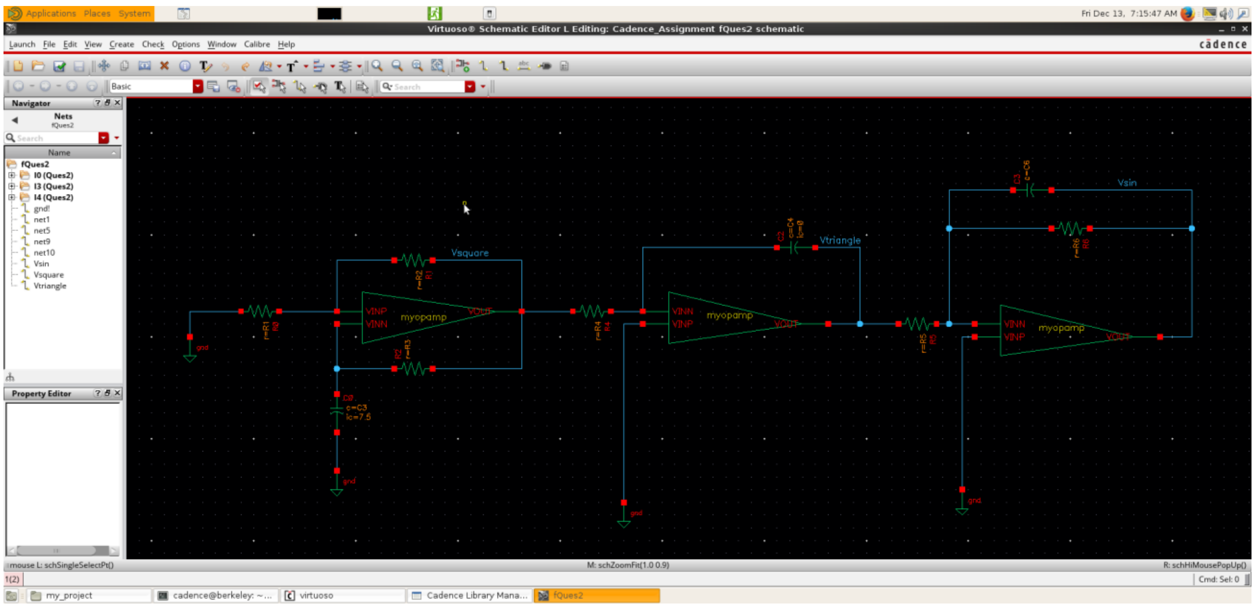


Figure 46: The Schematic for the circuit

Hand Analysis for first part (A Stable circuit):

$V^+ = VO1 * \frac{R1}{R1+R2}$, So V^+ has 2 values depending on VO1 value :

If VO1= VCC then $V^+= VCC * \beta$

And if VO1= VCC then $V^+= -VCC * \beta$,Where $\beta = \frac{R1}{R1+R2}$

$Vc = Vi + (Vf - Vi)e^{-t/\tau}$ >> $t = \tau\ ln(\frac{Vf - Vi}{Vf + Vi})$, Where τ = RC (Time Constant)

To get T_H, We put $Vi = -VCC * \beta$ & Vf = VCC and by solving the equation:

$T_H = T_L = \tau\ ln(\frac{1+\beta}{1-\beta})$ & $F = \frac{1}{TH+TL} = \frac{1}{2 * R3 * C3 * ln(\frac{1+\beta}{1-\beta})}$

To get A Stable circuit parameters, Let R1=R2=R3=10 KΩ

$\beta = \frac{1}{2}$, C3 @ F = 100 KHZ = 4.55 pF and @ F = 10 MHZ =0.455 nF

Hand Analysis for Second part (Integrator):

$I_R = I_C >> \frac{VO1}{R4} = C\,\frac{d\,(0-VO2)}{dt}$

$V_{O2} = \frac{-1}{R4*C4}\int VO1\,dt = \frac{-VO1}{R4*C4}t$, So V_{O2} has 2 values depending on VO1 value :

If V_{O1}= VCC then $V_{O2}= \frac{-VO1}{R4*C4}t$

And if V_{O1}= VCC then $V_{O2}= \frac{+V01}{R4*C4}t$

VO MAX = $\frac{VCC*T}{R4*C4}$ & VO MAX = $-\frac{VCC*T}{R4*C4}$, Where T is the half period = $\frac{1}{2F}$

Vpp = $\frac{2*VCC*T}{R4*C4}$, Assumed R4 is 10KΩ ,Vpp is 5V and VCC is 10V

C4 @ F = 100 KHZ = 1 nF and @ F = 10 MHZ =10 pF

Hand Analysis for third part (Low Pass Filter):

Cut-Off frequency Fc = $\frac{1}{2*pi*R6*C6}$

Let R5=R6=10 KΩ, C3 @F = 100 KHZ = .156 nF and @F = 10 MHZ =1.591 pF

LPF Gain = $\frac{1}{\sqrt[2]{1+(2*pi*Fc*R6*C6)^2}}$

Final values for circuit parameters:

C3	0.455n
C4	1n
C6	0.156n
COUT	79.5p
GM	10000
R1	10k
R2	10k
R3	10k
R4	10k
R5	10k
R6	10k

Figure 47: The Design Specs at f=100Khz

C3	4.55p
C4	10p
C6	1.591p
COUT	79.5p
GM	10000
R1	10k
R2	10k
R3	10k
R4	10k
R5	10k
R6	10k

Figure 48: The Design Specs at f=10Mhz

2. Simulate the schematic of the function generator using a model for the op-amps to have a gain and BW (you can use voltage controlled voltage source with gain=10,000 and a first order RC network to set the BW=100MHz).

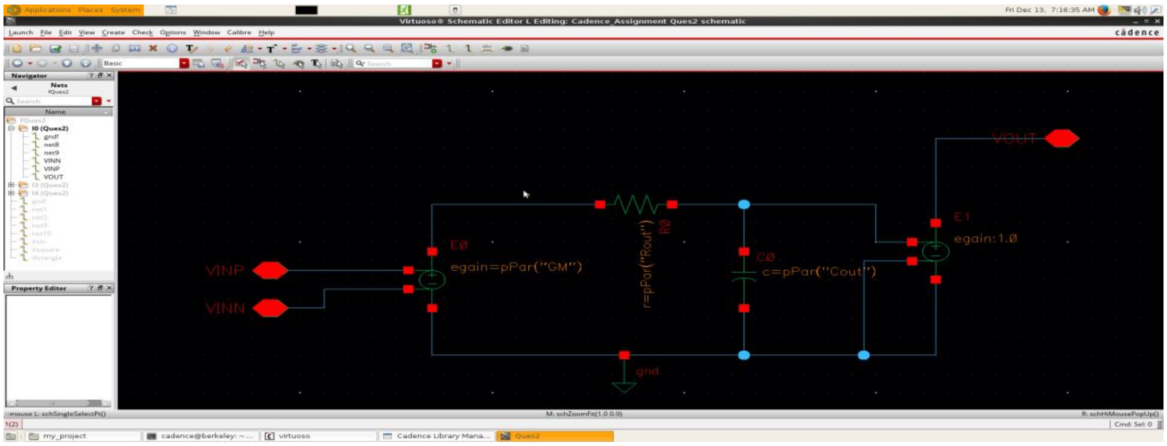


Figure 49: The Schematic for The OPamp model

$\underline{\boldsymbol{In\ Case:\ BW\ =\ 100Mhz}}$

$we\ assume\ R_{out}\ =\ 20\Omega\ \ so,$

$$\mathbf{f = \frac{1}{2\Pi RC} ----> C_{out}\ =\ 79.5PF}$$

$$\boldsymbol{In\ Case:\ BW = 1Mhz}$$

$$\boldsymbol{we\ assume\ R_{out}\ =\ 20\Omega\ \ so,}$$

$$\boldsymbol{f = \frac{1}{2\Pi RC} ----> C_{out}\ =\ 7.95nF}$$

$$\boldsymbol{In\ Case:\ BW = 1Khz}$$

$$\boldsymbol{we\ assume\ R_{out}\ =\ 20\Omega\ \ so,}$$

$$\boldsymbol{f = \frac{1}{2\Pi RC} ----> C_{out}\ =\ 7.95uF}$$

$\boldsymbol{BW}$	$\boldsymbol{100Mhz}$	$\boldsymbol{1Khz}$	$\boldsymbol{1Mhz}$
$\boldsymbol{R_{out}}$	$\boldsymbol{20\Omega}$	$\boldsymbol{20\Omega}$	$\boldsymbol{20\Omega}$
$\boldsymbol{C_{out}}$	$\boldsymbol{79.5PF}$	$\boldsymbol{7.95uF}$	$\boldsymbol{7.95nF}$

3. Plot the output waveforms from the three stages showing the minimum and maximum frequencies.

- **At frequency = 100Khz**

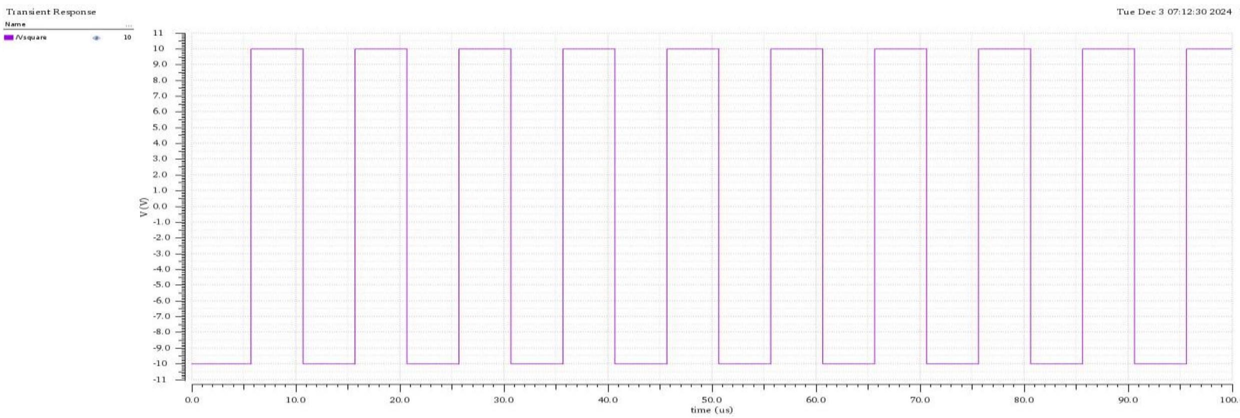


Figure 50: The Square Wave at frequency 100Khz Gain = 10000 and BW = 100Mhz

As shown in the figure it is a Square wave at frequency = 100Khz and it is generated by the Astable multivibrator circuit (1st Stage) with voltage peak-to-peak = 20v (2Vcc).

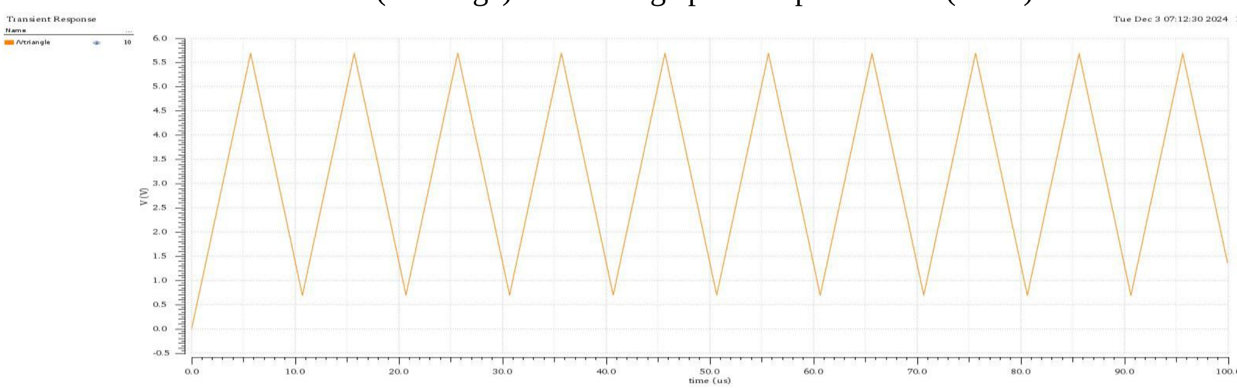


Figure 51: The Triangular Wave at frequency 100Khz Gain = 10000 and BW = 100Mhz

As shown in the figure, it is a triangular wave with a frequency of 100 kHz, generated by integrating the square wave using an inverting integrator (2nd stage) with a peak-to-peak voltage of **5V**. However, we previously assumed the peak-to-peak voltage to be 10V. because the capacitor requires a discharge time of 10 µs, but in the figure, it only takes 5 µs. Therefore, the capacitor does not have enough time to fully discharge.

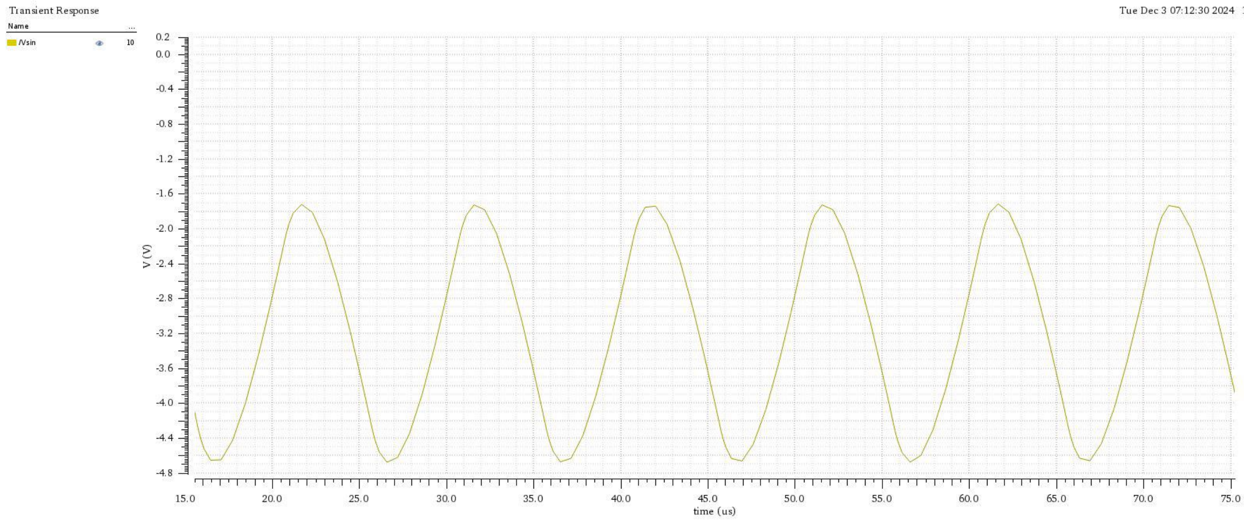


Figure 52: The Sin Wave at frequency 100Khz Gain = 10000 and BW = 100Mhz

As shown in the figure it is a Sin wave at frequency = 100Khz and it is generated by using a Low-Pass-Filter to select the Fundamental frequency with voltage peak-to-peak = 5v.

- **At frequency = 10Mhz**

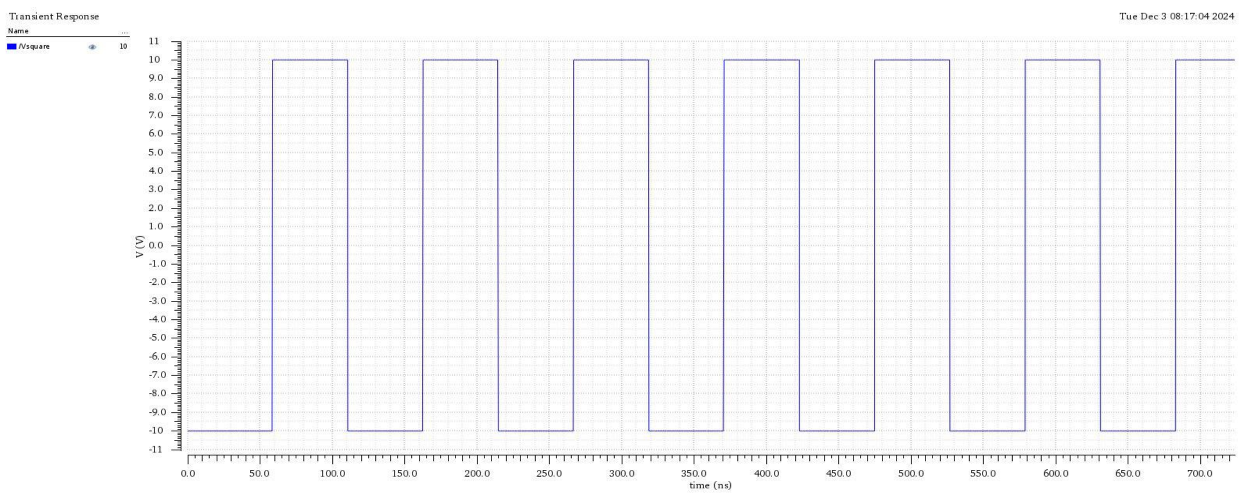


Figure 53: The Square Wave at frequency 10Mhz Gain = 10000 and BW = 100Mhz

As shown in the figure it is a Square wave at frequency = 10Mhz and it is generated by the Astable multivibrator circuit (1st Stage) with voltage peak-to-peak = 20v (2Vcc).

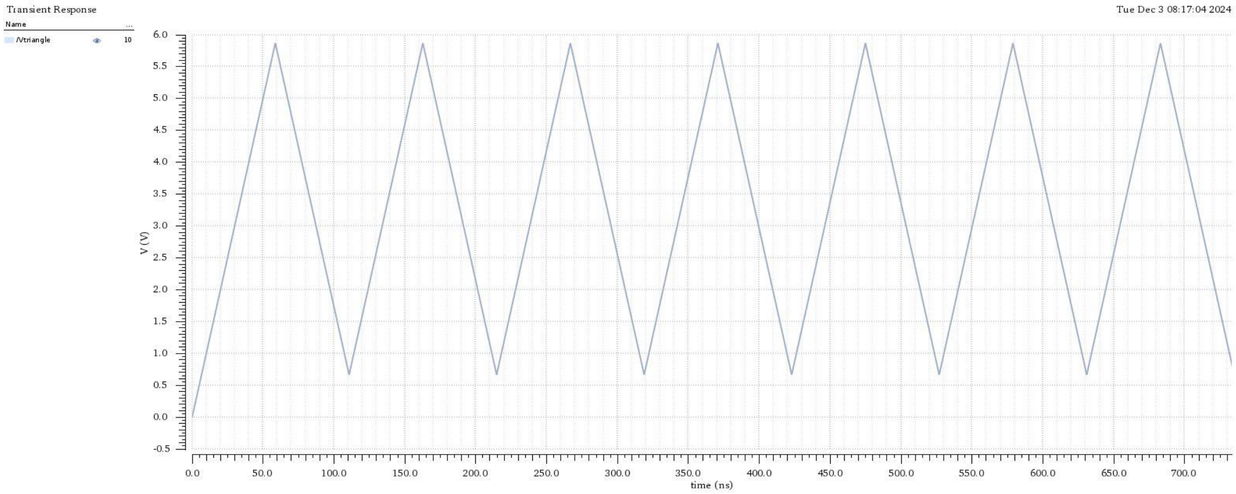


Figure 54: The Triangular Wave at frequency 10Mhz Gain = 10000 and BW = 100Mhz

As shown in the figure, it is a triangular wave with a frequency of 100 kHz, generated by integrating the square wave using an inverting integrator (2nd stage) with a peak-to-peak voltage of 5V. However, we previously assumed the peak-to-peak voltage to be 10V. because the capacitor requires a discharge time of 10 µs, but in the figure, it only takes 5 µs. Therefore, the capacitor does not have enough timeto fully discharge.

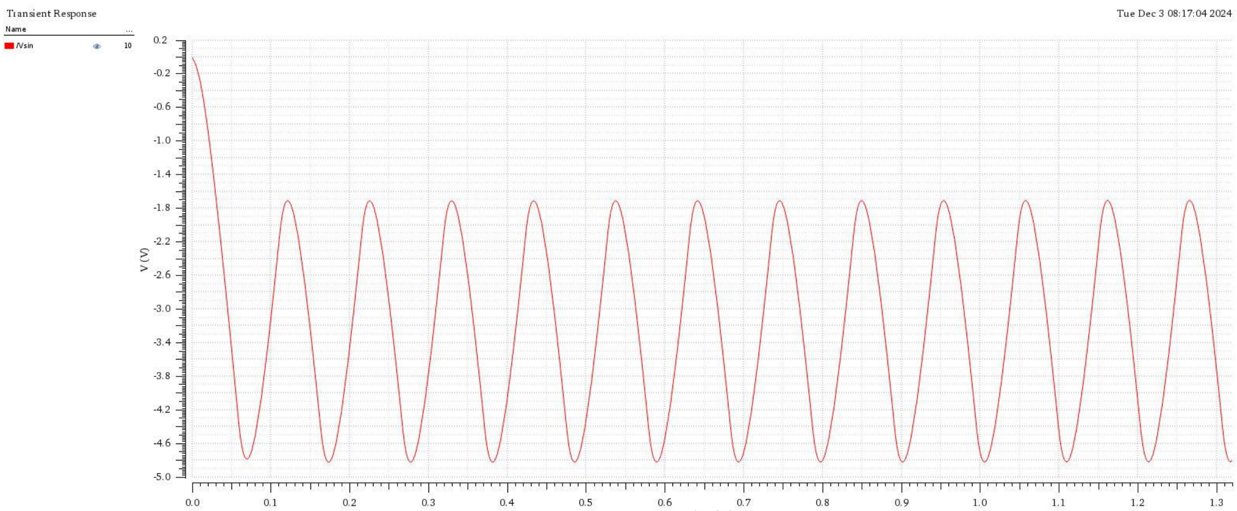


Figure 55: The Sin Wave at frequency 10Mhz Gain = 10000 and BW = 100Mhz

As shown in the figure it is a Sin wave at frequency = 10Mhz and it is generated by using a Low-Pass-Filter to select the Fundamental frequency with voltage peak-to-peak = 5v.

4. Show the purity of the output sine wave using Discrete Fourier Transform (DFT) and total harmonic distortion (THD) in dB.

Show clearly the definition of THD and how to get the value of THD from the DFT.

The Total Harmonic Distortion (THD) is a measure of the distortion present in a signal due to the presence of harmonics. It quantifies how much the harmonic components of a waveform deviate from the fundamental frequency component, providing an indicator of the signal's fidelity.

$$\boldsymbol{THD = \frac{Sum\ of\ the\ powers\ of\ all\ harmonic\ components}{the\ power\ of\ the\ fundamental\ frequency}}$$

$$\boldsymbol{THD\ = \frac{\sum_{n=2}^{\infty}\frac{1}{2}A_n^2}{\frac{1}{2}A_1^2}}$$

- **At frequency = 100Khz**

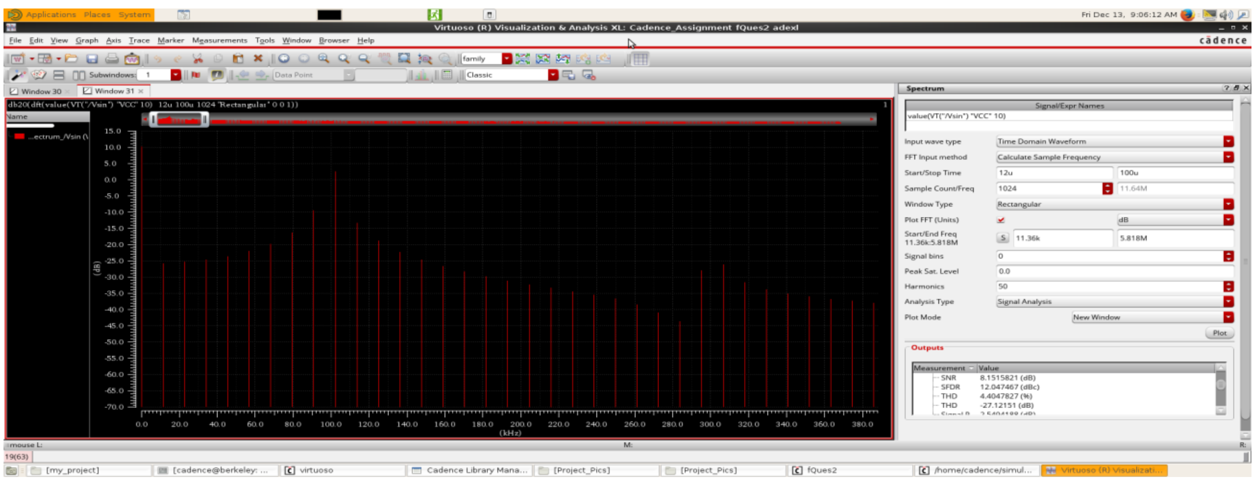


Figure 56: The DFT Sin Wave at frequency 100Khz and Gain = 10000 and BW = 100Mhz

As shown in the figure it is the Discrete Fourier Transform for the sin wave at frequency 100Khz and the THD = -27.1215 dB

- At frequency = 10Mhz

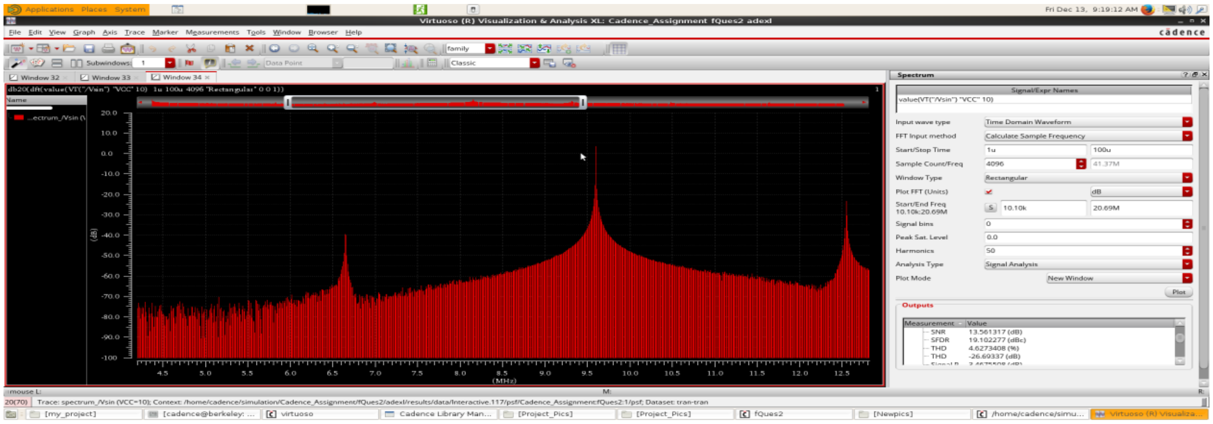


Figure 57: The DFT Sin Wave at frequency 10Mhz and Gain = 10000 and BW = 100Mhz

As shown in the figure it is the Discrete Fourier Transform for the sin wave at frequency 10Mhz and the THD = -26.69 dB

5. Change the gain of the ideal operational amplifiers (to be 1000 & 100) and show the effect on #3 & #4.

- At Gain = 1000 and frequency = 100Khz

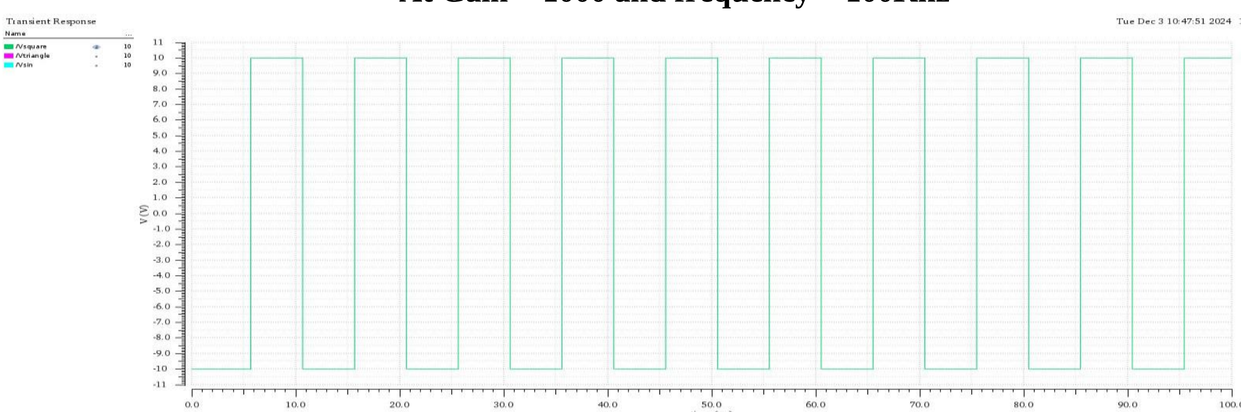


Figure 58: The Square Wave at frequency 100Khz Gain = 1000 and BW = 100Mhz

As shown in the figure it is a Square wave at frequency = 100Khz and it is generated by the Astable multivibrator circuit (1st Stage) with voltage peak-to-peak = 20v (2Vcc).

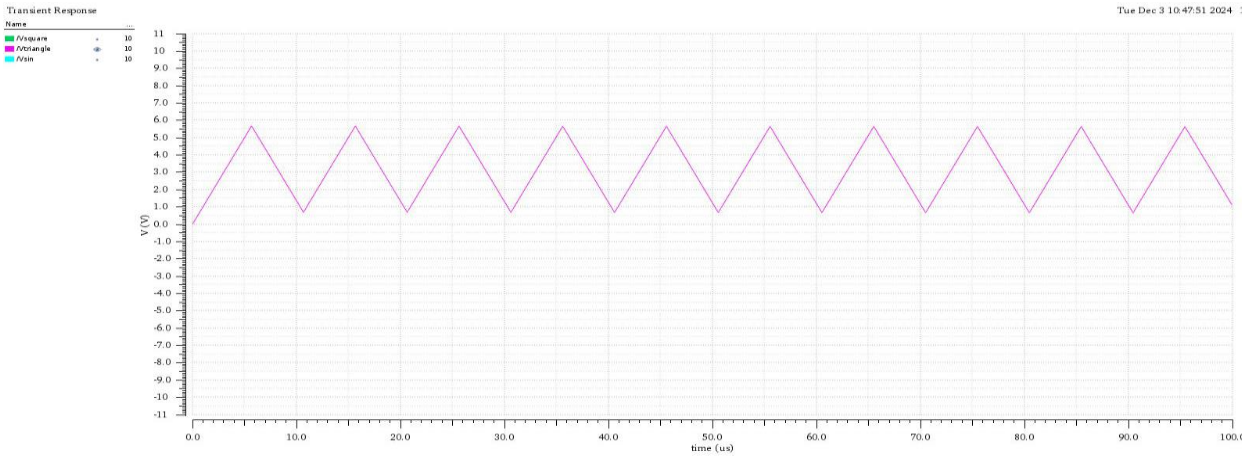


Figure 59: The Triangular Wave at frequency 100Khz Gain = 1000 and BW = 100Mhz

As shown in the figure, it is a triangular wave with a frequency of 100 kHz, generated by integrating the square wave using an inverting integrator (2nd stage) with a peak-to-peak voltage of **5V**.

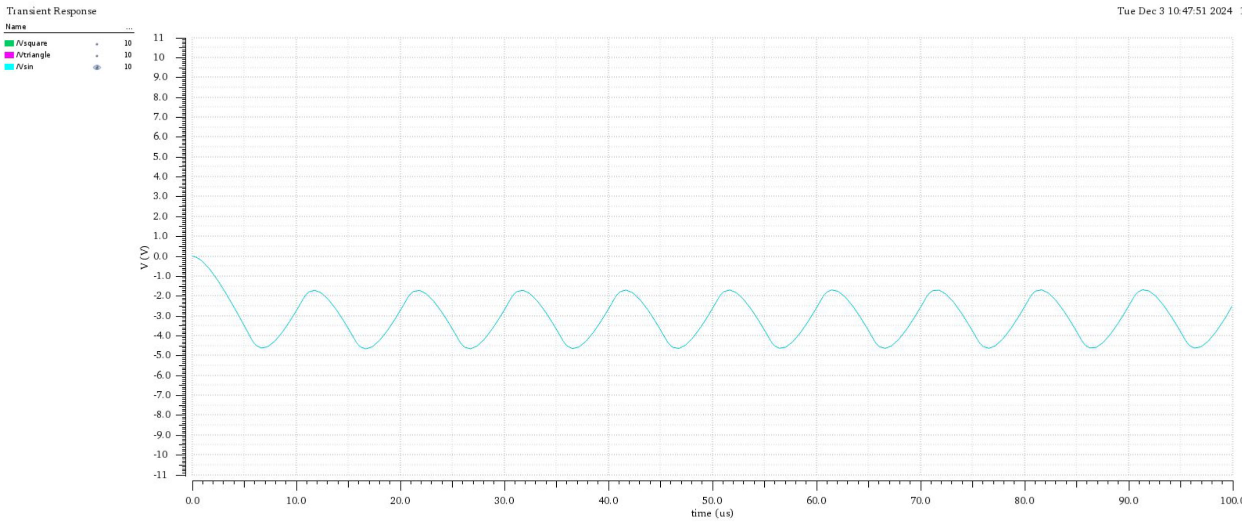


Figure 60: The Sin Wave at frequency 100Khz Gain = 1000 and BW = 100Mhz

As shown in the figure it is a Sin wave at frequency = 100Khz and it is generated by using a Low-Pass-Filter to select the Fundamental frequency with voltage peak-to-peak = 5v.

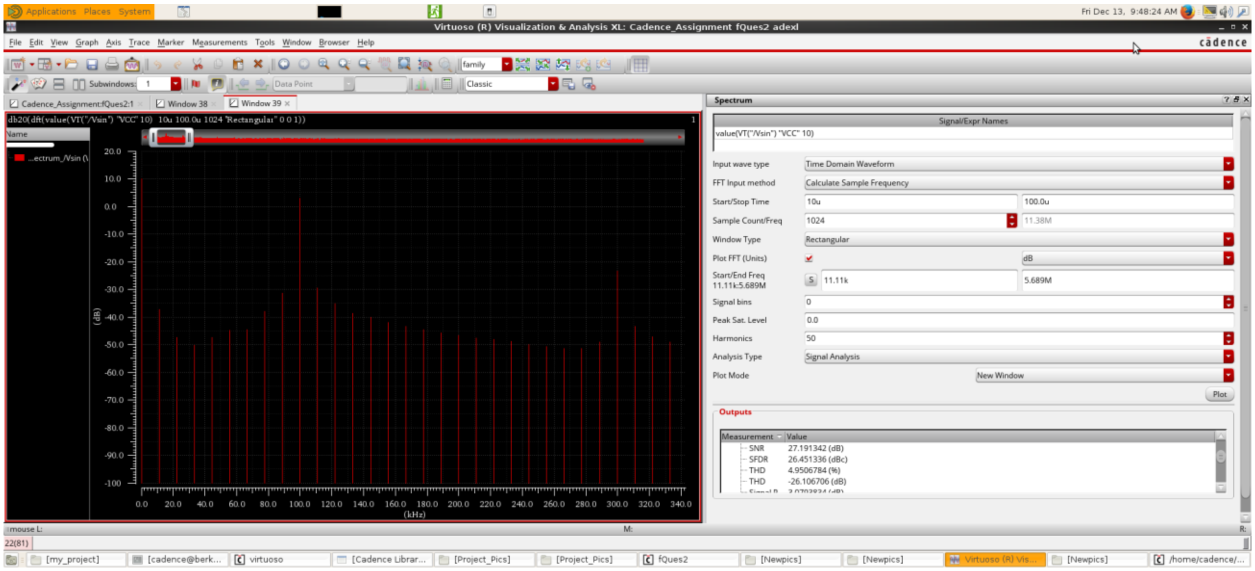


Figure 61: The DFT Sin Wave at frequency 100Khz and Gain = 1000 and BW = 100Mhz

As shown in the figure it is the Discrete Fourier Transform for the sin wave at frequency 100Khz and the THD = -26.1067 dB

When the gain decreased the Settele time increased.

- **At Gain = 100 and frequency = 100Khz**

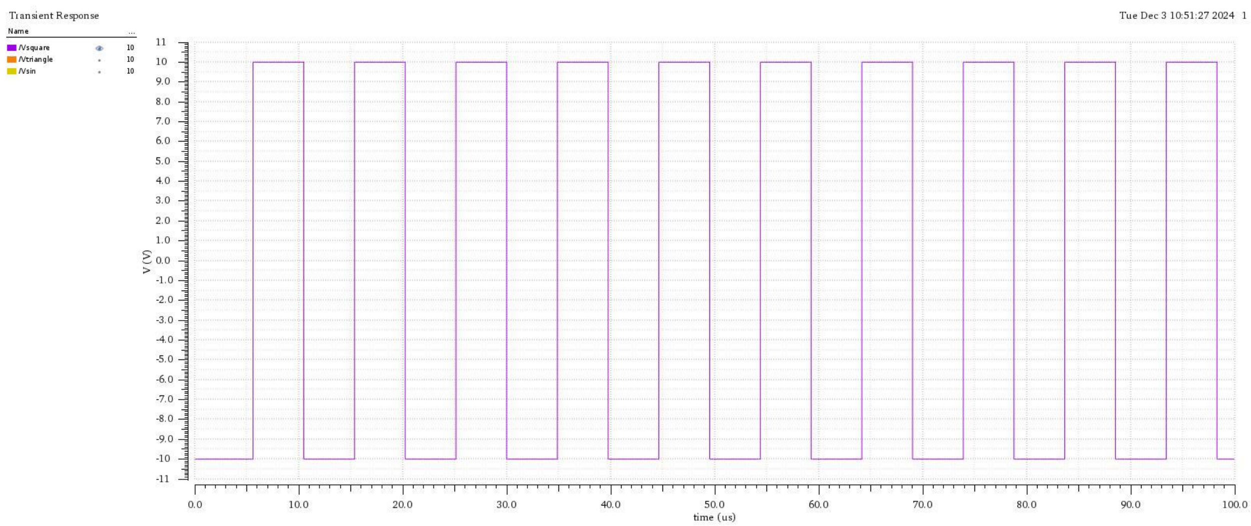


Figure 62: The Square Wave at frequency 100Khz Gain = 100 and BW = 100Mhz

As shown in the figure it is a Square wave at frequency = 100Khz and it is generated by the Astable multivibrator circuit (1st Stage) with voltage peak-to-peak = 20v (2Vcc).

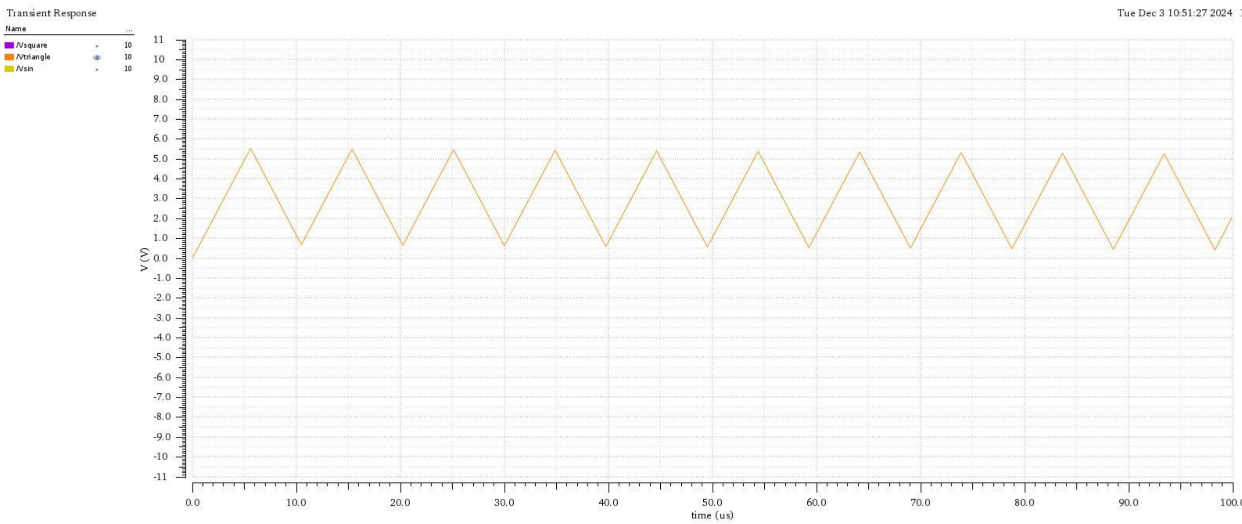


Figure 63: The Triangular Wave at frequency 100Khz Gain = 100 and BW = 100Mhz

As shown in the figure, it is a triangular wave with a frequency of 100 kHz, generated by integrating the square wave using an inverting integrator (2nd stage) with a peak-to-peak voltage of **5V**.

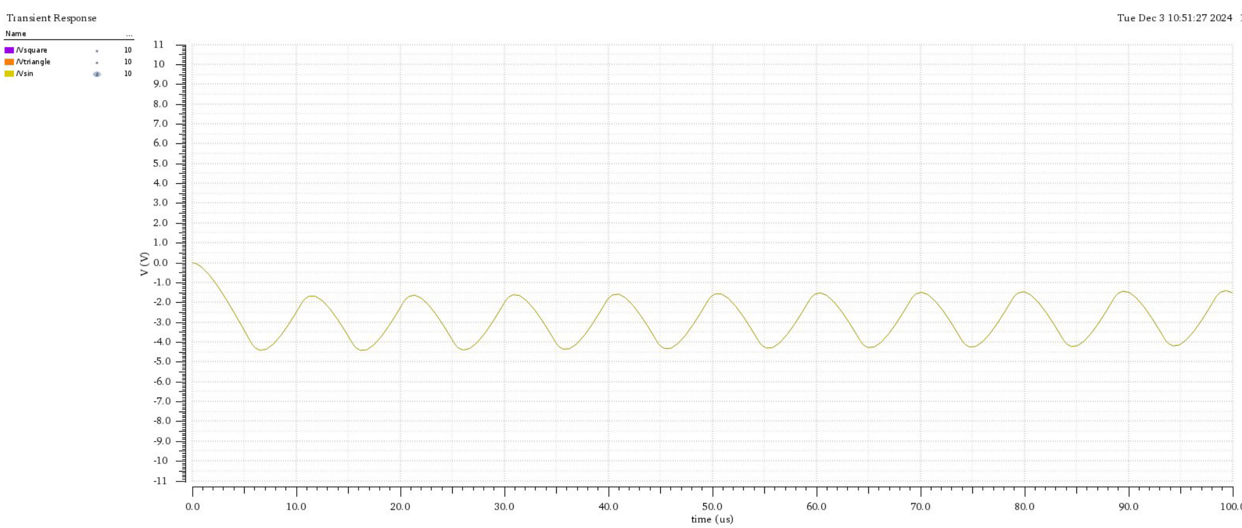


Figure 64: The Sin Wave at frequency 100Khz Gain = 100 and BW = 100Mhz

As shown in the figure it is a Sin wave at frequency = 100Khz and it is generated by using a Low-Pass-Filter to select the Fundamental frequency with voltage peak-to-peak = 5v.

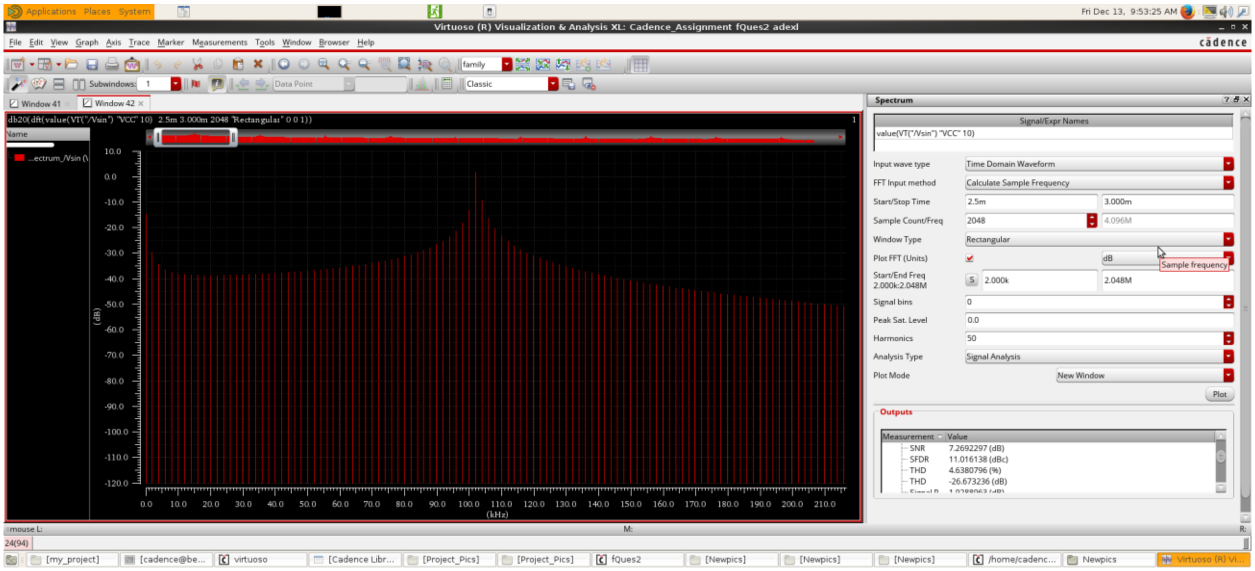


Figure 65: The DFT Sin Wave at frequency 100Khz and Gain = 100 and BW = 100Mhz

As shown in the figure it is the Discrete Fourier Transform for the sin wave at frequency 100Khz and the THD = -26.6732 dB

When the gain decreased the Settele time increased.

- At Gain = 1000 and frequency = 10Mhz

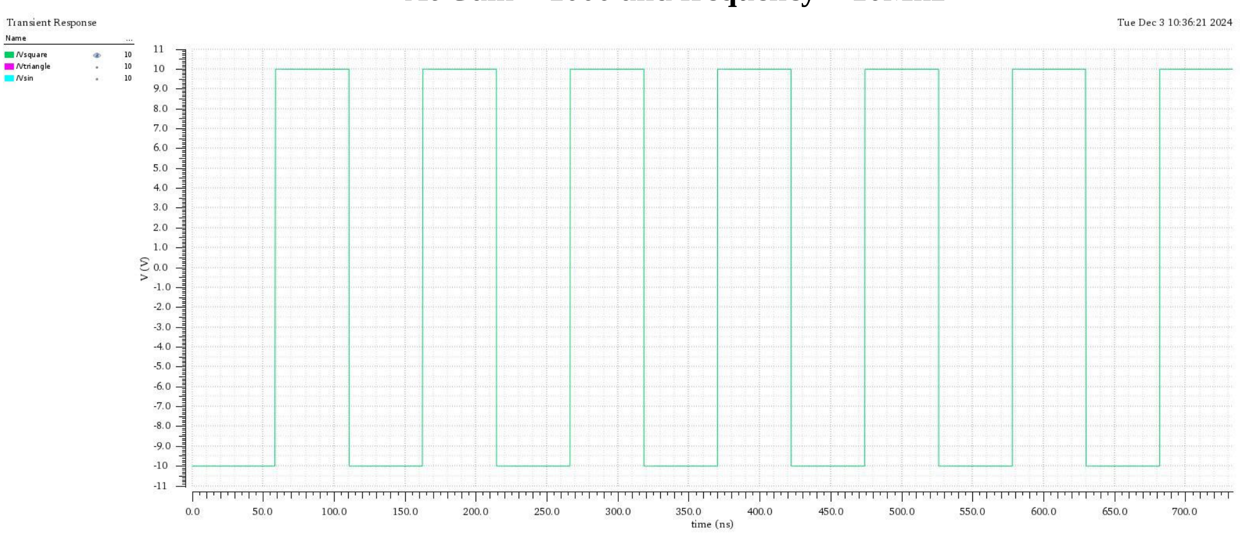


Figure 66: The Square Wave at frequency 10Mhz Gain = 1000 and BW = 100Mhz

As shown in the figure it is a Square wave at frequency = 10Mhz and it is generated by the Astable multivibrator circuit (1st Stage) with voltage peak-to-peak = 20v (2Vcc).

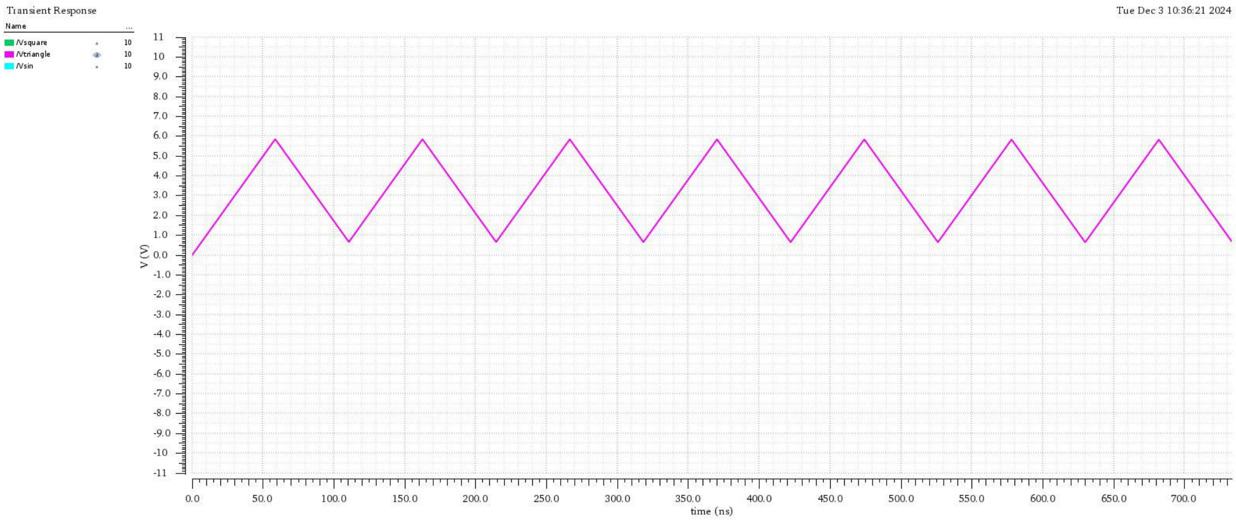


Figure 67: The Triangular Wave at frequency 10Mhz Gain = 1000 and BW = 100Mhz

As shown in the figure, it is a triangular wave with a frequency of 10MHz, generated by integrating the square wave using an inverting integrator (2nd stage) with a peak-to-peak voltage of **5V**.

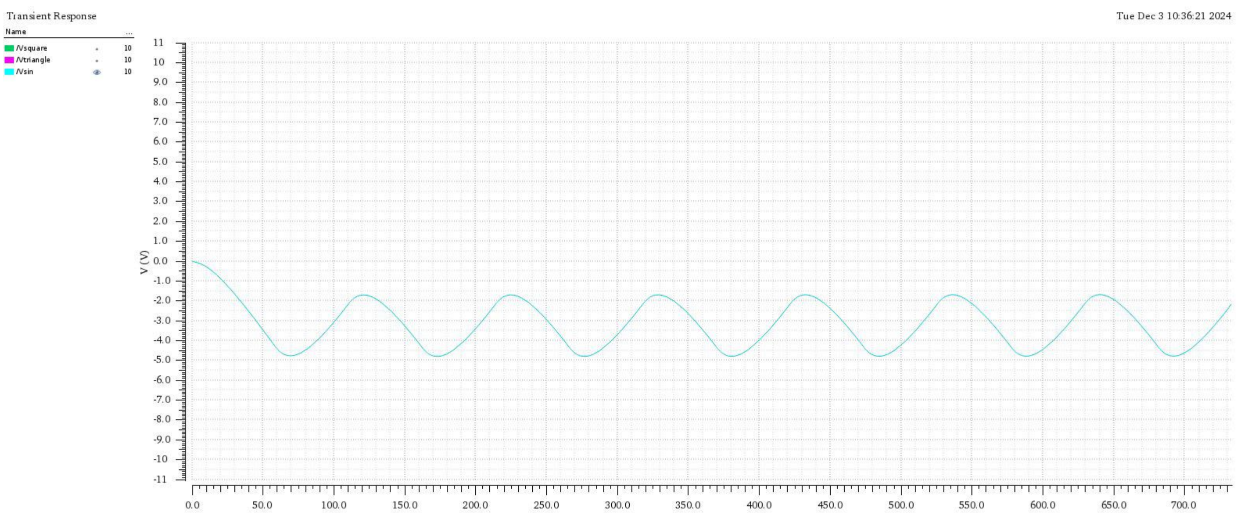


Figure 68: The Sin Wave at frequency 10Mhz Gain = 1000 and BW = 100Mhz

As shown in the figure it is a Sin wave at frequency = 10Mhz and it is generated by using a Low-Pass-Filter to select the Fundamental frequency with voltage peak-to-peak = 5v.

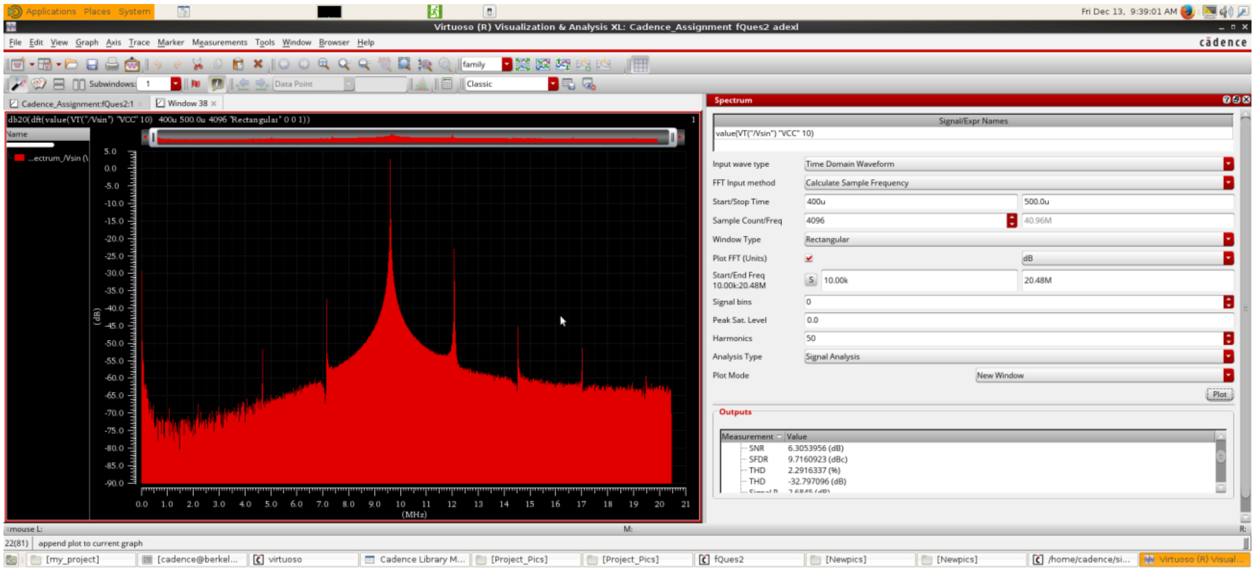


Figure 69: The DFT Sin Wave at frequency 10Mhz and Gain = 1000 and BW = 100Mhz

As shown in the figure it is the Discrete Fourier Transform for the sin wave at frequency 10Mhz and the THD = -23.797 dB

When the gain decreased the Settele time increased.

- At Gain = 100 and frequency = 10Mhz

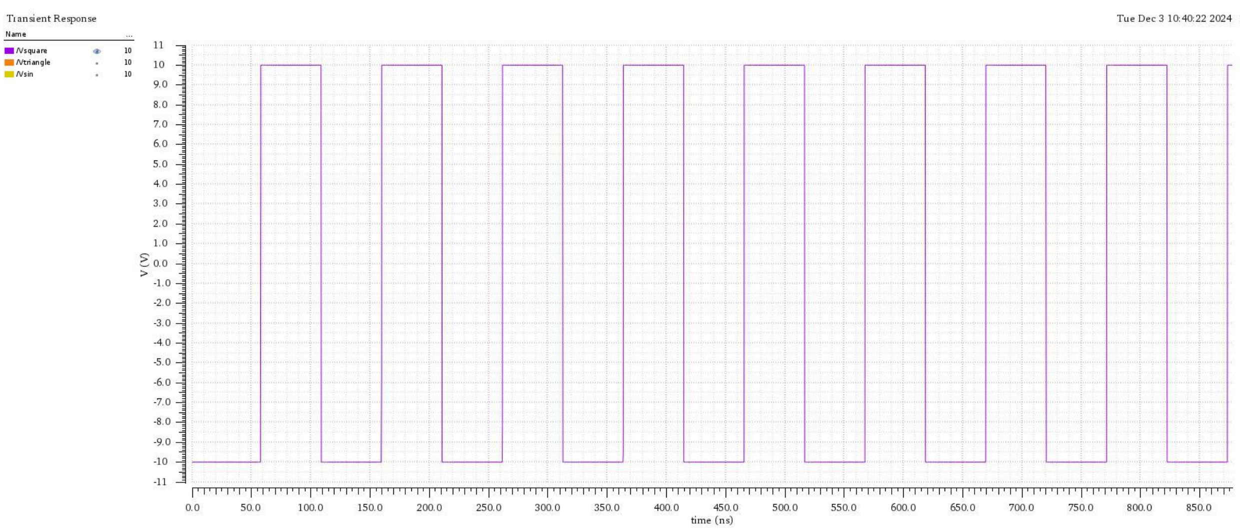


Figure 70: The Square Wave at frequency 10Mhz Gain = 100 and BW = 100Mhz

As shown in the figure it is a Square wave at frequency = 10Mhz and it is generated by the Astable multivibrator circuit (1st Stage) with voltage peak-to-peak = 20v (2Vcc).

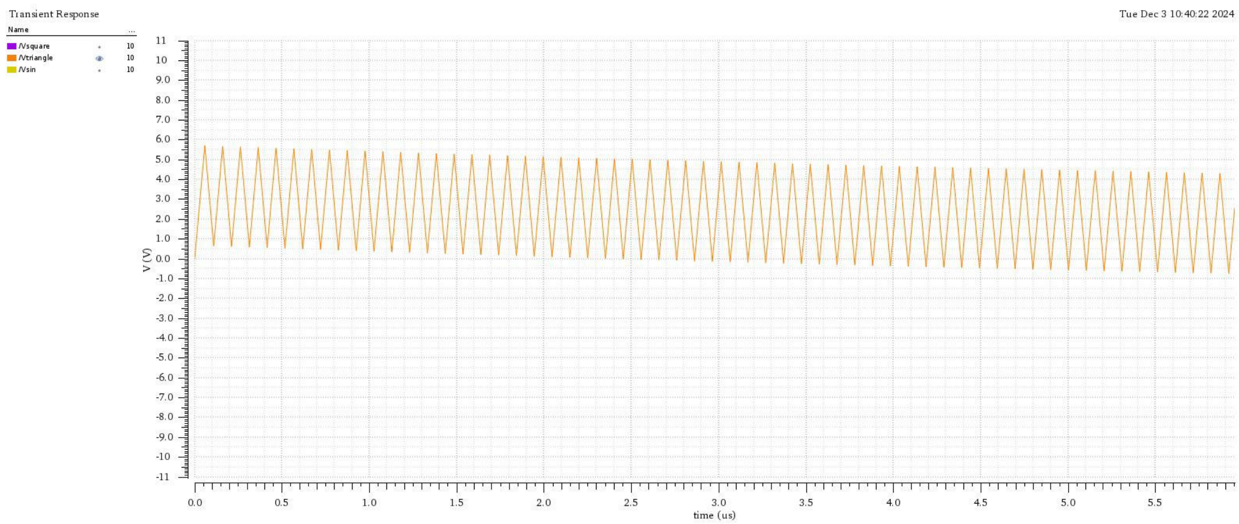


Figure 71: The Triangular Wave at frequency 10Mhz Gain = 100 and BW = 100Mhz

As shown in the figure, it is a triangular wave with a frequency of 10MHz, generated by integrating the square wave using an inverting integrator (2nd stage) with a peak-to-peak voltage of **5V**.

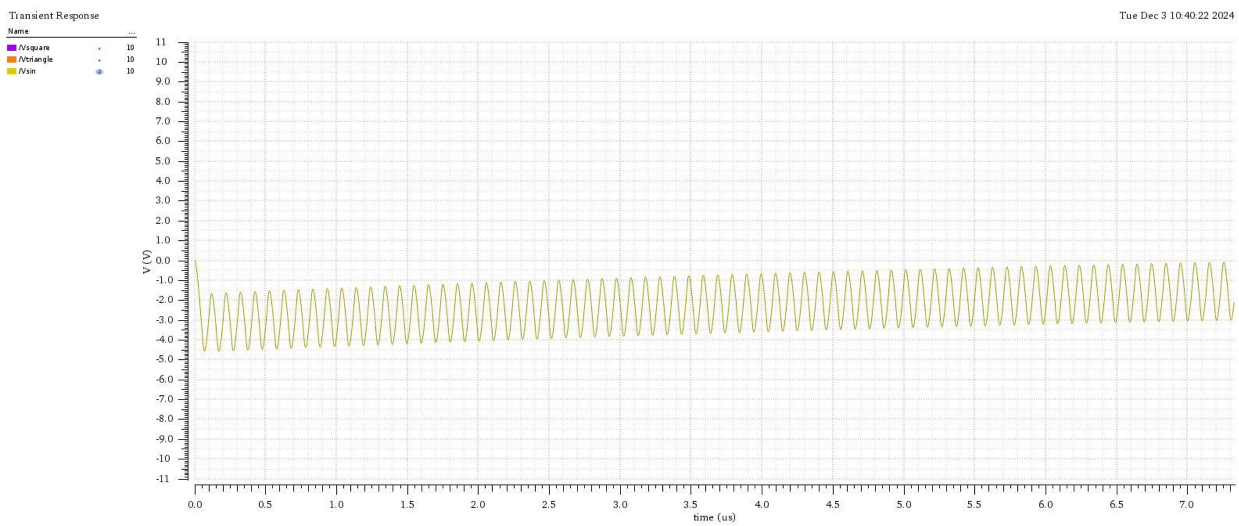


Figure 72: The Sin Wave at frequency 10Mhz Gain = 100 and BW = 100Mhz

As shown in the figure it is a Sin wave at frequency = 10Mhz and it is generated by using a Low-Pass-Filter to select the Fundamental frequency with voltage peak-to-peak = 5v.

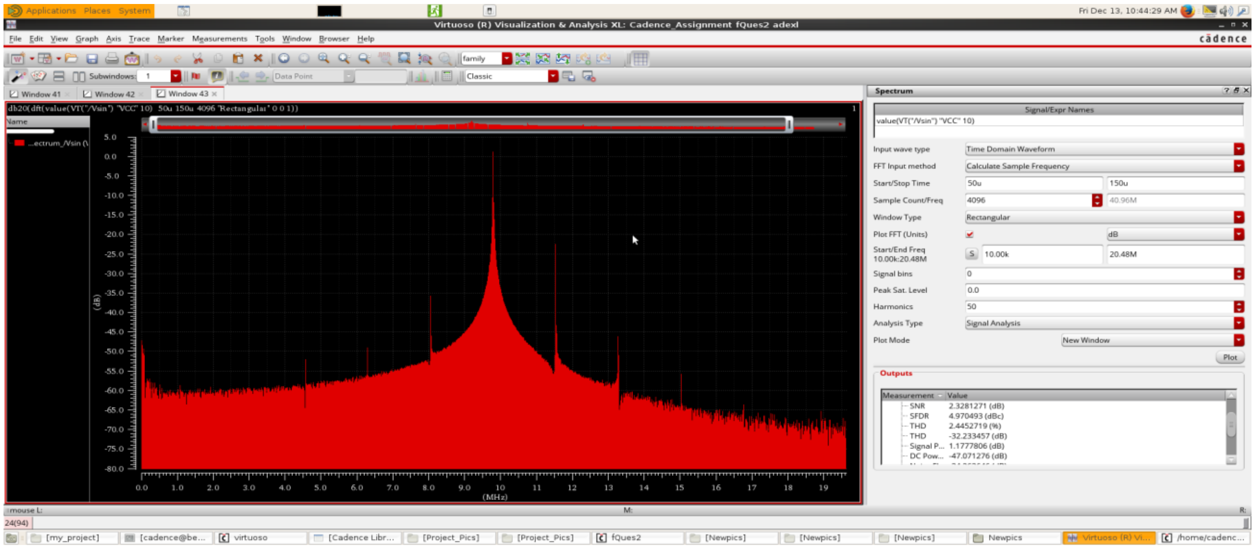


Figure 73: The DFT Sin Wave at frequency 10Mhz and Gain = 100 and BW = 100Mhz

As shown in the figure it is the Discrete Fourier Transform for the sin wave at frequency 10Mhz and the THD = -32.233 dB

When the gain decreased the Settle time increased.

6. Change the BW of the ideal operational amplifiers (to be 1MHz & 1KHz) and show the effect on #3 & #4.

- **At BW = 1Khz and frequency = 100Khz**

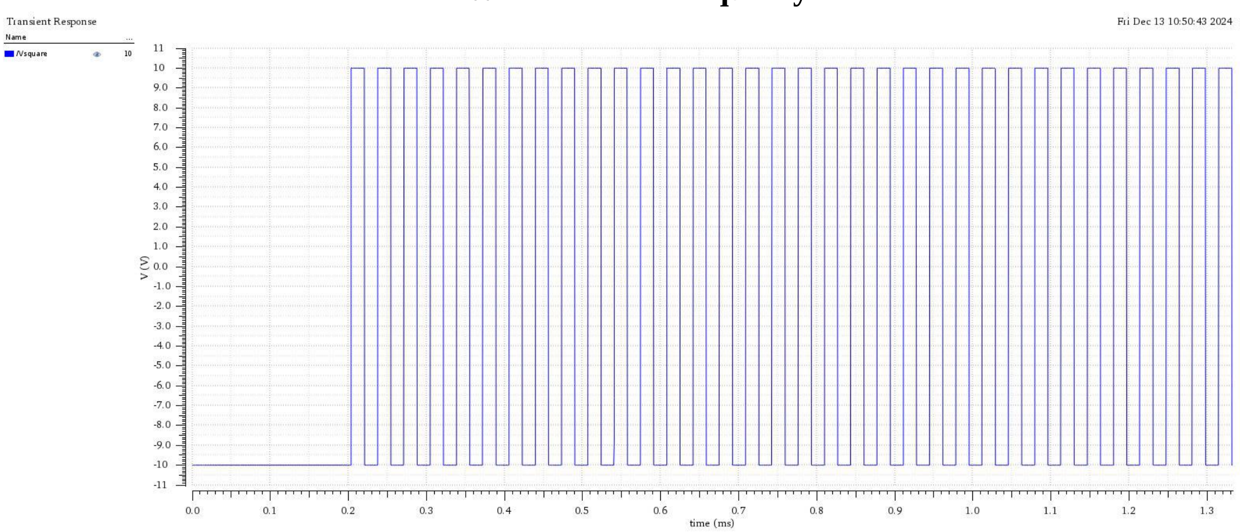


Figure 74: The Square Wave at frequency 100Khz Gain = 10k and BW = 1Khz

As shown in the figure it is a Square wave generated by the Astable multivibrator circuit (1st Stage) with voltage peak-to-peak = 20v (2Vcc) at frequency = 30Khz but it should be 100Khz because the BW is very narrow and it has distortion at the first 200us.

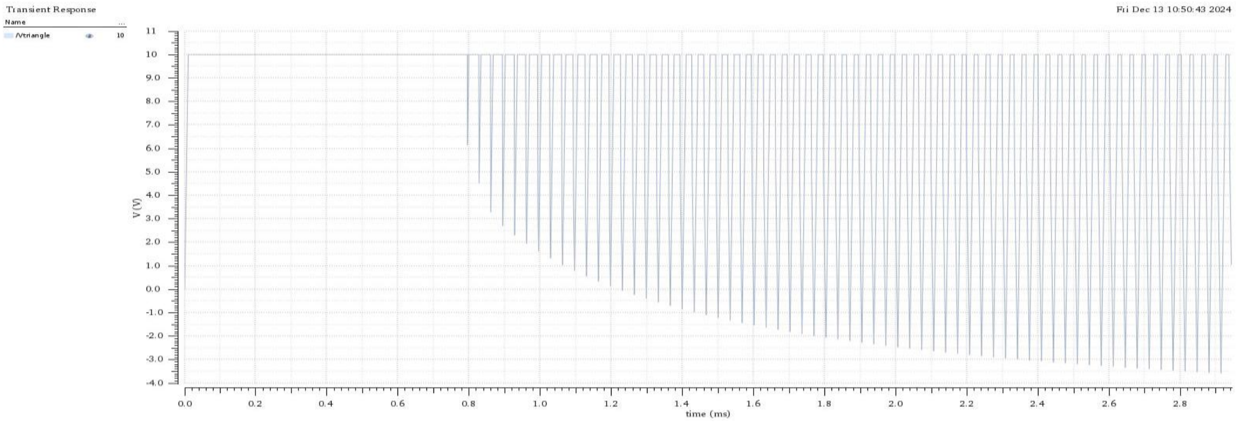


Figure 75: The Triangular Wave at frequency 100Khz Gain = 10000 and BW = 1Khz

As shown in the figure, it is a triangular wave with a frequency of 30KHz, generated by integrating the square wave using an inverting integrator (2nd stage) with a peak-to-peak voltage of **5V**.

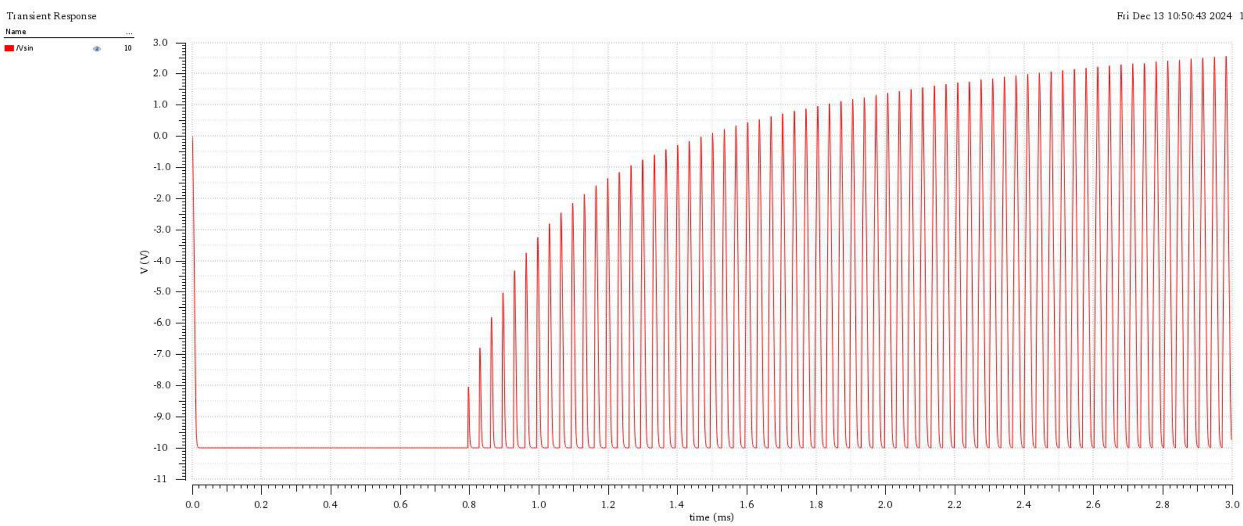


Figure 76: The Sin Wave at frequency 100Khz Gain = 10000 and BW = 1Khz

As shown in the figure it is a Sin wave at frequency = 30Khz and it is generated by using a Low-Pass-Filter to select the Fundamental frequency with voltage peak-to-peak = 5v.

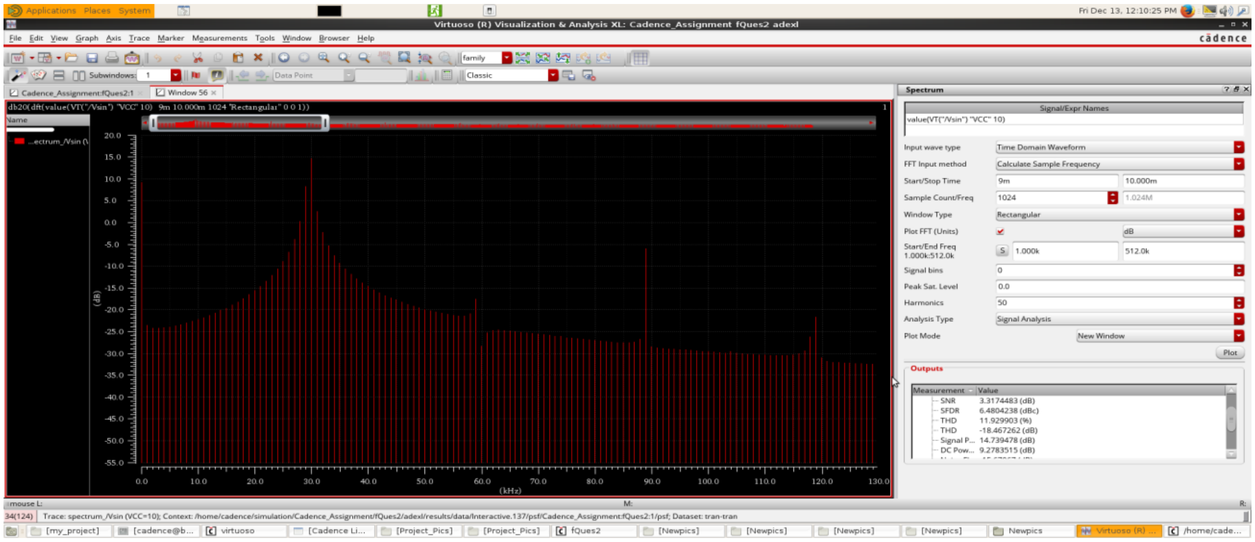


Figure 77: The DFT Sin Wave at frequency 100Khz and Gain = 10000 and BW = 1Khz

As shown in the figure it is the Discrete Fourier Transform for the sin wave at frequency 30Khz and the THD = -18.467 dB
When the BW decreased from 100Mhz to 1Khz the frequency decreased from 100Khz to 30Khz.

- At BW = 1Khz and frequency = 10Mhz

Figure 78: The Square Wave at frequency 10Mhz Gain = 10000 and BW = 1Khz

As shown in the figure it is a Square wave generated by the Astable multivibrator circuit (1st Stage) with voltage peak-to-peak = 20v (2Vcc) at frequency = 3Mhz but it should be 10Mhz because the BW is very narrow and it has distortion at the first 200us.

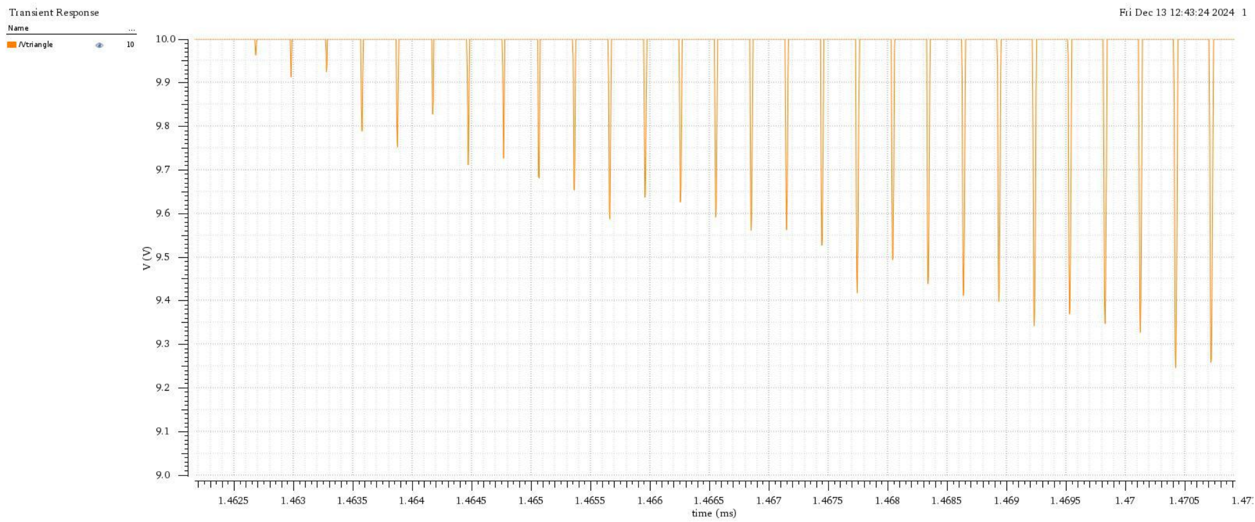


Figure 79: The Triangular Wave at frequency 10Mhz Gain = 10000 and BW = 1Khz

As shown in the figure, it is a triangular wave with a frequency of 3MHz, generated by integrating the square wave using an inverting integrator (2nd stage) with a peak-to-peak voltage of **5V**.

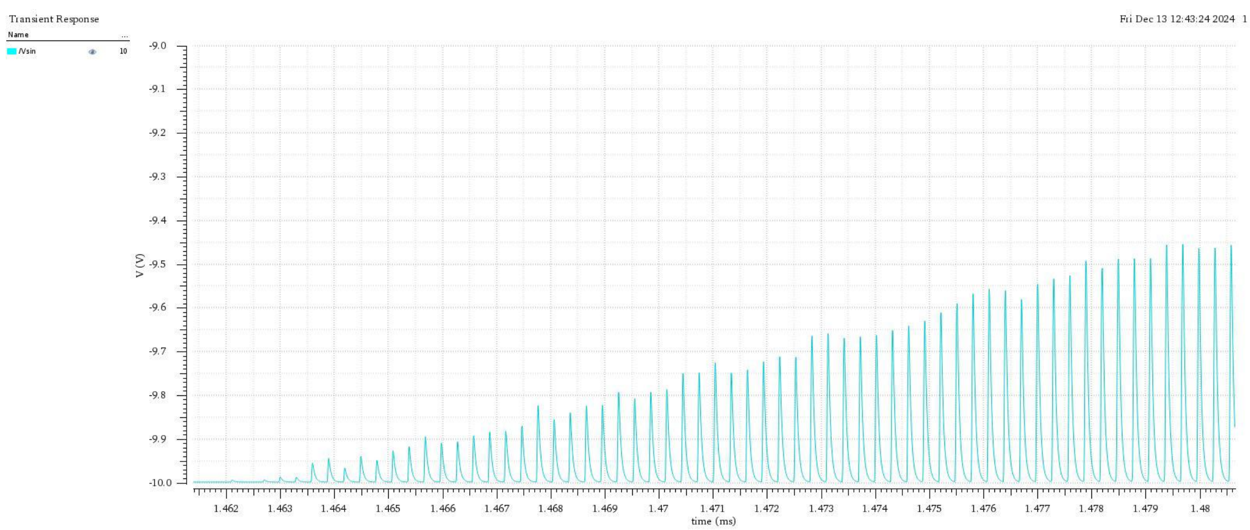


Figure 80: The Sin Wave at frequency 10Mhz Gain = 10000 and BW = 1Khz

As shown in the figure it is a Sin wave at frequency = 3Mhz and it is generated by using a Low-Pass-Filter to select the Fundamental frequency with voltage peak-to-peak = 5v.

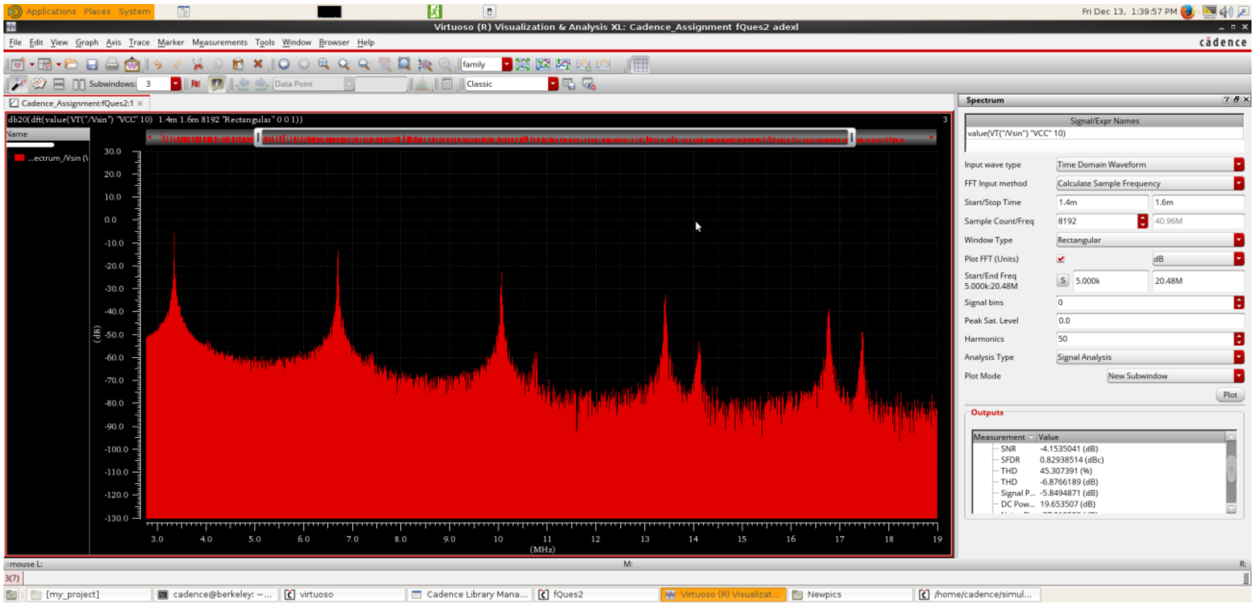


Figure 81: The DFT Sin Wave at frequency 10Mhz and Gain = 10000 and BW = 1Khz

As shown in the figure it is the Discrete Fourier Transform for the sin wave at frequency 3Mhz and the THD = -6.87 dB

When the BW decreased from 100Mhz to 1Khz the frequency decreased from 10Mhz to 3Mhz.

- **At BW = 1Mhz and frequency = 100Khz**

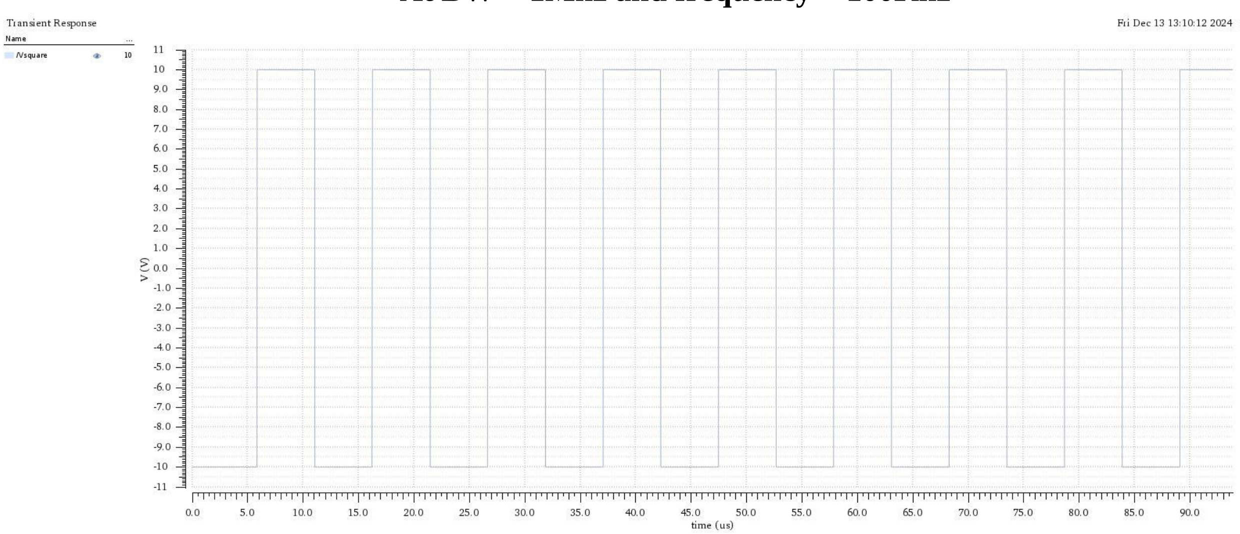


Figure 82: The Square Wave at frequency 100Khz Gain = 10k and BW = 1Mhz

As shown in the figure it is a Square wave generated by the Astable multivibrator circuit (1st Stage) with voltage peak-to-peak = 20v (2Vcc) at frequency = 96Khz but it should be 100Khz because the BW is 1Mhz and that lower than 100Mhz (the initial BW) but it still in the Mhz

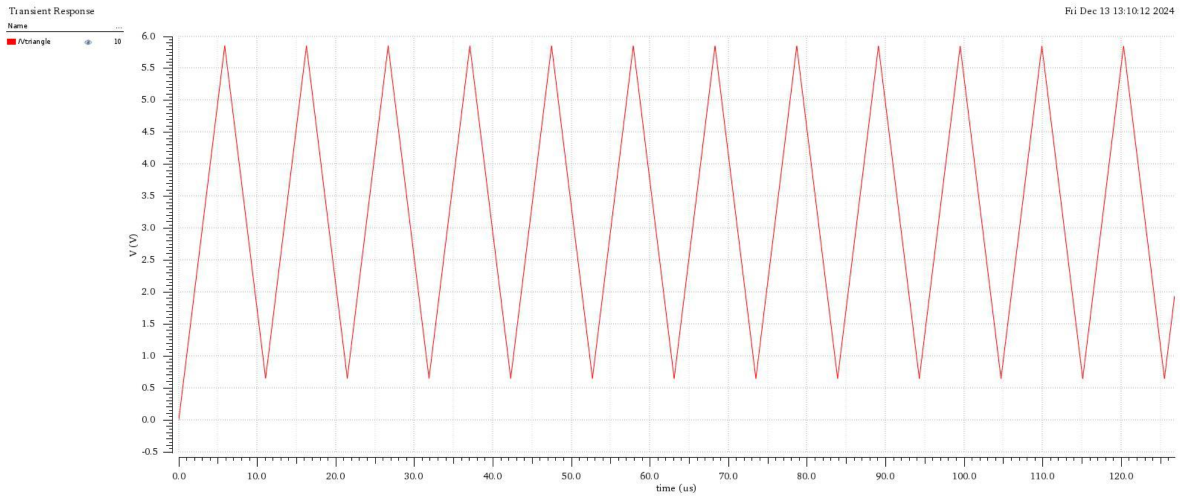


Figure 83: The Triangular Wave at frequency 100Khz Gain = 10000 and BW = 1Mhz

As shown in the figure, it is a triangular wave with a frequency of 96KHz, generated by integrating the square wave using an inverting integrator (2nd stage) with a peak-to-peak voltage of **5V**.

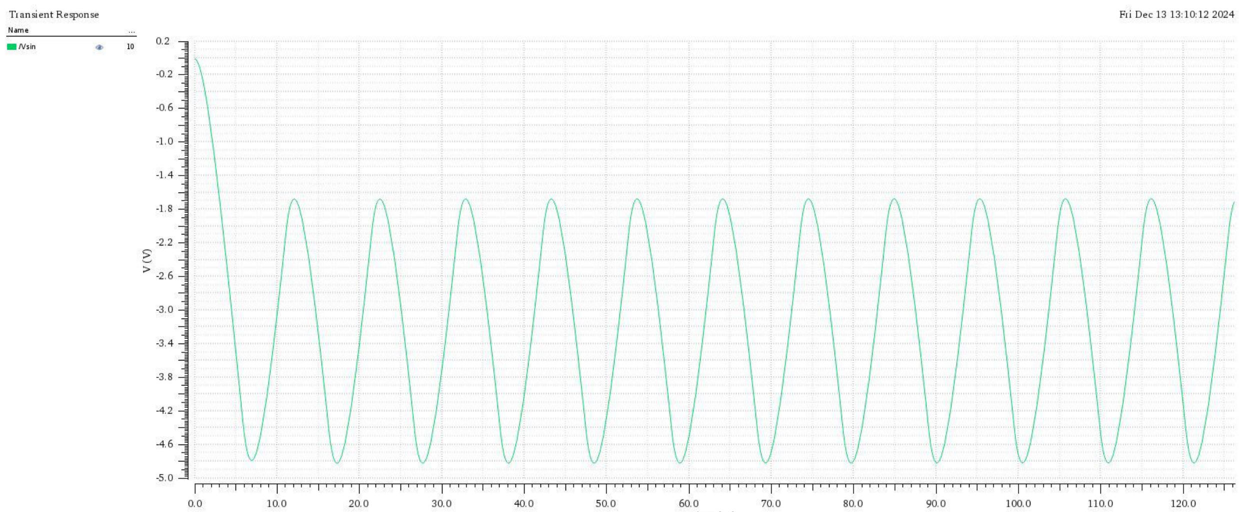


Figure 84: The Sin Wave at frequency 100Khz Gain = 10000 and BW = 1Mhz

As shown in the figure it is a Sin wave at frequency = 96Khz and it is generated by using a Low-Pass-Filter to select the Fundamental frequency with voltage peak-to-peak = 5v.

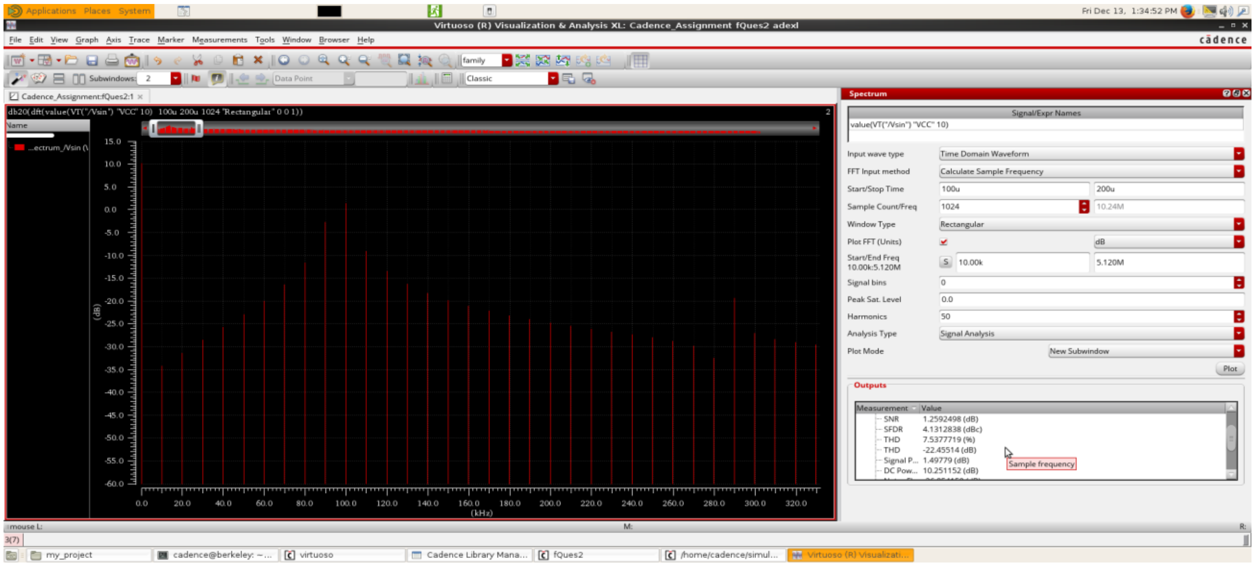


Figure 85: The DFT Sin Wave at frequency 100Khz and Gain = 10000 and BW = 1Mhz

As shown in the figure it is the Discrete Fourier Transform for the sin wave at frequency 96Khz and the THD = -22.455 dB

When the BW decreased from 100Mhz to 1Mhz the frequency decreased from 100Khz to 96Khz.

- At BW = 1Mhz and frequency = 10Mhz

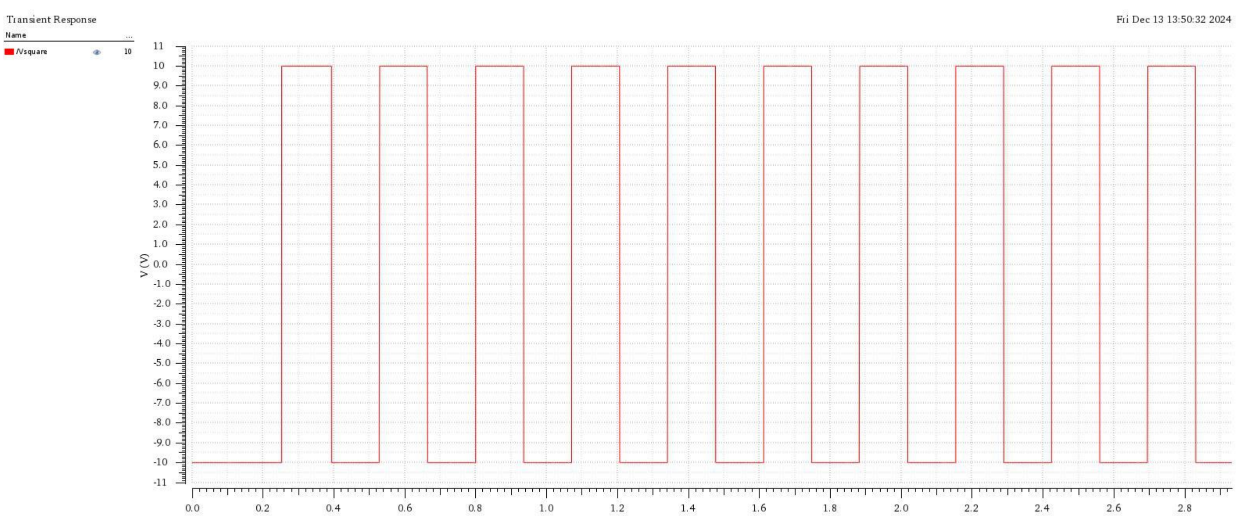


Figure 86: The Square Wave at frequency 10Mhz Gain = 10000 and BW = 1Mhz

As shown in the figure it is a Square wave generated by the Astable multivibrator circuit (1st Stage) with voltage peak-to-peak = 20v (2Vcc) at frequency = 3.6Mhz but it should be 10Mhz because the BW is narrow.

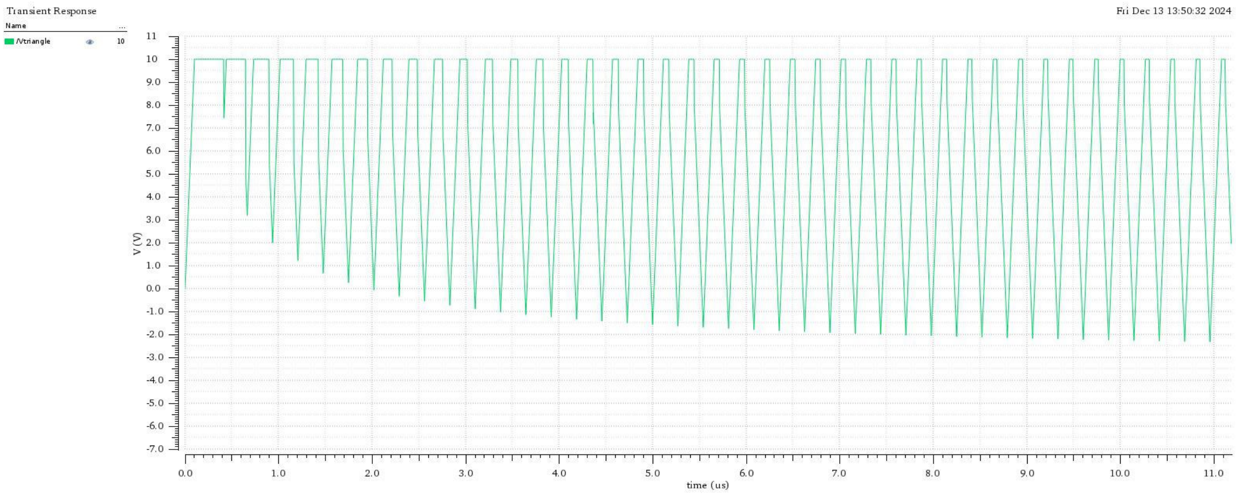


Figure 87: The Triangular Wave at frequency 10Mhz Gain = 10000 and BW = 1Mhz

As shown in the figure, it is a triangular wave with a frequency of 3.6MHz, generated by integrating the square wave using an inverting integrator (2nd stage) with a peak-to-peak voltage of **5V**.

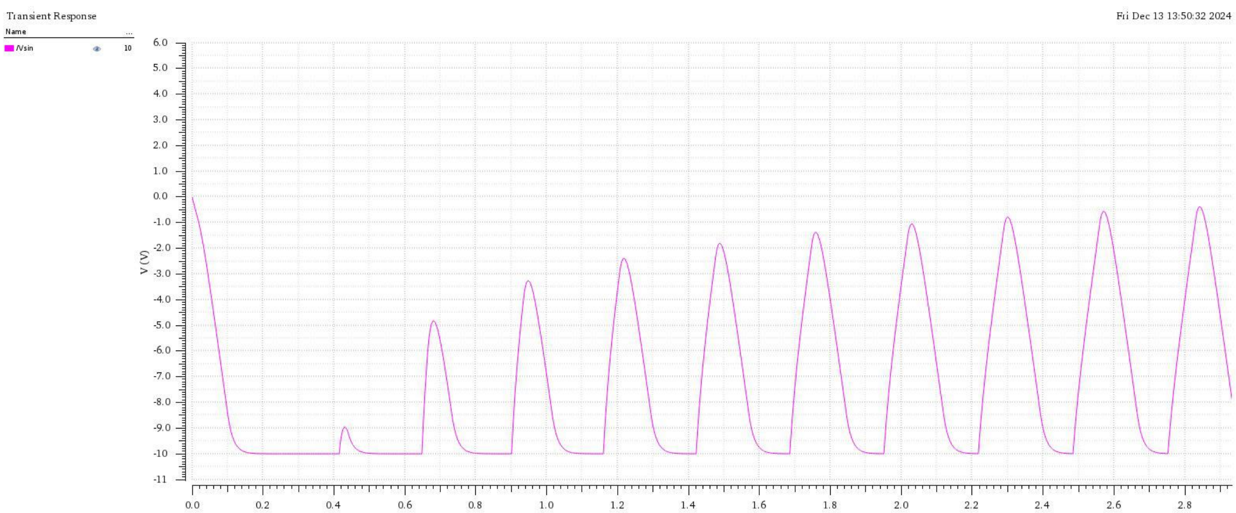


Figure 88: The Sin Wave at frequency 10Mhz Gain = 10000 and BW = 1Mhz

As shown in the figure it is a Sin wave at frequency = 3.6Mhz and it is generated by using a Low-Pass-Filter to select the Fundamental frequency with voltage peak-to-peak = 5v.

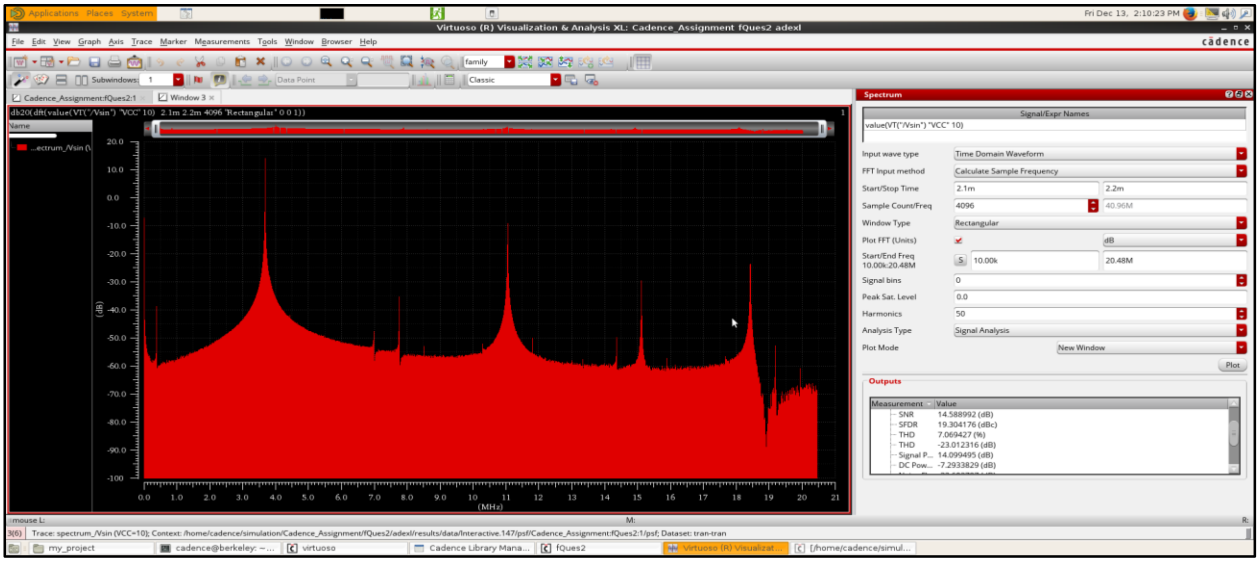


Figure 89: The DFT Sin Wave at frequency 10Mhz and Gain = 10000 and BW = 1Mhz

As shown in the figure it is the Discrete Fourier Transform for the sin wave at frequency 3.6Mhz and the THD = -23.0123 dB

When the BW decreased from 100Mhz to 1Mhz the frequency decreased from 10Mhz to 3.6Mhz.