Lab 5: Operational Amplifiers Part 3

ECEN 325 - 511

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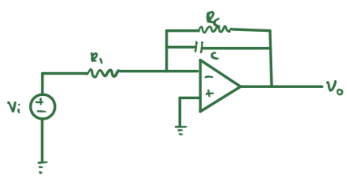
Due Date: October 19, 2021

Purpose

The purpose of this lab was to learn about some more op-amp configurations and understand the non-idealities of op-amps. For this lab, students built Lossy Integrator, Pseudo Differentiator, Finite GBW Limitations, Slew Rate Limitations.

Calculations

Lossy Integrator



low

$\frac{V_o(s)}{V_i(s)} = 22$

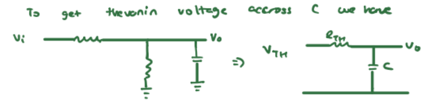
we have $R_2 = 22k$, $C = 220nF$,

$\hookrightarrow V_c(t) = V_c(\infty) + (V_c(0) - V_c(\infty)) e^{-t/\tau}$

$\tau \rightarrow$ constant time

$V_c(t)$ = voltage accross capacitor

To get thevonin voltage accross C we have



voltage accross R_2 will be V_{TH} and $R_{TH} = R_1 || R_2$

$$V_{TH} = \frac{R_2}{R_1 + R_2} V_i \quad - ①$$

$V_c(\infty) = 0$

$V_c(0) = V_{TH}$

$$V_o(t) = V_{TH} e^{-t/\tau}$$

we have $\tau = R_{TH} C = \frac{R_1 R_2 C}{R_1 + R_2} \quad - ②$

1) $$\boxed{V_o(t) = \frac{R_2}{R_1 + R_2} e^{-t\left(\frac{R_1 + R_2}{R_1 R_2 C}\right)}}$$

2) Voltage Gain $\frac{V_o(s)}{V_i(s)} = \frac{-R_2 || Z_c}{R_1}$

$$= \frac{R_2 Z_c}{R_2 + Z_c} \frac{1}{R_1}$$

$$= -\frac{R_2}{R_1}\left(\frac{1/cs}{R_2 + \frac{1}{cs}}\right) = \frac{-R_2}{R_1}\left(1 / R_2 cs + 1\right)$$

$$\boxed{\frac{V_o(s)}{V_i(s)} = \frac{-R_2}{R_1}}$$ Finite gain

now $-22 = -R_2/R_1$

$R_2 = 22k\Omega$

$$\boxed{R_1 = 1k\Omega}$$

the 3dB frequence $= \frac{1}{\tau} = \frac{R_1 + R_2}{R_1 R_2 C}$

$$= \frac{1k\Omega + 22k\Omega}{22k\Omega * 1k\Omega \times 220nF}$$

$$= \boxed{4.75 kHz}$$

3) $\dfrac{V_O(s)}{V_i(s)} = \dfrac{-R_2}{R_1}\left(\dfrac{1}{R_2 S C + 1}\right)$

$\dfrac{V_o(s)}{V_i(s)} = \dfrac{-22\,k\Omega}{1\,k\Omega}\left(\dfrac{1}{22k\Omega\, s\, 220nF + 1}\right)$

$= \dfrac{-22}{4.84 \times 10^{-3} s + 1} = \dfrac{-22}{\frac{s}{206.61} + 1} = \dfrac{-22}{1 + \frac{s}{206.61}}$ compare w/ $\dfrac{-k}{1 + s/\omega}$ $f = 206.61$ $k = 22$

only one pole at 206.61

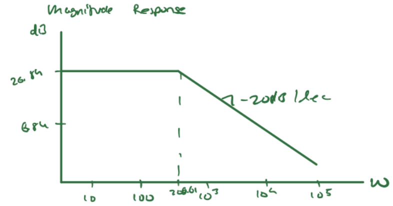
so $|T_o(s)| = +20 \log(22)$

$\lim |T_o(s)| = +20\log(22) = 26.85$

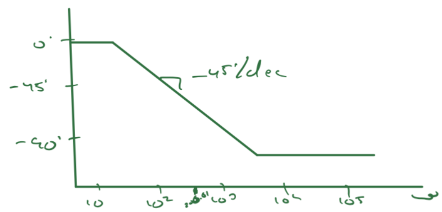
phase $[T(s)] = -\tan^{-1}\left(\frac{s}{206.61}\right)$

$\lim_{s \to 0}$ phase $[T(0)] = -\tan^{-1}\left(\frac{0}{206.61}\right) = 0°$

Magnitude Response



Phase Response



4) $\dfrac{V_o(s)}{V_i(s)} = \dfrac{22}{1 + \frac{s}{206.61}} = \dfrac{22}{\sqrt{1 + \frac{\omega^2}{206.61^2}}} \angle -\tan^{-1}\left(\omega/206.61\right)$

at $\omega = 2\pi 1000t$

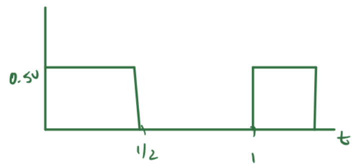
$= \dfrac{22}{\sqrt{1 + \frac{(2000\pi)^2}{(206.61)^2}}} \angle -\tan^{-1}\left(\dfrac{2000\pi}{206.61}\right) = -0.723 \angle -88.11$

$V_o = -0.723 \angle -88.11 \times 0.5 \angle 0°$

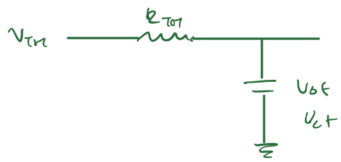
$V_o = -.3615 \angle -88.11$

$$\boxed{V_o(t) = -0.3615 \sin(2\pi 1000t - 88.11)}$$

5) Given square wave



From thevenin circuit



$V_{TH} = \frac{R_2}{R_1 + R_2} V_i = \frac{22}{1 + 22} V_i \approx 0.95 V_i$

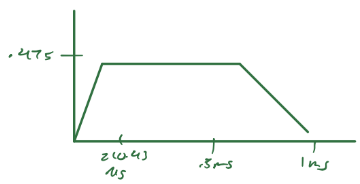
$R_{TH} = \frac{R_1 R_2}{R_1 + R_2} = 0.95\ k\Omega$

$\tau = R_{th} C = 0.95 \times 220nF = 210.43\ \mu s$

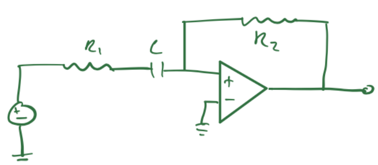
since $V_i = 0.5V$ $\quad V_{TH} = 0.9 \times 0.5V$

$= 0.475V = 475mV$

$V_0(t) = (V_{TH} - V_{TH} e^{-t/\tau})$ $\quad = \tau = 210.43\ \mu s$



Pseudo Differentiator



we have gain = -22
$R_1 = 1k\Omega$
$C = 33nF$

As $t \to \infty$ $\quad V_0 = 0$ $\quad \tau\ (R_1 + R_2)C$

$V_0(t) = V_0(t) \left(\frac{R_2}{R_1 + R_2}\right)$ for $t = 0$ to τ

$V_0(t) = V_i(t) \times R_2 / R_1 + R_2$ for $t = 0$ to τ

$V_0(t) = V_i'(t) \times \frac{R_2}{R_1 + R_2} e^{-t/\tau_1}$

$$\boxed{V_0(t) = V_i(t) \frac{R_2}{R_1 + R_2} e^{-t/(R_1 + R_2)C}}$$

for high freq $\omega \to \infty$ ie $= \frac{1}{sc} = 0$ and C acts as a short circuit

$\frac{V_2}{V_1} = A_v = -R_2/R_1 = -22$, $R_2 = 22 \times 1k = 22k\Omega$

$$\left|\frac{V_o(s)}{V_i(s)}\right| = \frac{R_2}{R_2 + (R_1 + 1/cs)} = \frac{R_2 Cs}{1 + C(R_2+R_1)s}$$

$$= \frac{7.26 \times 10^{-4} s}{1 + 7.59 \times 10^{-4} s} = 7.26 \times 10^{-4} \frac{s}{1 + \frac{s}{1317.5}}$$

here the transfer function has zero at 1317.5 and pole at 0

3dB freq at 1317.3 rad/sec

$\frac{1}{T} = (R_1 + R_2) C$

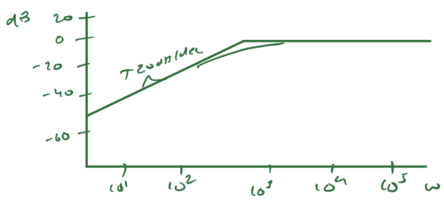
$= (23k)(33nF) = \boxed{7.59 \times 10^{-4} Hz}$

for magnitude: $\lim_{\omega \to 0} \left|\frac{V_o(s)}{V_i(s)}\right| = 20\log(7.26 \times 10^{-4})$

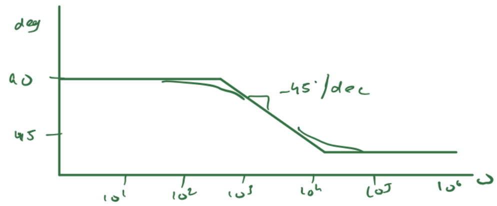
$= \underline{-62.78 \text{ dB}}$

for phase : $\lim_{\omega \to 0} \angle \frac{V_o(s)}{V_i(s)} = \tan^{-1}\left(\frac{0}{0}\right) - \tan^{-1}\left(\frac{0}{1317.3}\right) = 90^\circ$

magnitude Resp



phase



4) $v_i = 0.1 \sin(2\pi 1000 t)$

$v_i = 0.1 \angle 0^\circ$ $\rightarrow$ transfer func. 1317.5 Hz

$$\frac{V_o(1317.5)}{V_i(1317.5)} = \frac{7.26 \times 10^{-4} \times 2000\pi j}{1 + 7.54 \times 10^{-4} \times 2000\pi j}$$

$$= 0.936$$

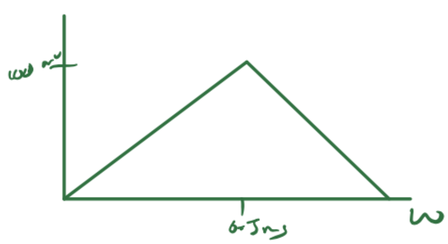
$$\angle \frac{V_o}{V_i} = \tan^{-1}\left(\frac{7.26 \times 10^{-4} \times 2000\pi}{0}\right) - \tan^{-1}\left(\frac{7.54 \times 10^{-4} \times 2000\pi}{1}\right)$$

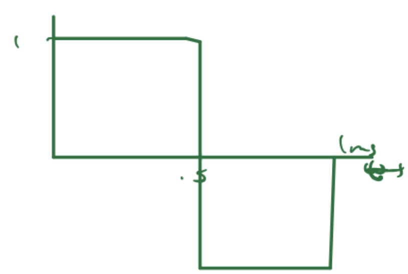
$$= 11.84$$

$$V_o = 0.0936 \angle 11.84$$

$$= \boxed{0.0936 \sin(2\pi 1000 t + 11.84)}$$

5)





Finite GBW Limitations

1) gain = 23 $\quad R_1 = 1k\Omega$

$$\text{gain} = 1 + \frac{R_2}{R}$$

so $\boxed{R_2 = 22k\Omega}$

gain = 57 $\quad 57 = 1 + \frac{R_2}{1k\Omega}$

$$\boxed{R_2 = 56k\Omega}$$

gain for 83 $\quad 83 = 1 + \frac{R_2}{1k\Omega}$

$$\boxed{R_2 = 82k\Omega}$$

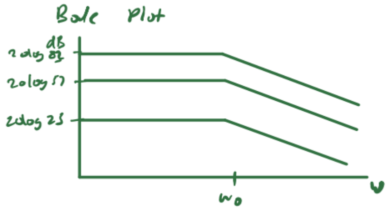
2) $\frac{V_o}{V_i} = \frac{G_o}{1\ s/\omega_o}$

for 23 $\rightarrow \frac{V_o}{V_i} = \frac{23}{1 + \frac{s}{\omega_o}}$

for 57 $\Rightarrow \frac{V_o}{V_i} = \frac{57}{1 + \frac{s}{\omega_o}}$

for 83 $\rightarrow \frac{V_o}{V_i} = \frac{83}{1 + \frac{s}{\omega_o}}$, phase resp. $= -\tan^{-1}\left(\frac{\omega}{\omega_o}\right)$

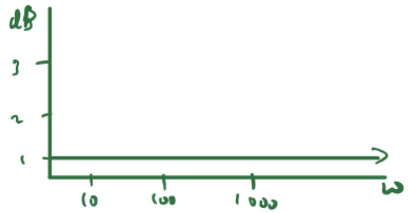
Bode Plot



slew rate limitation

from circuit $\frac{V_0}{V_i} = 1$

Bode Plot



Here slew rate = 0.5V/μs

$V_{in} = 1V$

$V_{in} = \sin \omega t = V_0$

$\frac{dV_0}{dt} = \omega \cos \omega t = 0.5V/\mu(s) = 2\pi f(1)$

$f = \frac{0.5}{2\pi} = \frac{0.5 \times 10^6}{2\pi} = \boxed{79.58 \text{ kHz}}$

slew rate = 0.5 V/μs

$V_{max} = ?$

$f = 75 \text{ kHz}$

$0.5 V/\mu s = 2\pi \, 75k V_m$

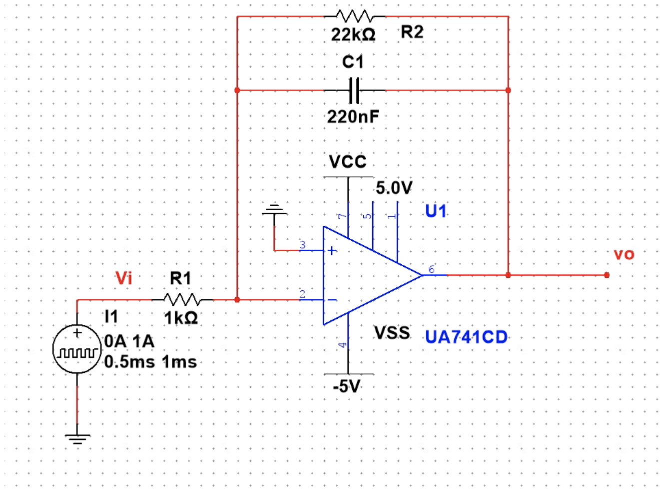
$V_m = \frac{0.5 \times 10^6}{2\pi \times 75k}$

$\boxed{V_m = 1.0610}$

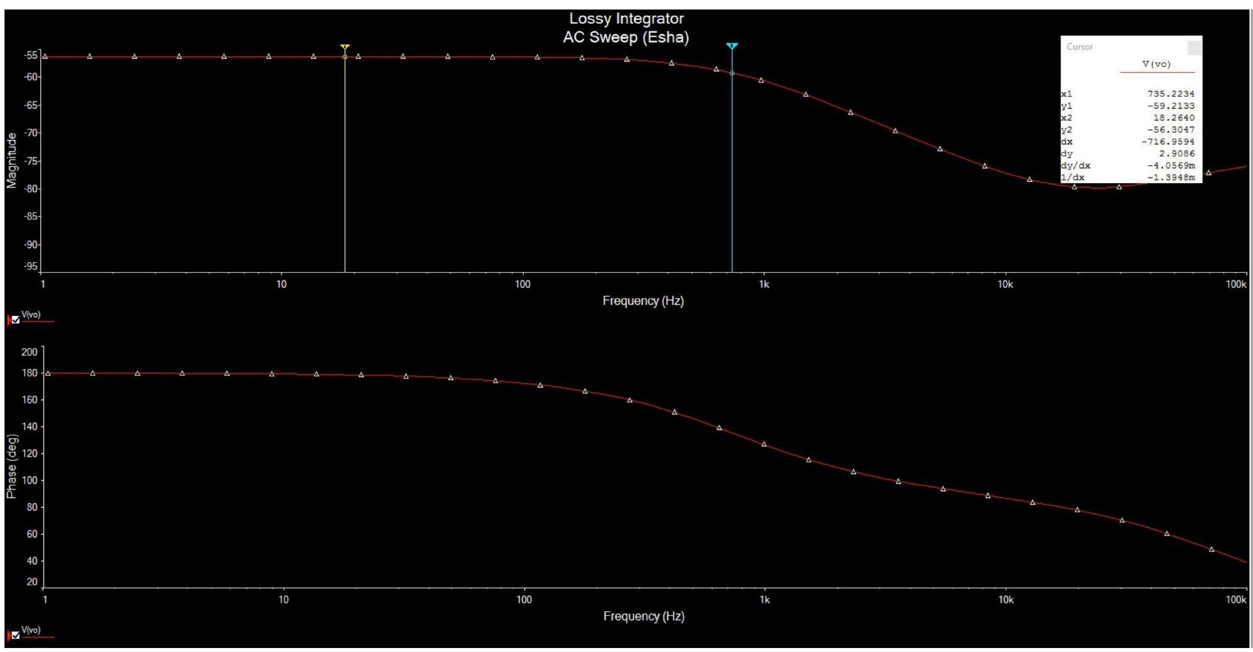
Simulations (on Multisim)

Lossy Integrator

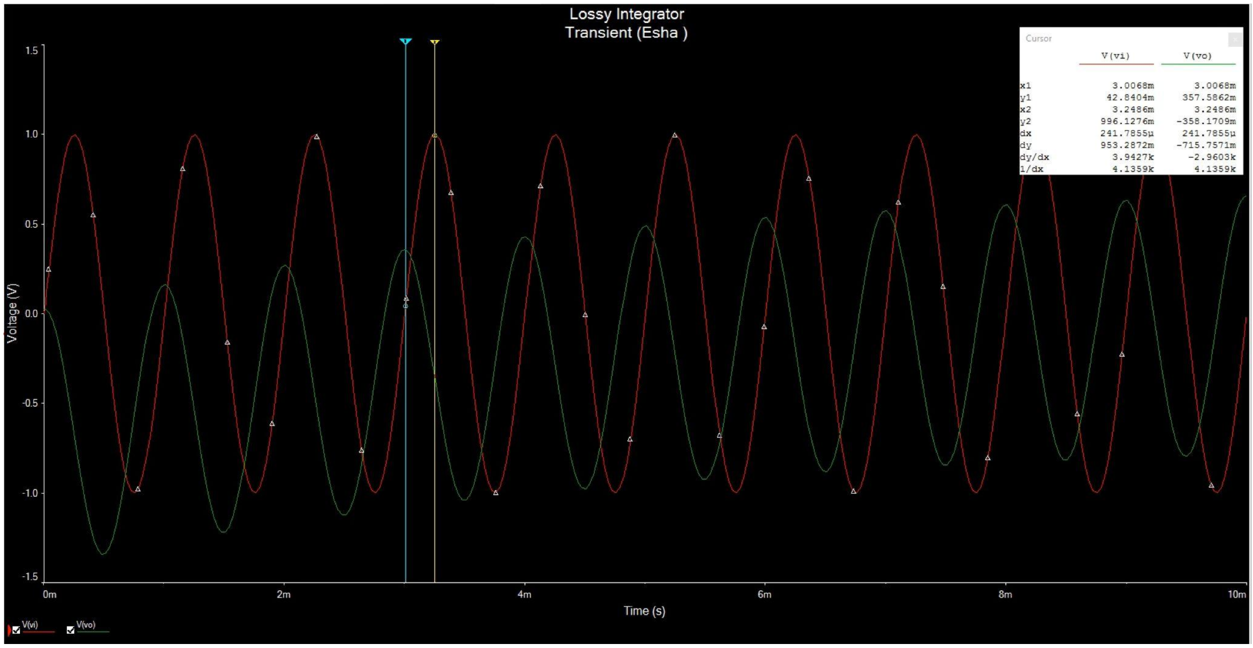
Schematic



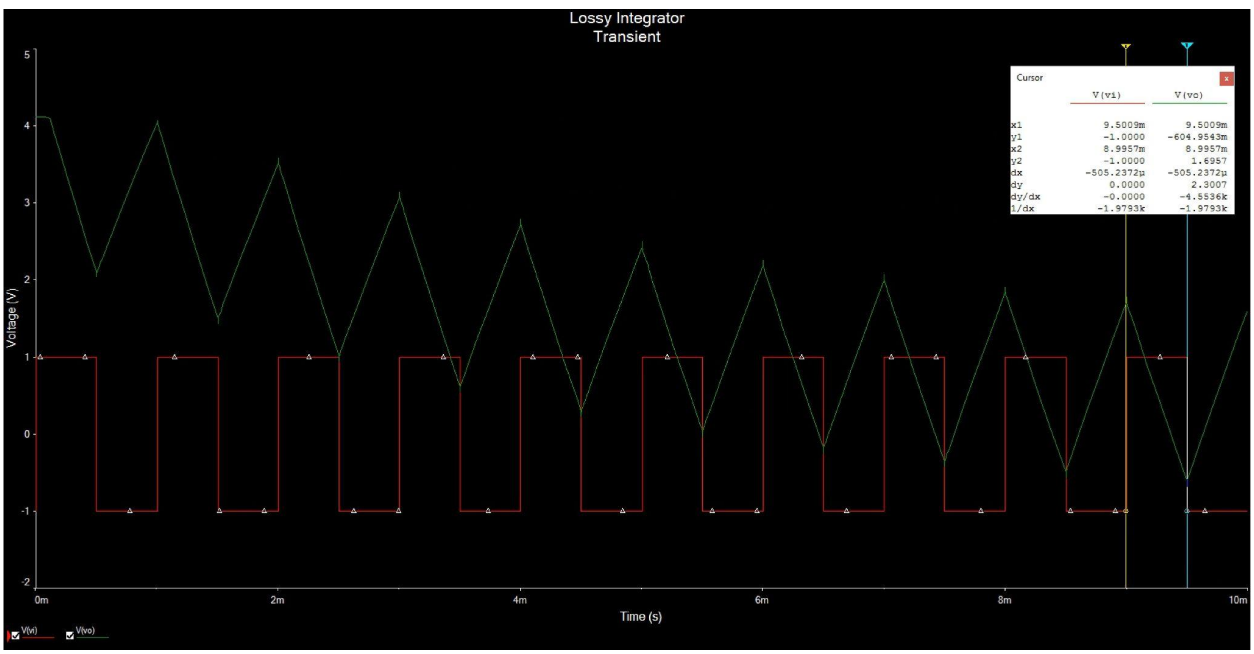
Bode



Sin Transient

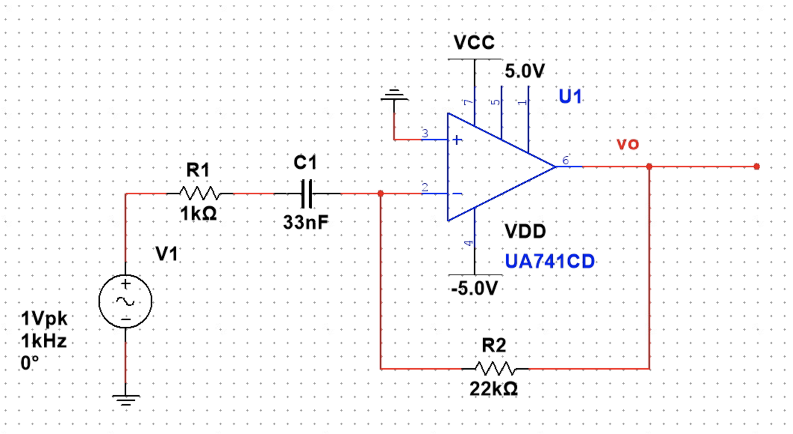


Square Transient

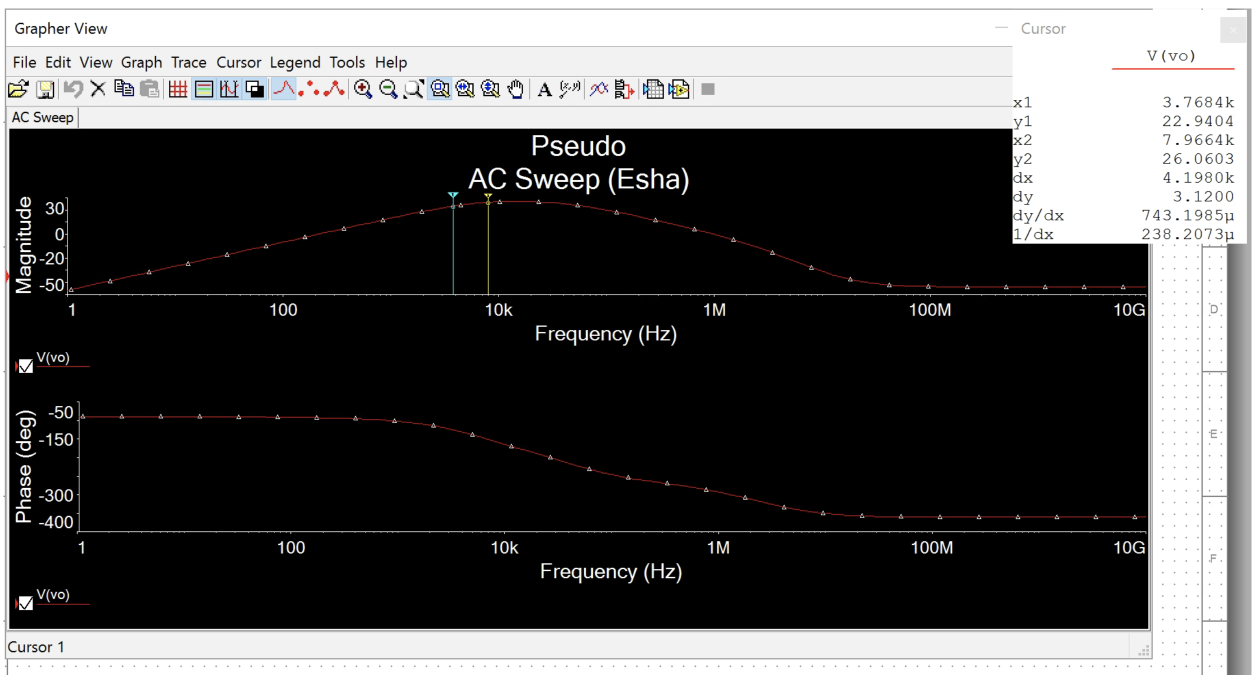


Psuedo Differentiator

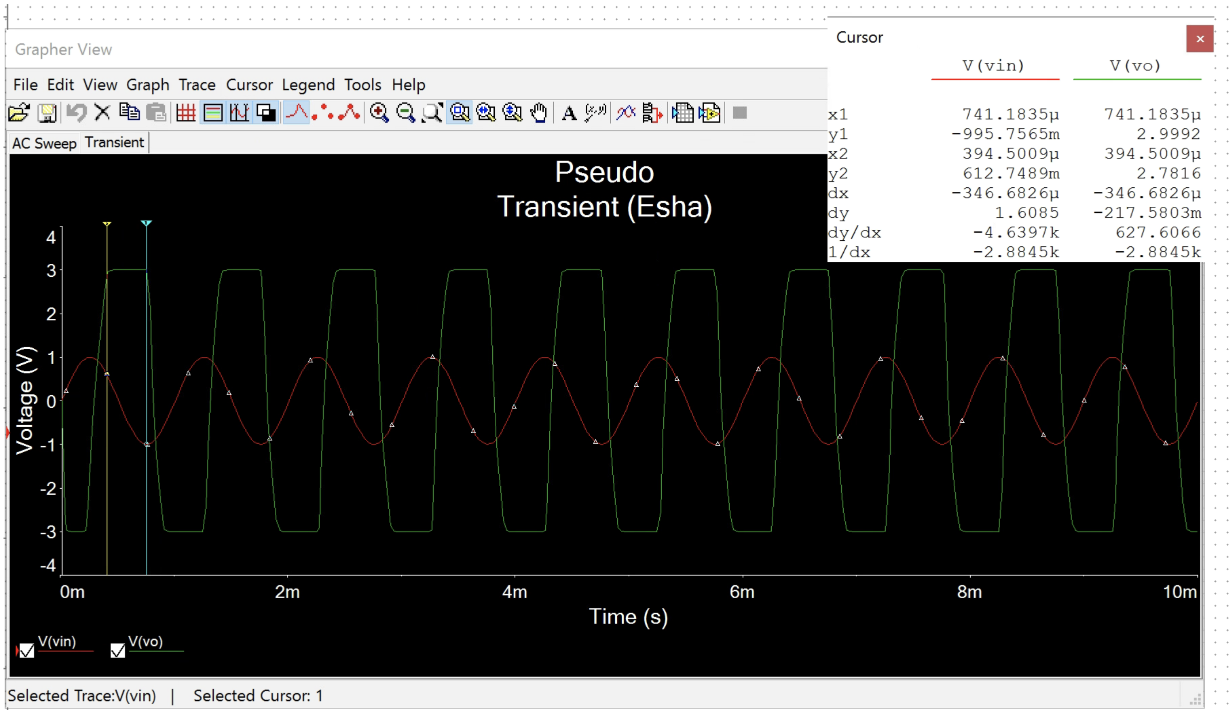
Schematic



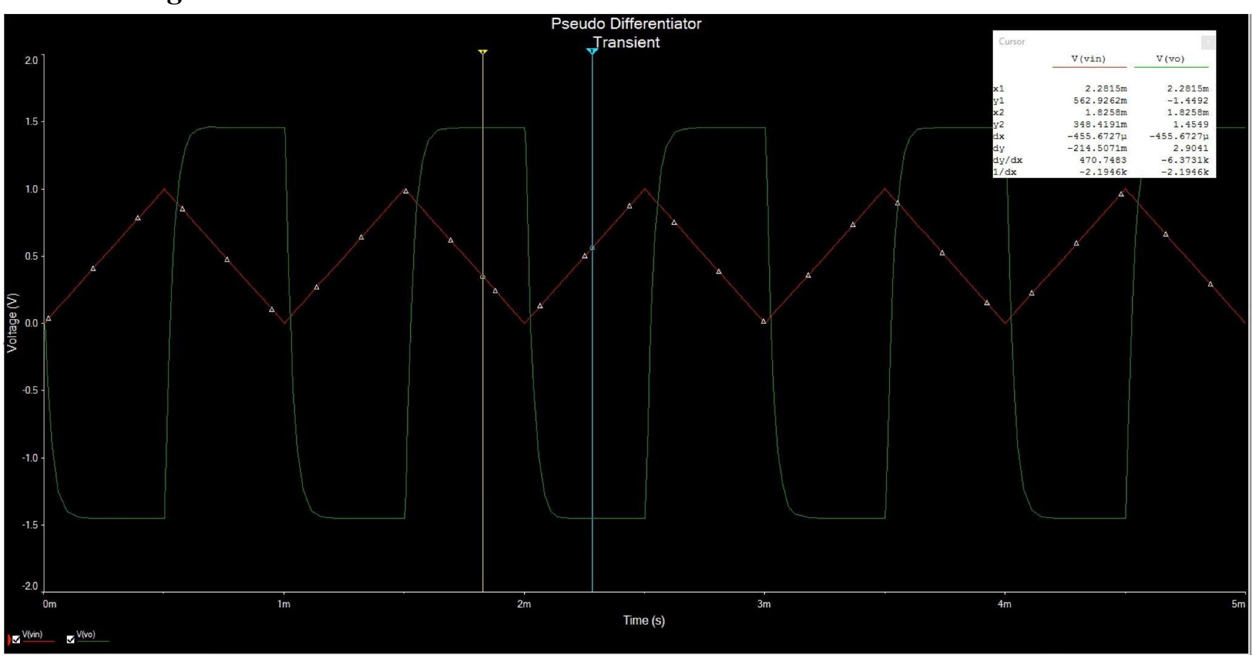
Bode



Sin Transient

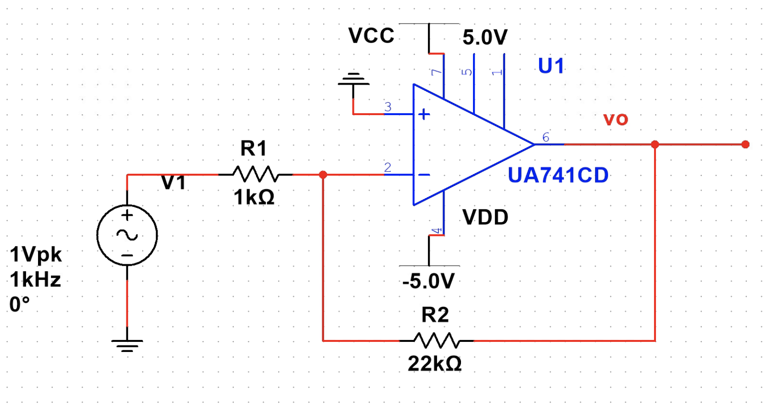


Triangle Transient

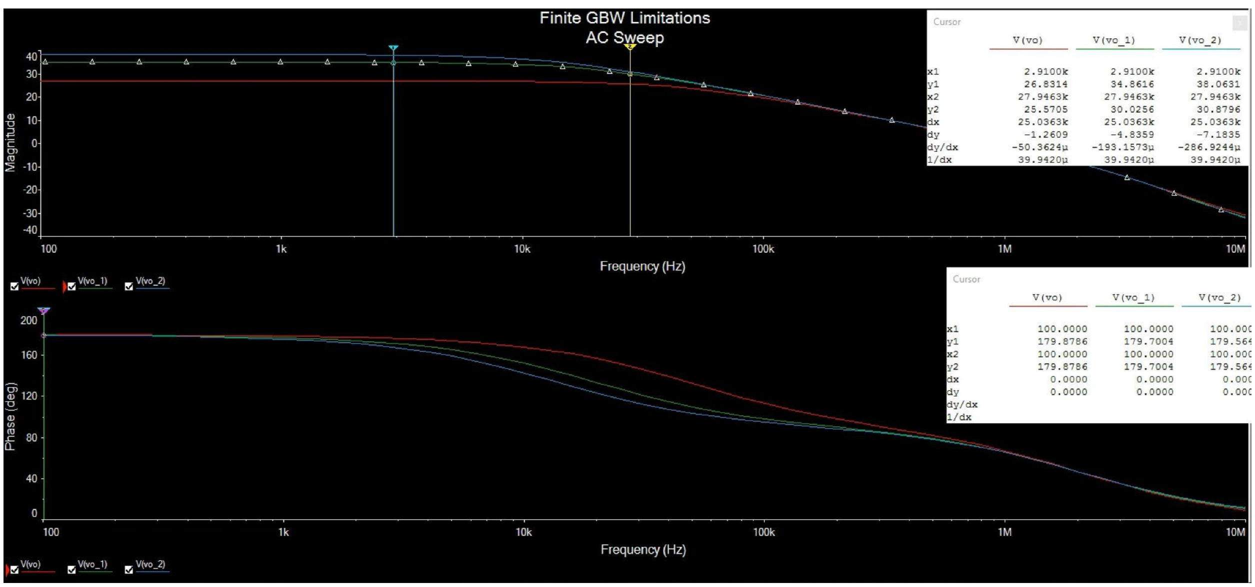


Finite GBW Limitations

Schematic

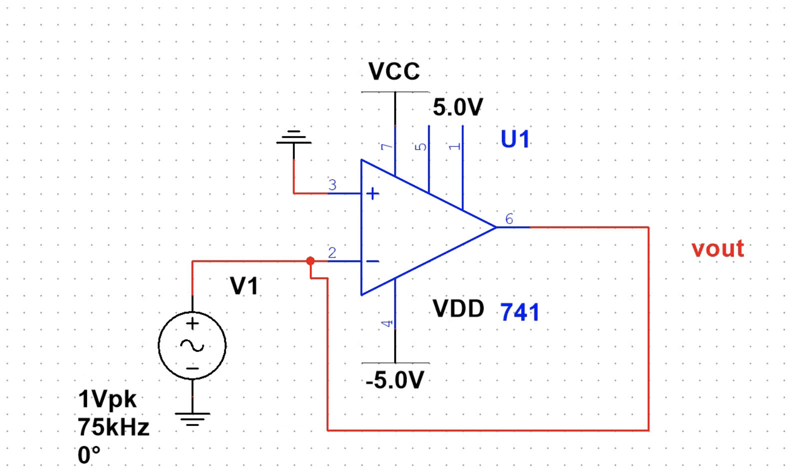


Bode

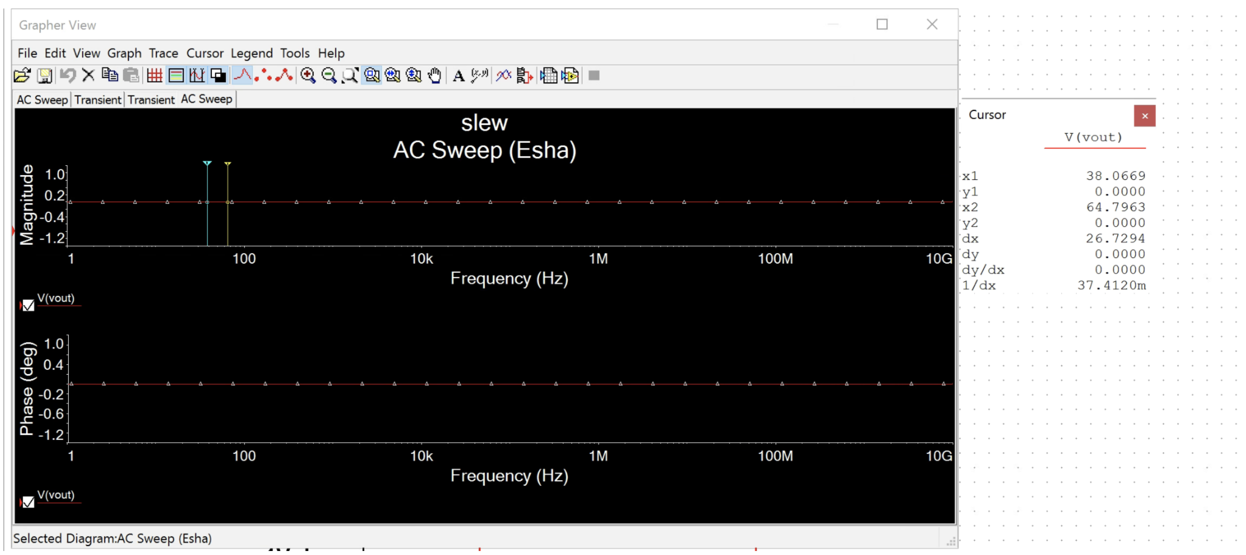


Slew Rate Limitations

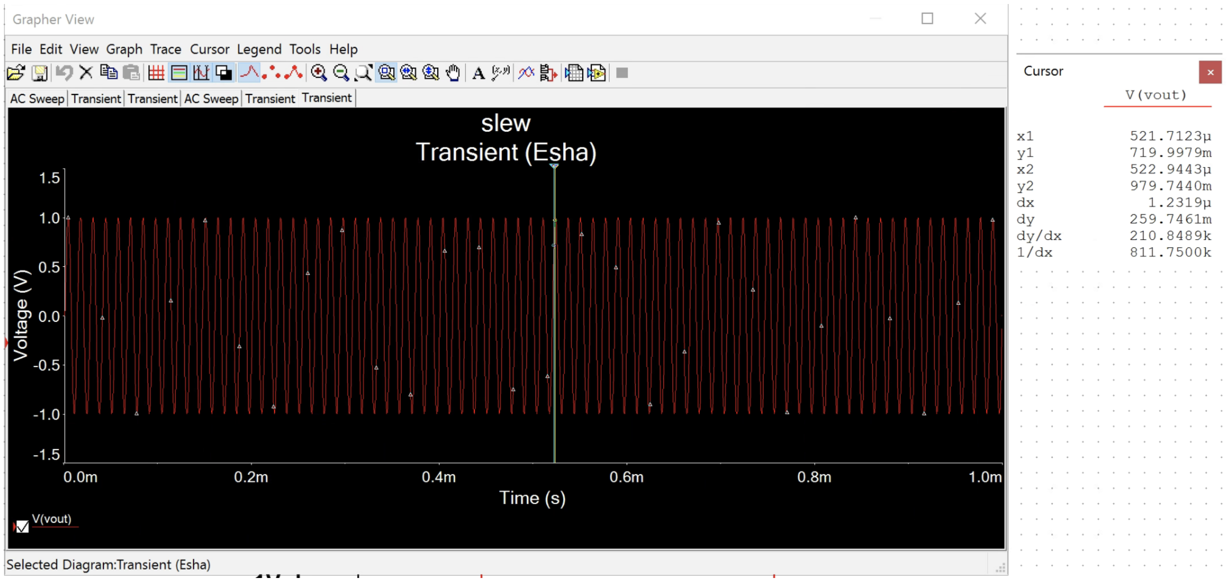
Schematic



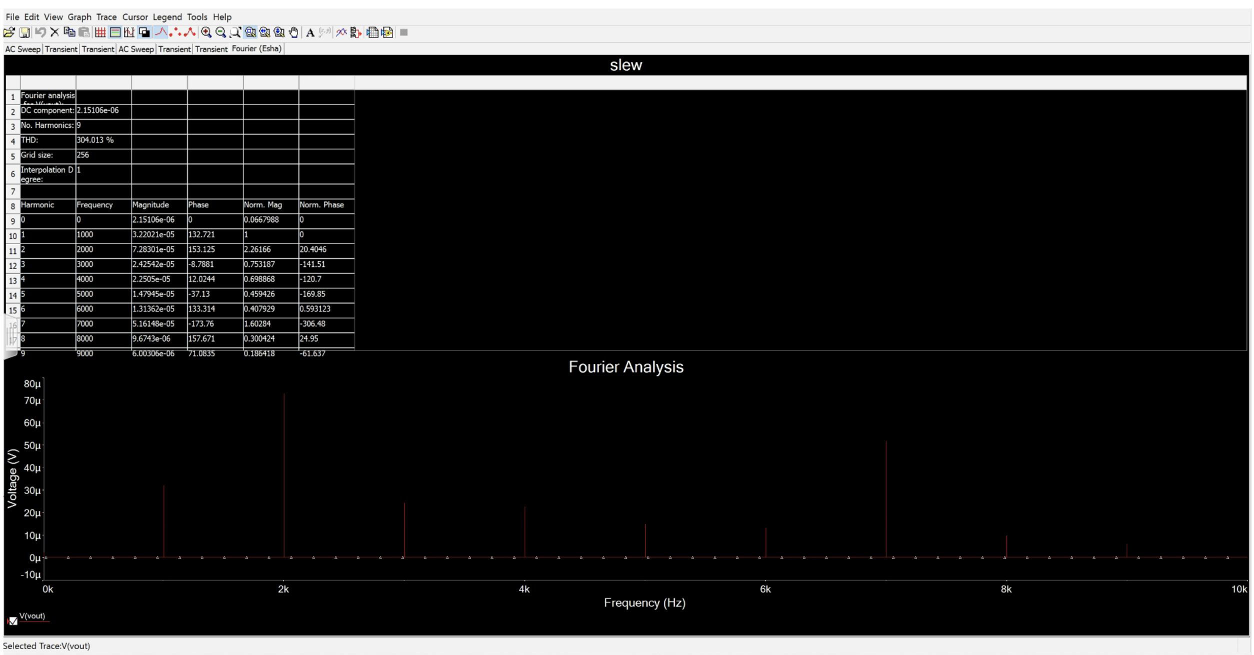
Bode



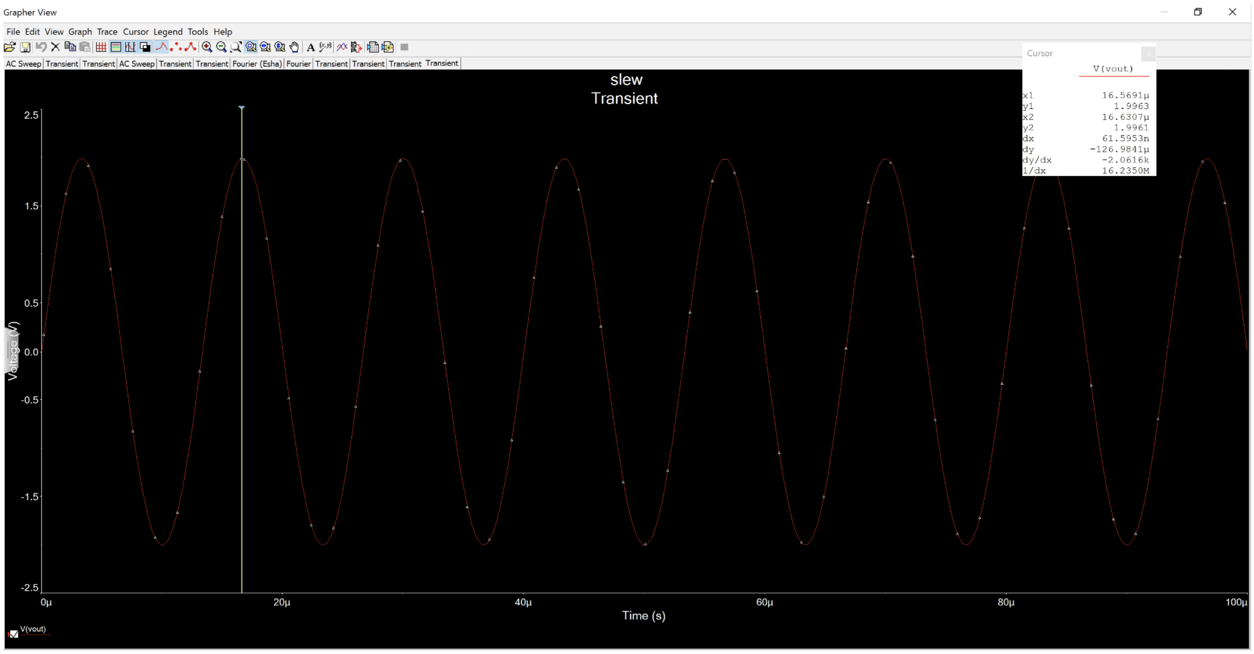
Sin Transient 75K 1V



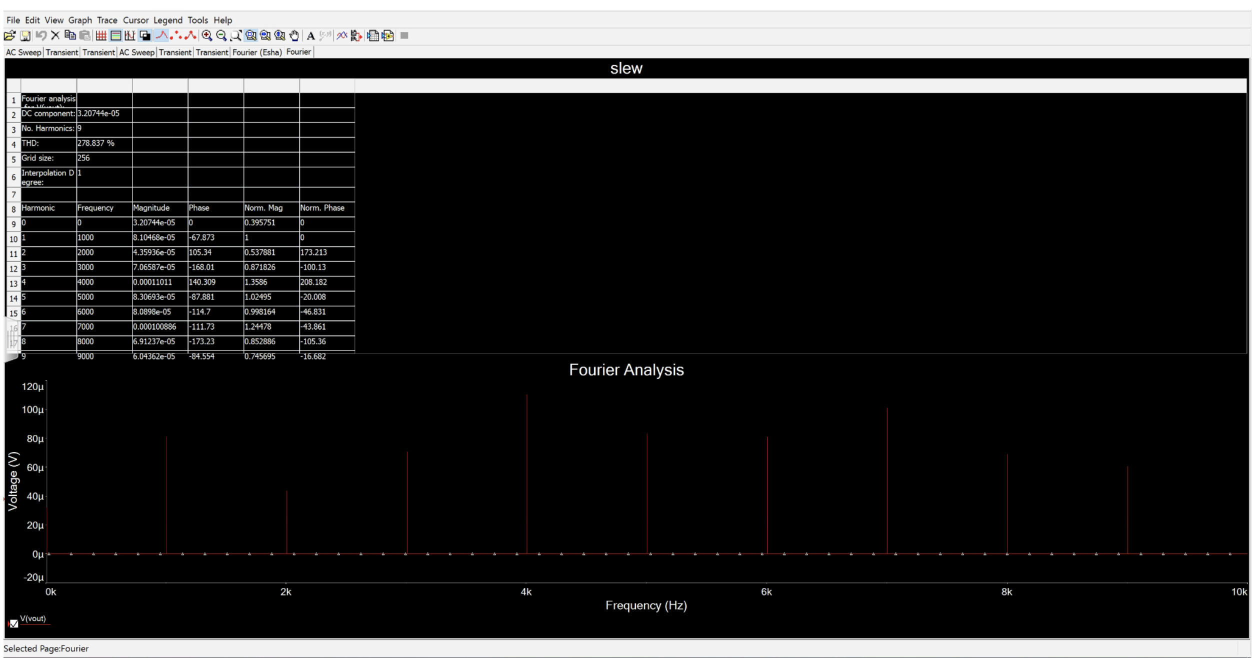
Fourier 75K 1V



Sin Transient 75K 2V

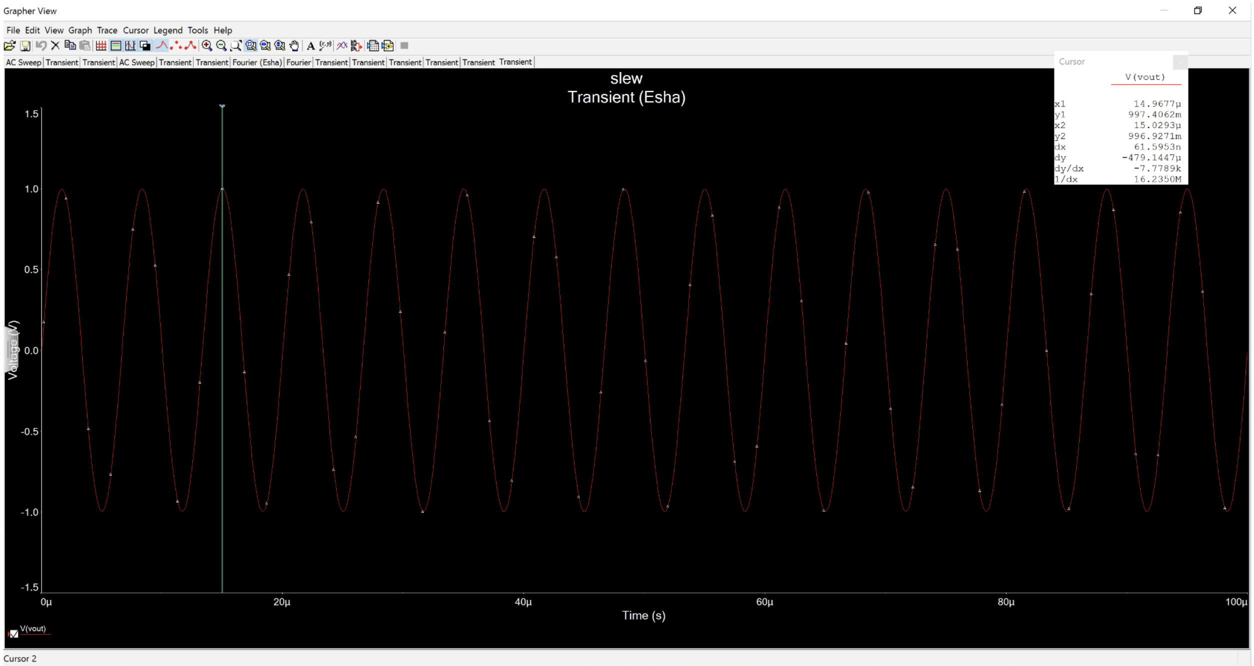


Fourier 75K 2V

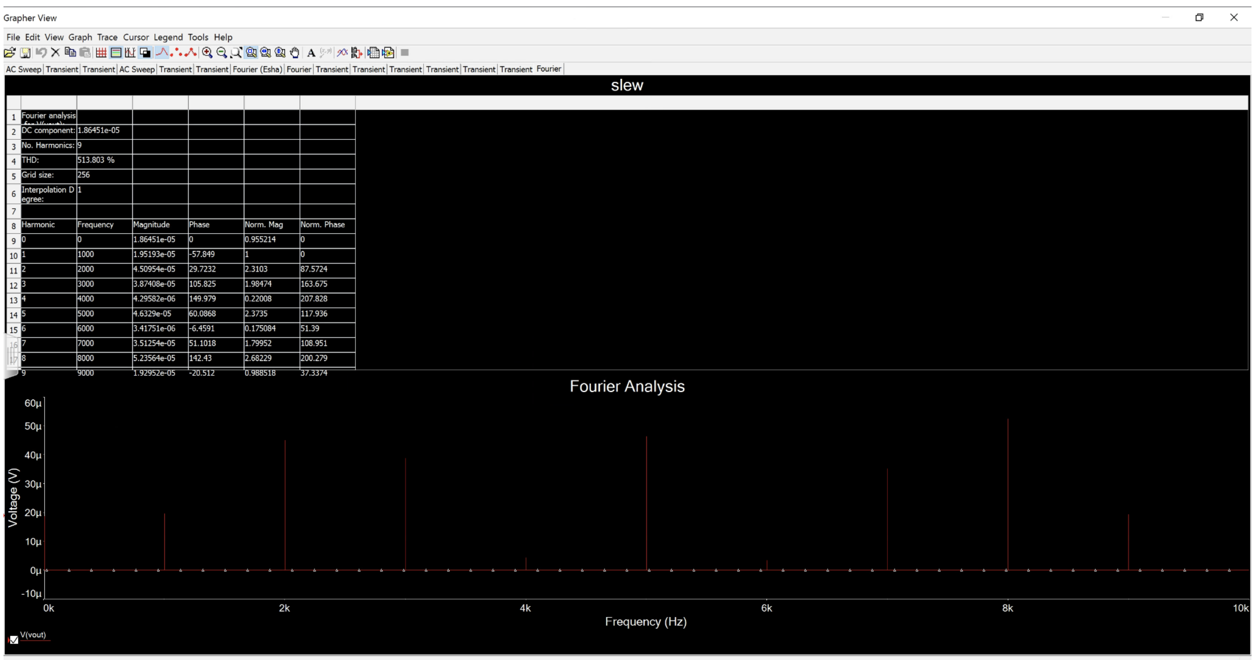


1	Fourier analysis for V(vout):					
2	DC component:	3.20744e-05				
3	No. Harmonics:	9				
4	THD:	278.837 %				
5	Grid size:	256				
6	Interpolation Degree:	1				
7						
8	Harmonic	Frequency	Magnitude	Phase	Norm. Mag	Norm. Phase
9	0	0	3.20744e-05	0	0.395751	0
10	1	1000	8.10468e-05	-67.873	1	0
11	2	2000	4.35936e-05	105.34	0.537881	173.213
12	3	3000	7.06587e-05	-168.01	0.871826	-100.13
13	4	4000	0.00011011	140.309	1.3586	208.182
14	5	5000	8.30693e-05	-87.881	1.02495	-20.008
15	6	6000	8.0898e-05	-114.7	0.998164	-46.831
16	7	7000	0.000100886	-111.73	1.24478	-43.861
17	8	8000	6.91237e-05	-173.23	0.852886	-105.36
	9	9000	6.04362e-05	-84.554	0.745695	-16.682

Sin Transient 150K 1V



Fourier 150K 1V

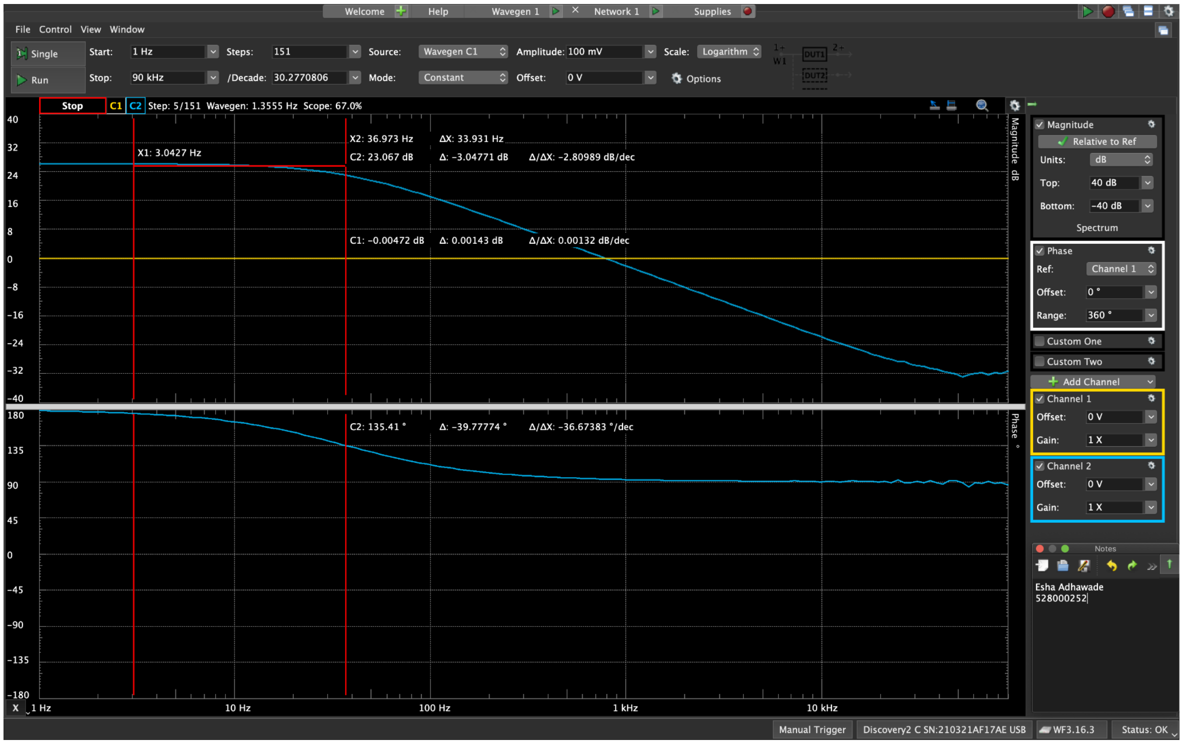


1	Fourier analysis for V(vout):					
2	DC component:	1.86451e-05				
3	No. Harmonics:	9				
4	THD:	513.803 %				
5	Grid size:	256				
6	Interpolation Degree:	1				
7						
8	Harmonic	Frequency	Magnitude	Phase	Norm. Mag	Norm. Phase
9	0	0	1.86451e-05	0	0.955214	0
10	1	1000	1.95193e-05	-57.849	1	0
11	2	2000	4.50954e-05	29.7232	2.3103	87.5724
12	3	3000	3.87408e-05	105.825	1.98474	163.675
13	4	4000	4.29582e-06	149.979	0.22008	207.828
14	5	5000	4.6329e-05	60.0868	2.3735	117.936
15	6	6000	3.41751e-06	-6.4591	0.175084	51.39
16	7	7000	3.51254e-05	51.1018	1.79952	108.951
17	8	8000	5.23564e-05	142.43	2.68229	200.279
	9	9000	1.92952e-05	-20.512	0.988518	37.3374

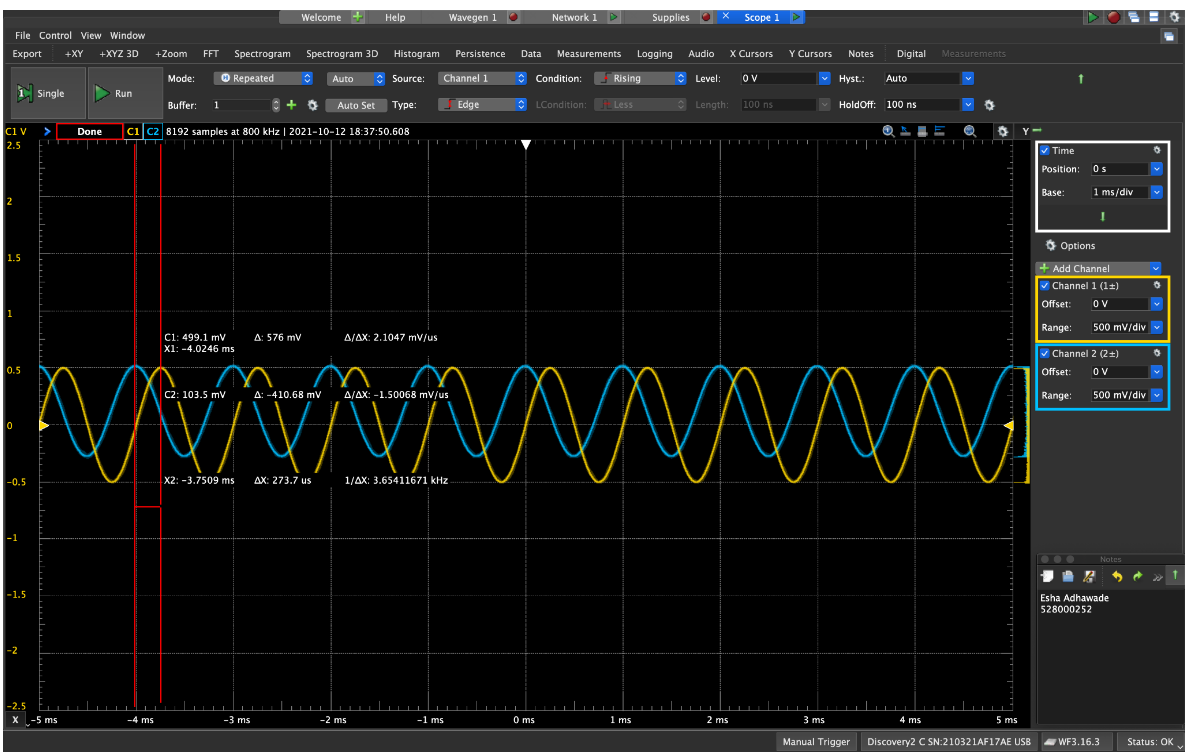
Measurements

Lossy Integrator

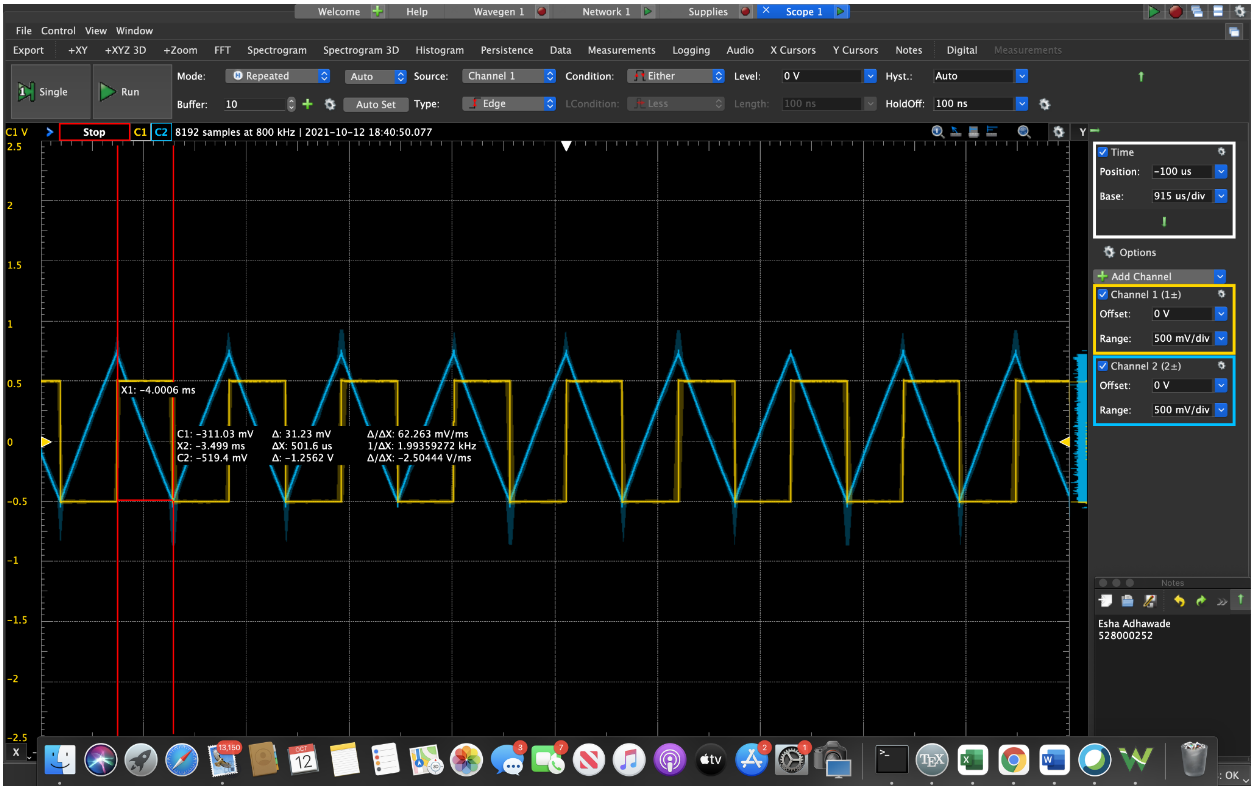
Bode



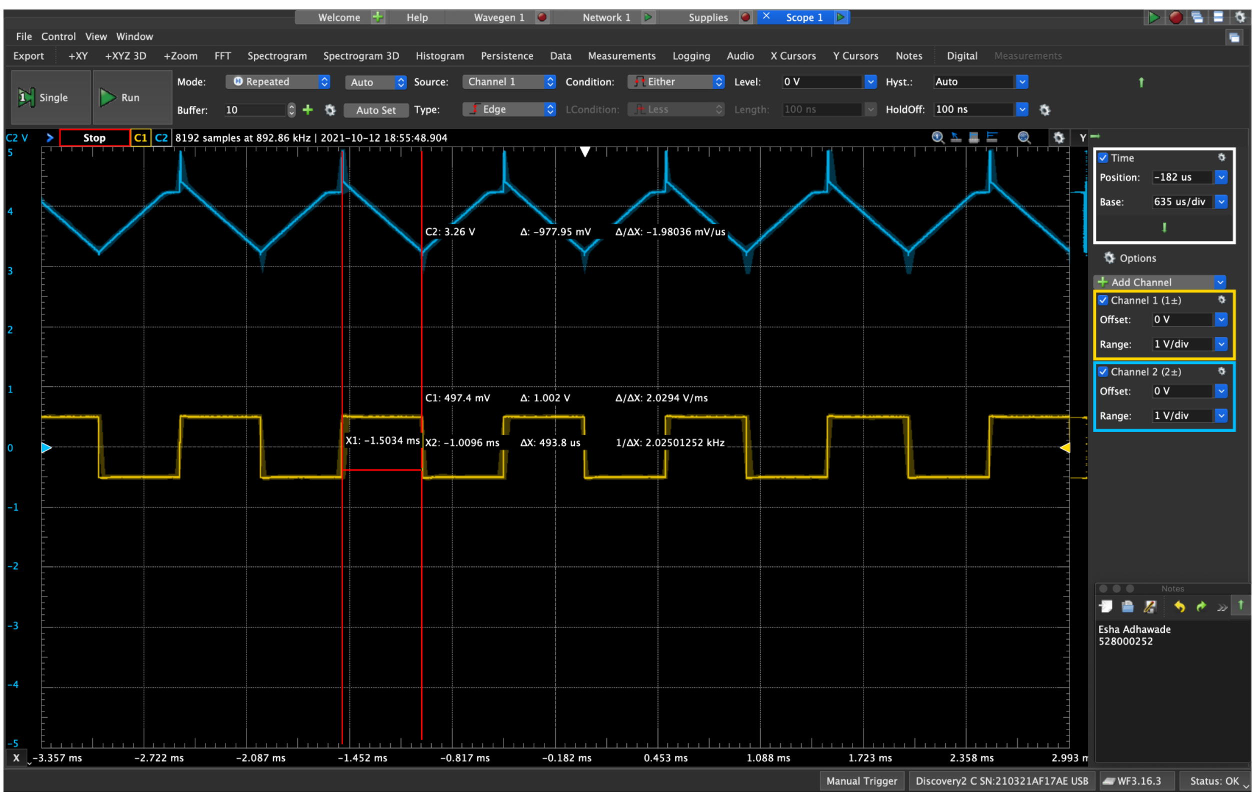
Sin Time Domain



Square Time Domain

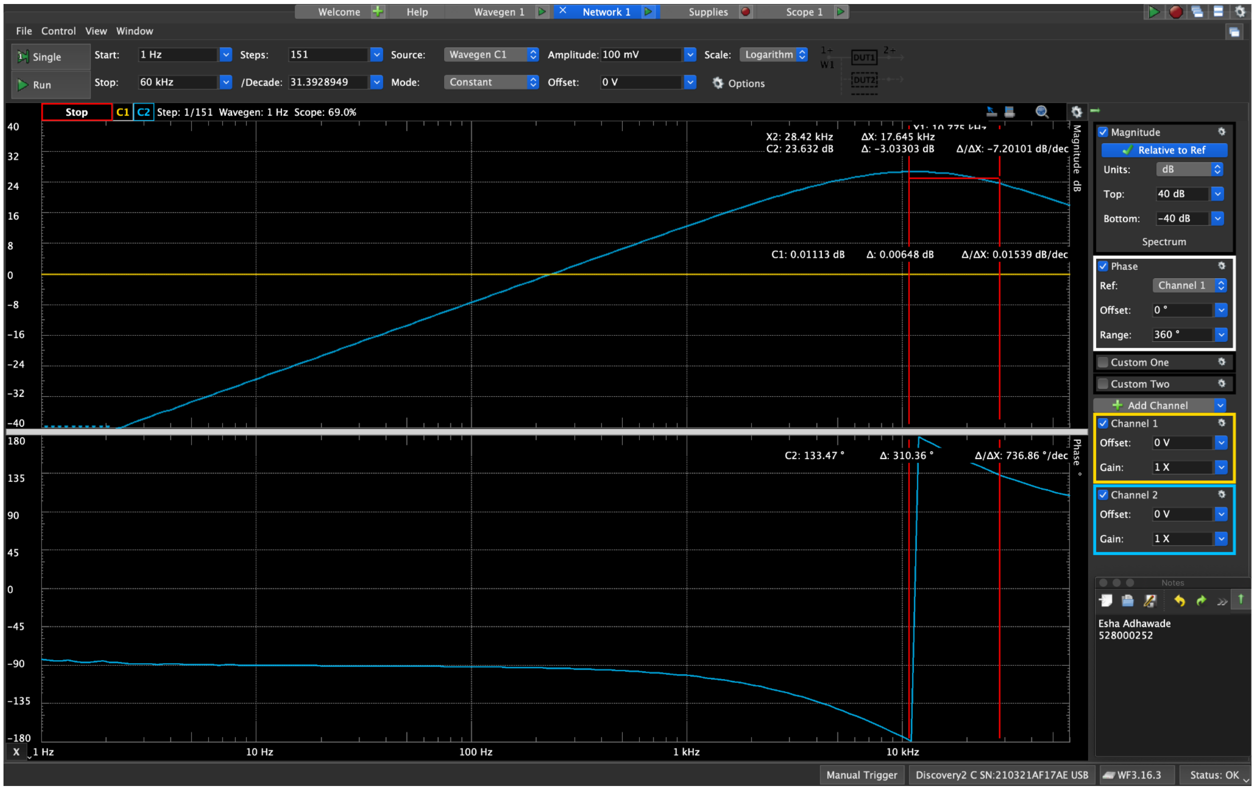


Without R2 (without R2 C2 moves up)

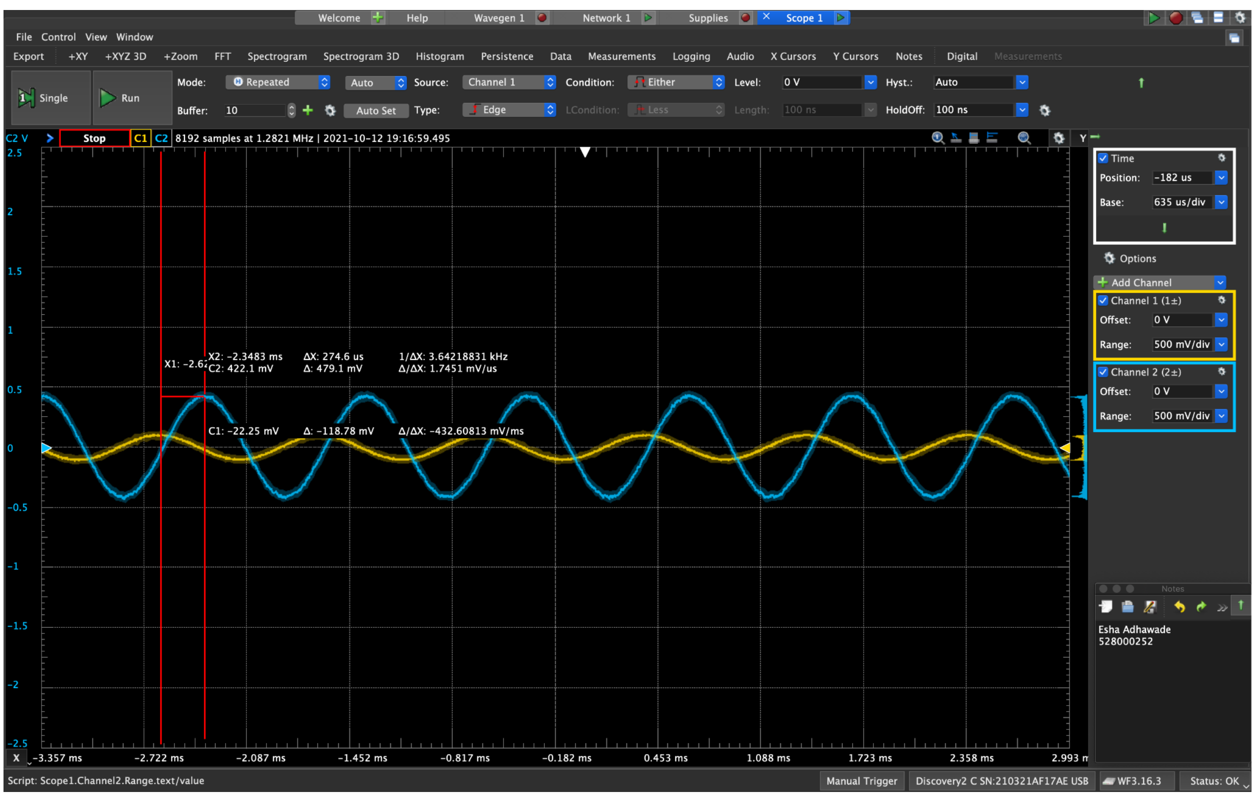


Pseudo Differentiator

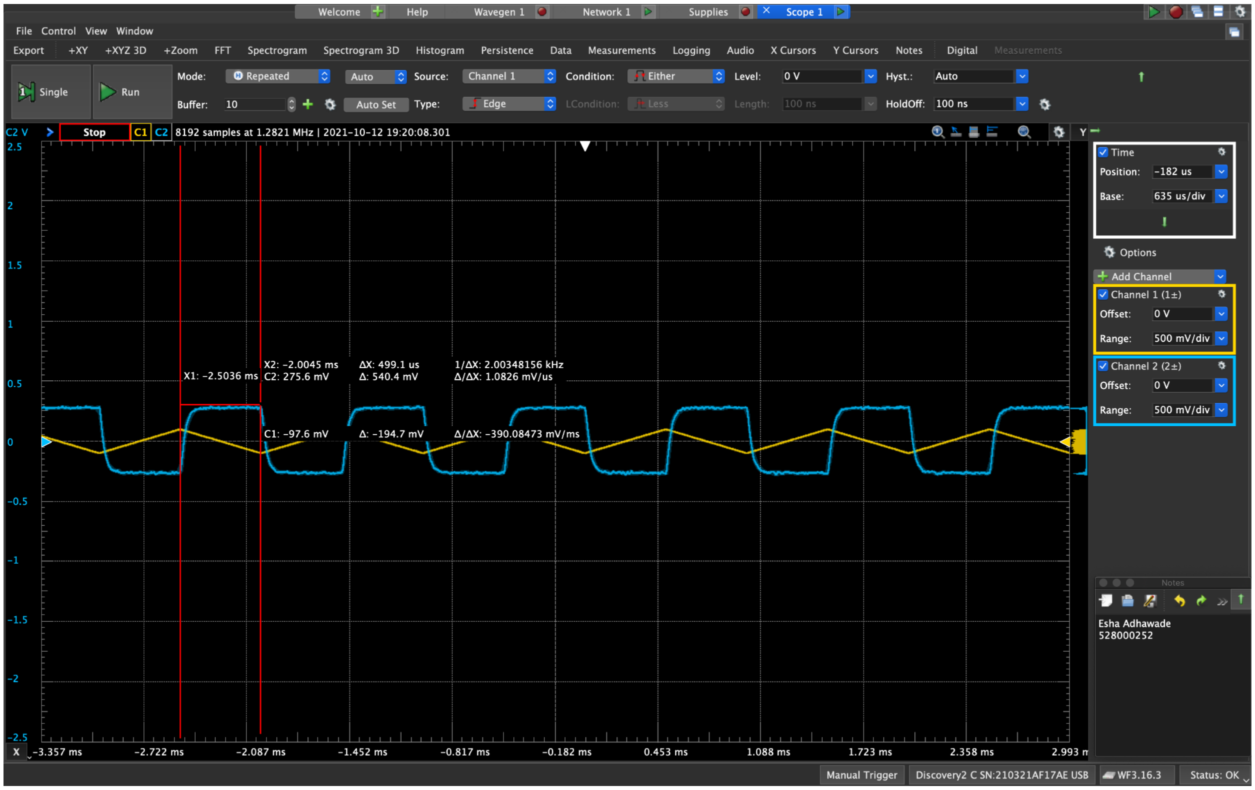
Bode



Sin Time Domain

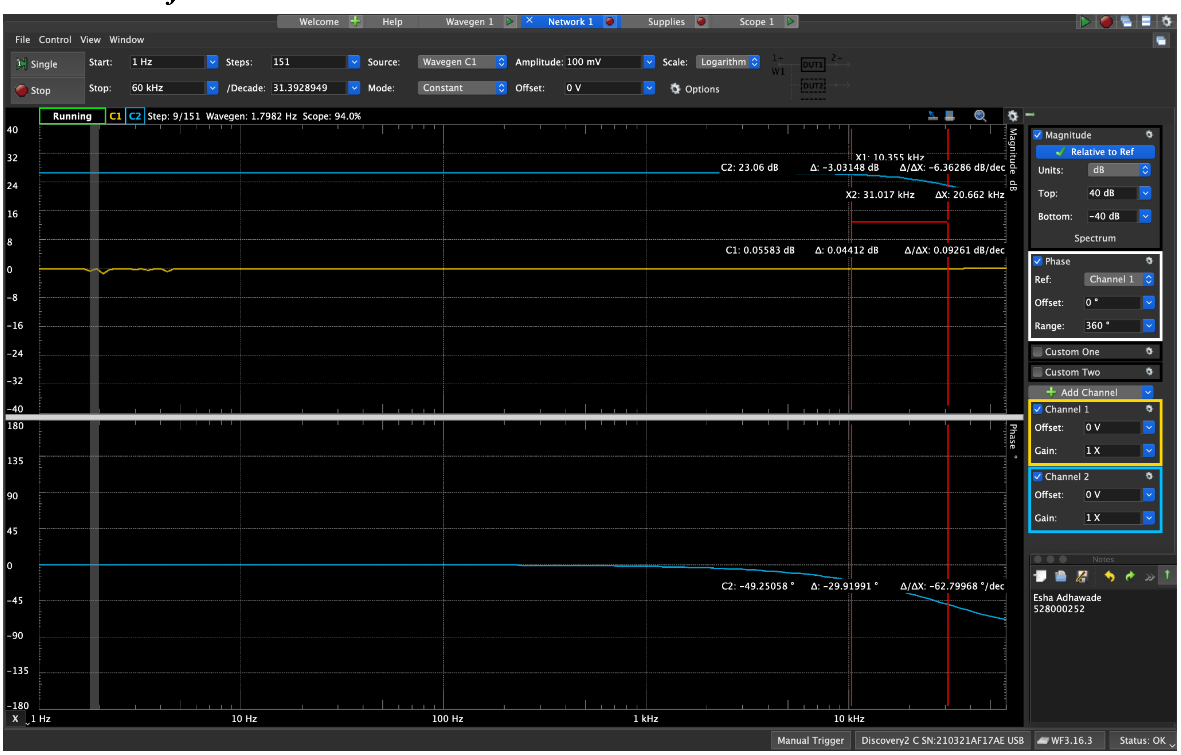


Triangle Time Domain

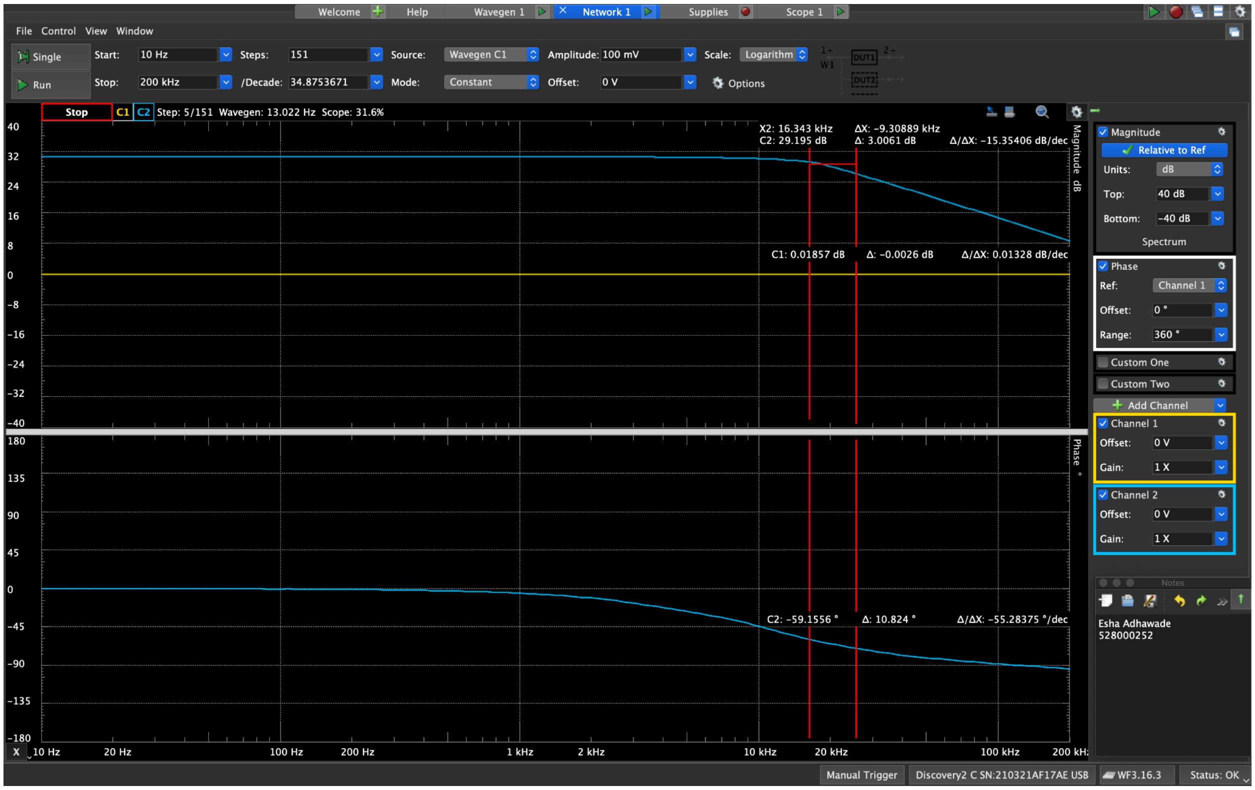


Finite GBW Limitations

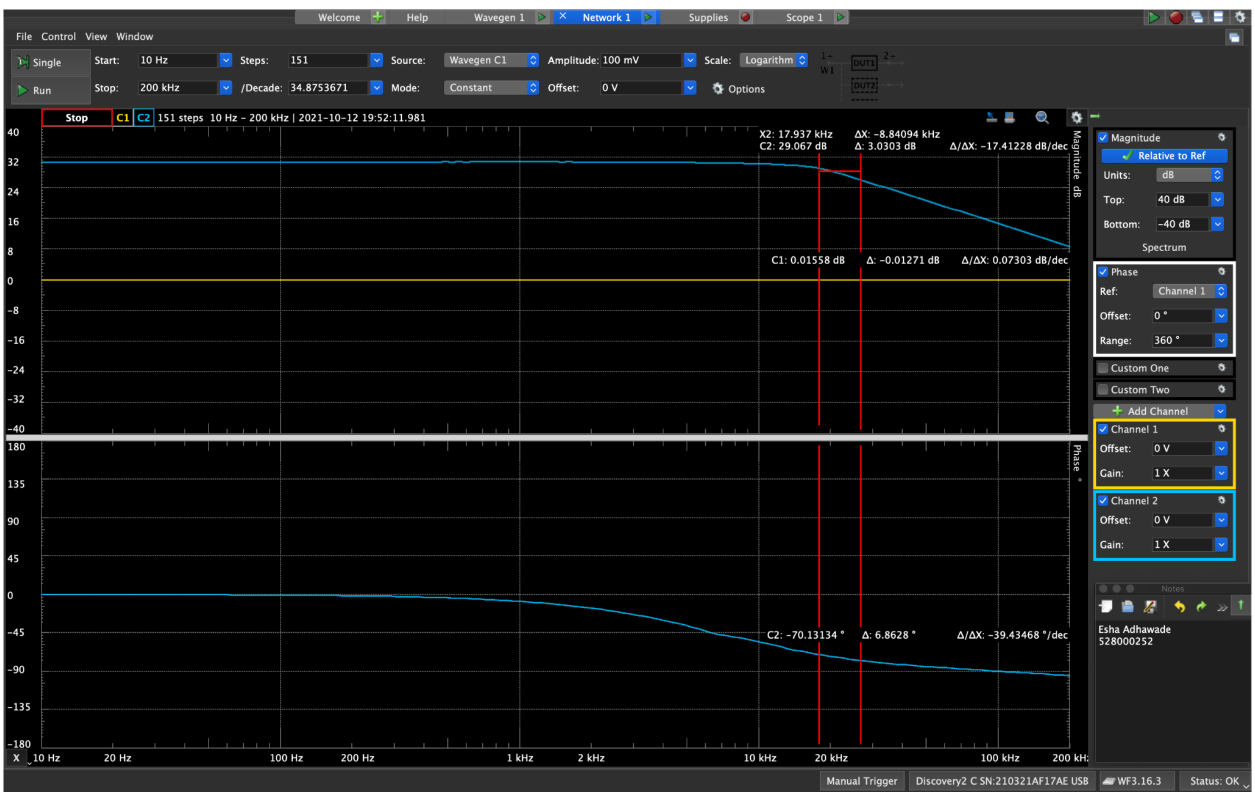
Bode for 23



Bode for 57

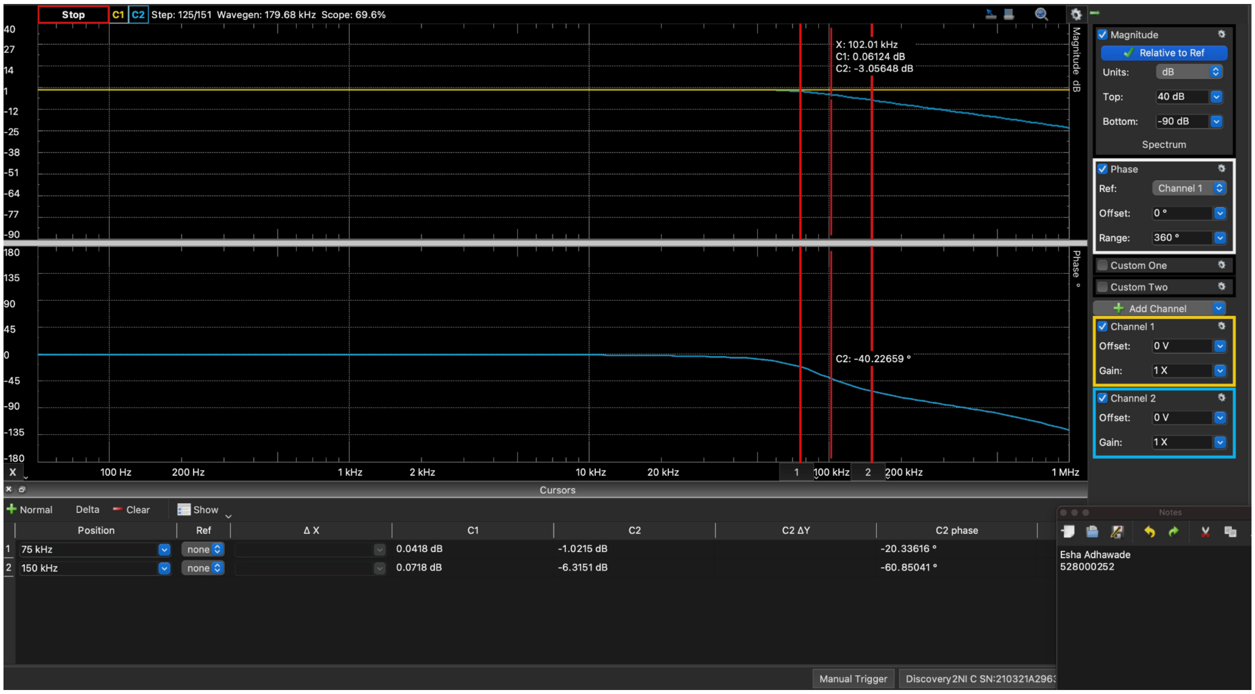


Bode for 83

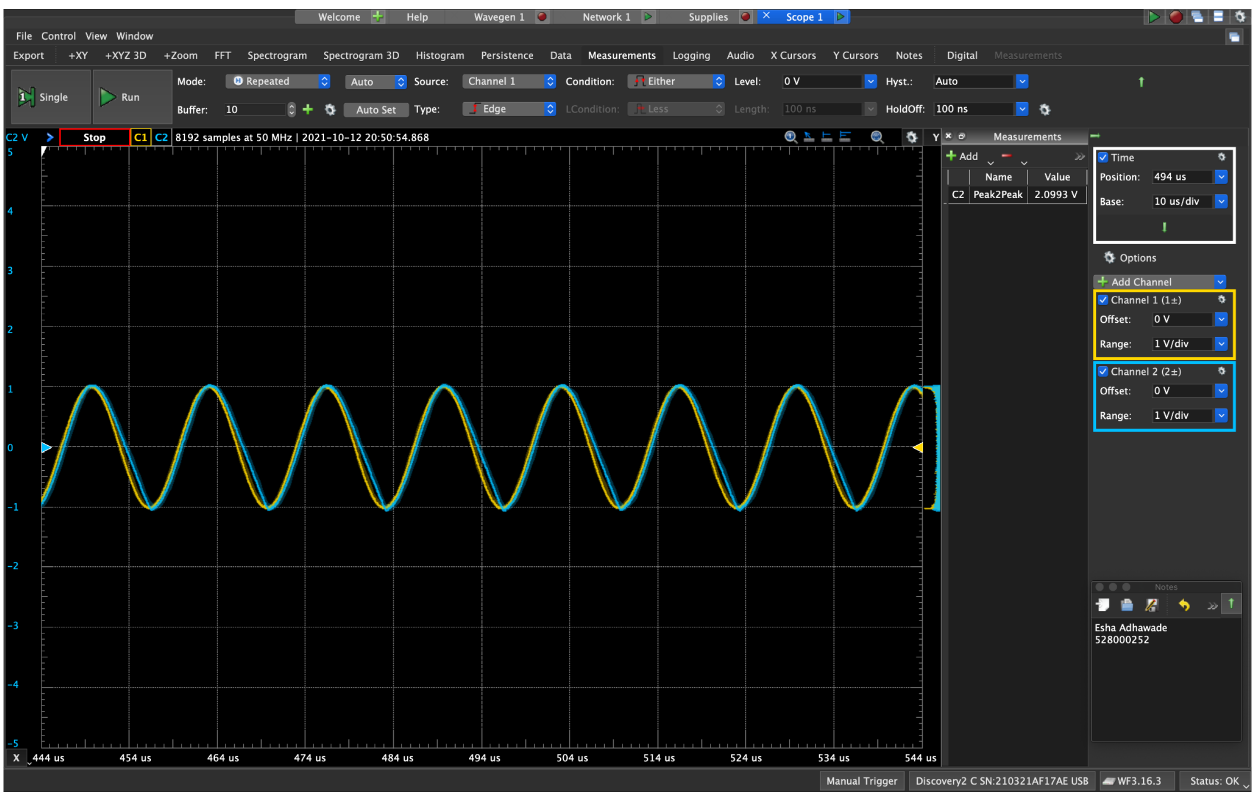


Slew Rate Limitations

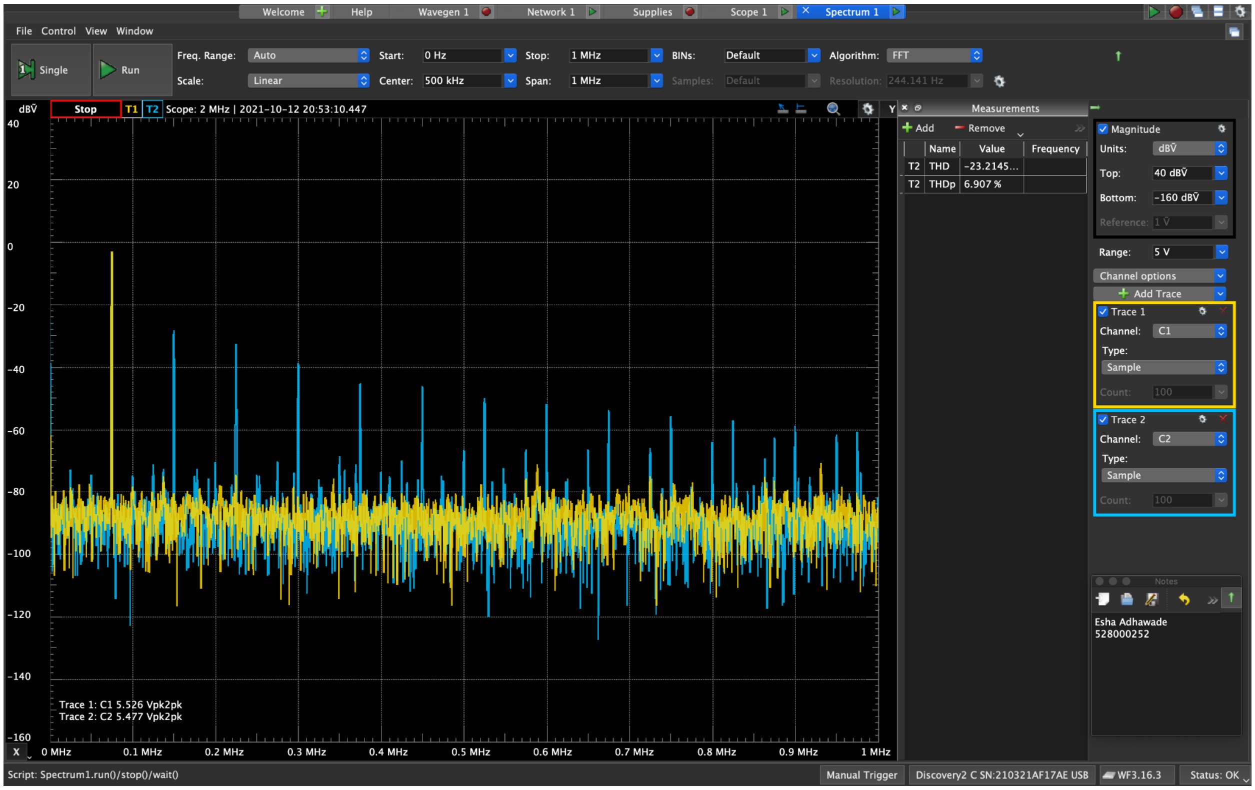
Bode



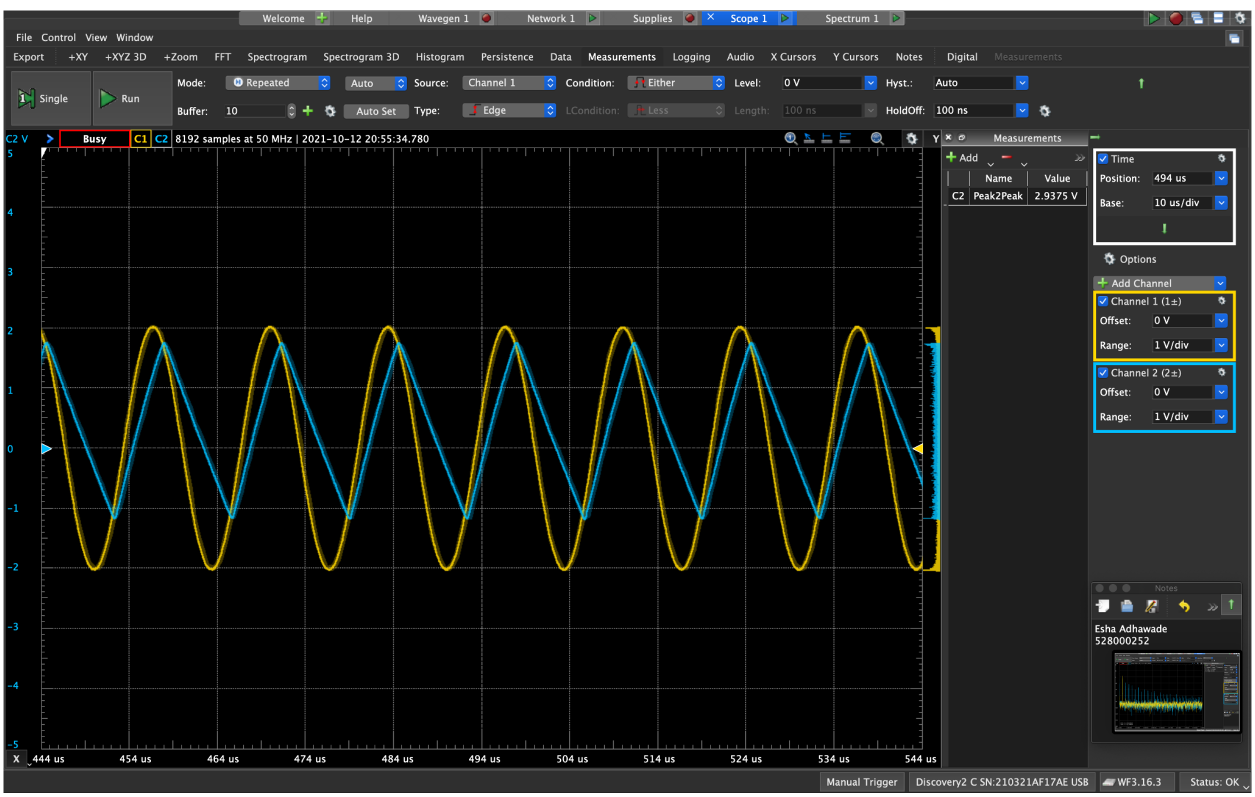
Time Domain 75k 1V



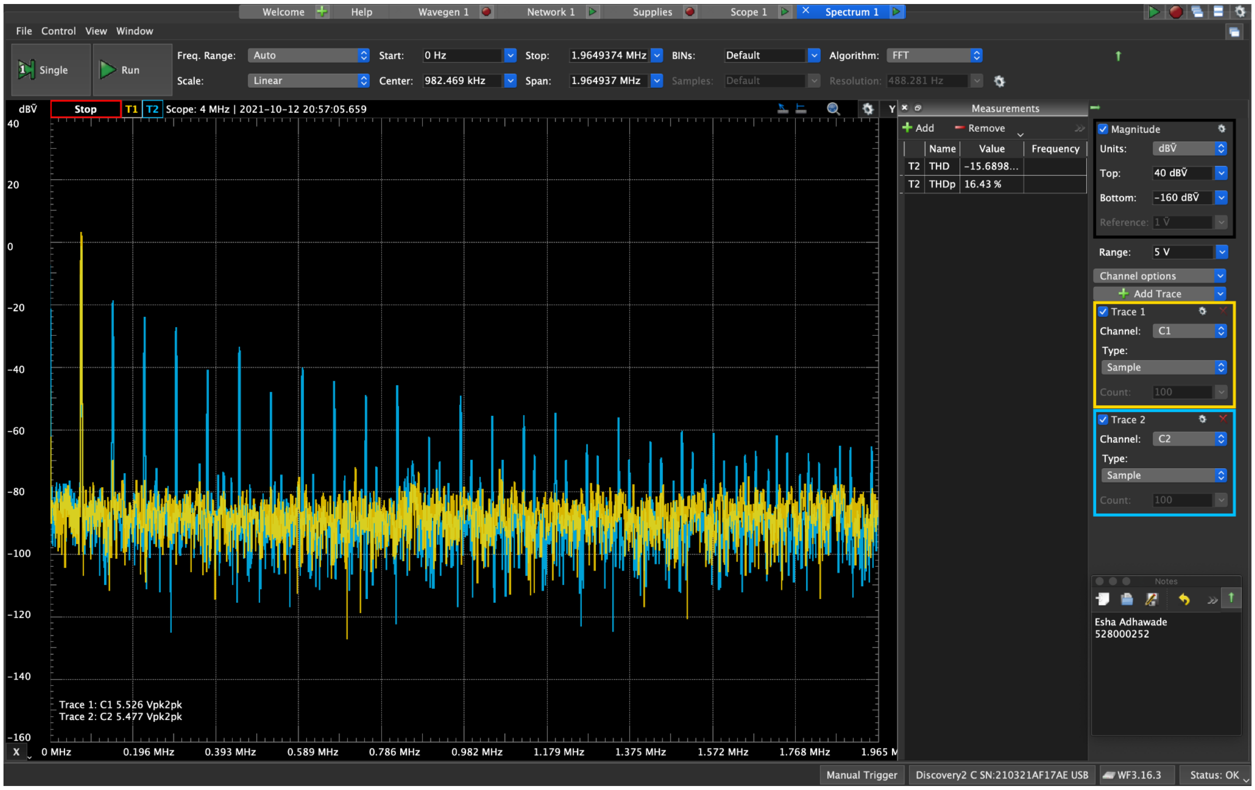
THD 75k 1V



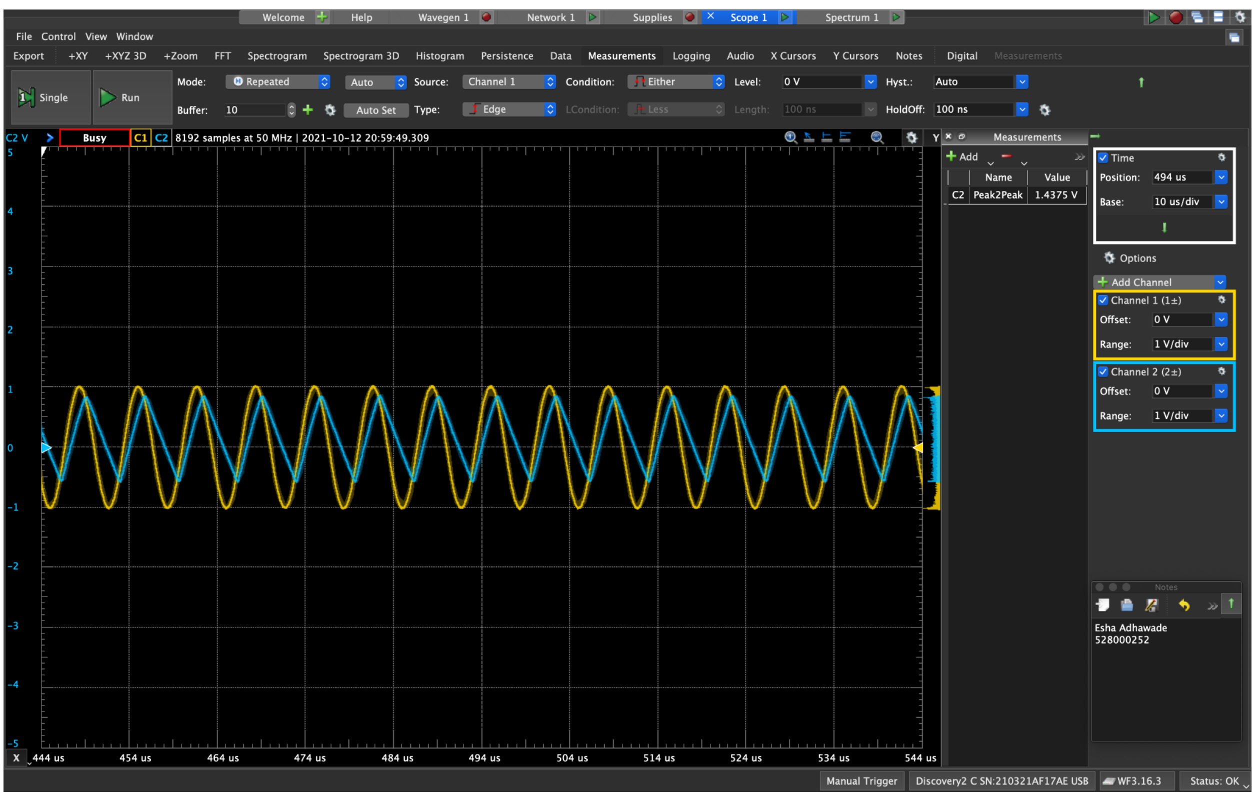
Time Domain 75k 2V



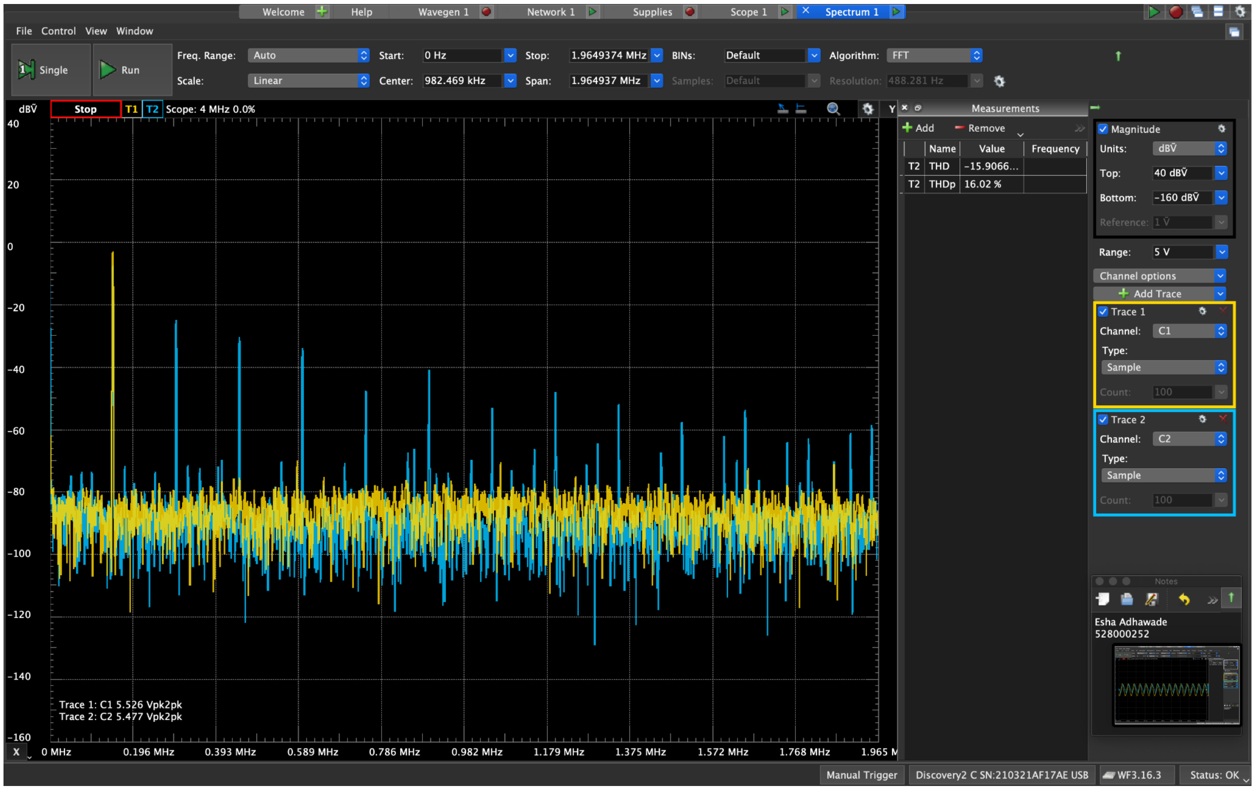
THD 75k 2V



Time Domain 150k 1V



THD 150k 1V



<u>Data Tables</u>

Lossy Integrator

	Low Frequency Gain	3dB Frequency	Vout Magnitude	Vout Phase
Calculations Lossy Integrator	22	206.61	0.3615	-88.11
Simulations Lossy Integrator	-8.36051	18.264	0.358	-87.042
Measurements Lossy Integrator	-3.26	36.793	0.468	-98.53

Pseudo Differentiator

	Low Frequency Gain	3dB Frequency	Vout Magnitude	Vout Phase

Calculations Pseudo Differentiator	-22	1317.5	0.0936	11.89
Simulations Pseudo Differentiator	4.901	3.7684k	2.7816	124.81
Measurements Pseudo Differentiator	-18.97	10.775k	0.4221	98.856

Finite GBW Limitations

	3dB Frequency
Calculations Finite GBW Limitations (23)	---
Simulations Finite GBW Limitations (23)	29.964k
Measurements Finite GBW Limitations (23)	31.017k
Calculations Finite GBW Limitations (57)	---
Simulations Finite GBW Limitations (57)	18.234k
Measurements Finite GBW Limitations (57)	16.343k
Calculations Finite GBW Limitations (83)	---
Simulations Finite GBW Limitations (83)	15.672k

Measurements Finite GBW Limitations (83)	17.937k

Slew Rate Limitations

There is no transfer function for slew rate, so there cannot exist a 3dB frequency. For magnitude and phase response between 75k and 150k will be the same.

Discussion

For lab 5, students learned about the different configurations for op amps and their non-idealities. Most of the values between the simulations and measurements were pretty consistent for the circuits. If there were any minor differences, that's probably because of component differences, old breadboards, or loose wires. My simulation for lossy integrator, used VSS instead of VDD so my 3db is different from measurements.