Analog Electronic Circuits – Lab 8

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1 CMOS inverter with feedback

1.1 Objective:

To construct a CMOS based Inverter and analyze its working.

1.2 Circuit Diagram:

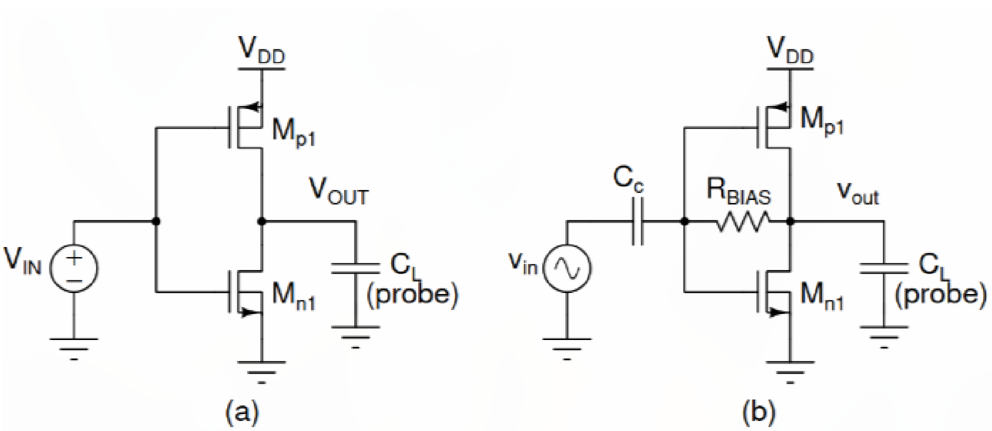


Figure 1.2.1: (a)-Circuit to determine VTC, (b)-Circuit for Amplifying action

1.3 LTSpice Simulations

To determine range of V_{in} where Amplifying action occurs, we need the range of V_{in} for which $|\frac{dv_{out}}{dv_{in}}| > 1$. To do this we can plot v_{out} vs v_{in}, and to be more accurate $\frac{dv_{out}}{dv_{in}}$ vs v_{in}.

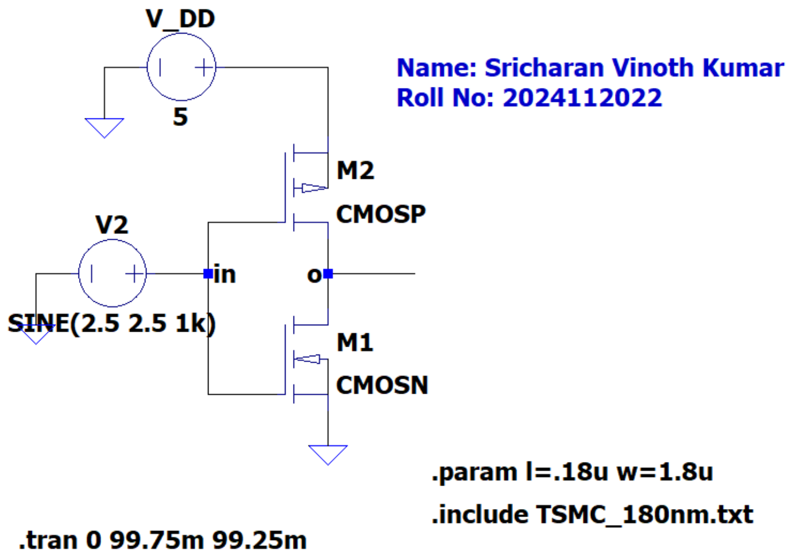


Figure 1.3.1: LTSpice Schematic to find input range

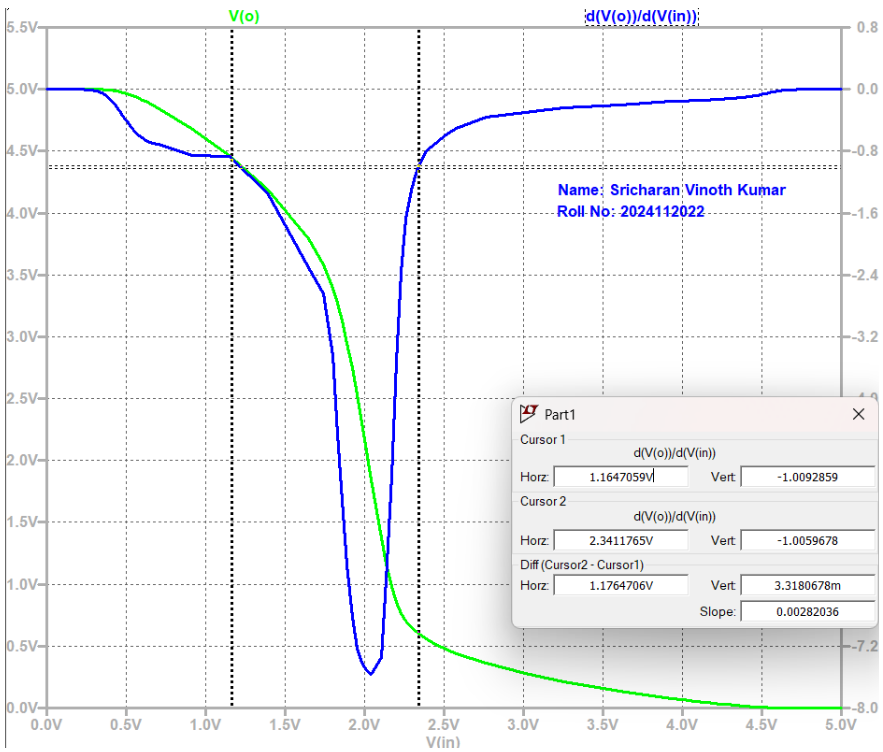


Figure 1.3.2: Plot of v_{out} vs v_{in} (Green) and $\frac{dv_{out}}{dv_{in}}$ vs v_{in} (Blue)

The obtained range is:

$$v_{in} \in (1.1647V, 2.3411V) \tag{1.3.1}$$

To observe Amplifying action,

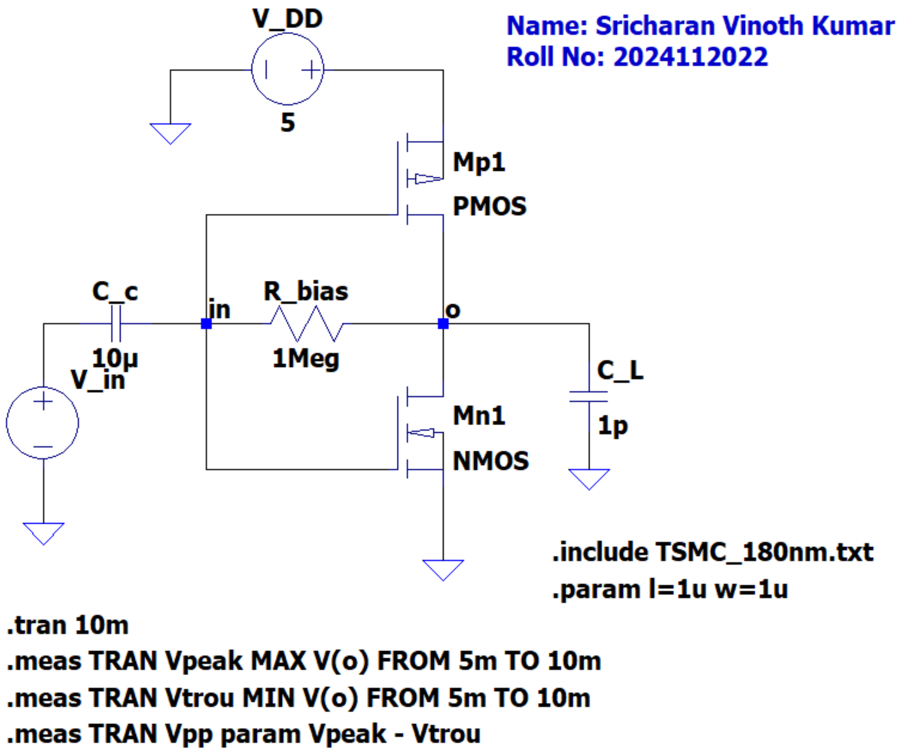


Figure 1.3.3: LTSpice Schematic to observe Amplifying action

The DC voltage at both the gate and drain terminals is 2.5V. The values observed are (the voltages mentioned are the amplitudes of the respective signals):

v_{in}	v_{out}	Gain $A_v = \frac{v_{out}}{v_{in}}$
0.1	1.217	12.17
0.2	1.701	8.505
0.3	2.05	6.833333333
0.4	2.329	5.8225
0.5	2.562	5.124
0.6	2.764	4.606666667
0.7	2.941	4.201428571
0.8	3.099	3.87375

Table 1: Observed Values

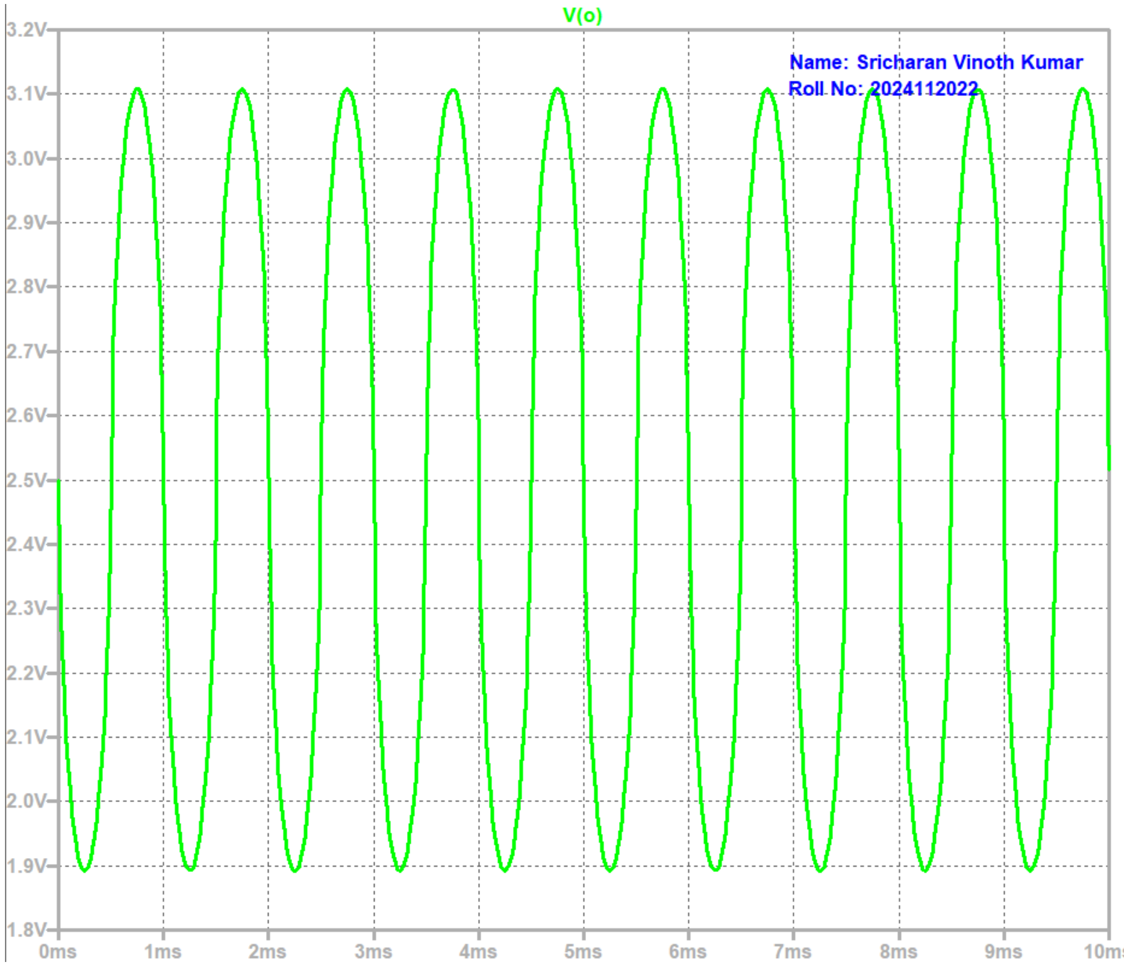


Figure 1.3.4: v_{out} waveform at Amplitude(v_{in}) = 100mV.

```
Vpeak: MAX(V(o))=3.10865807533 FROM 0.005 TO 0.01
Vtrou: MIN(V(o))=1.89148938656 FROM 0.005 TO 0.01
Vpp: Vpeak - Vtrou=1.21716868877
```

Figure 1.3.5: Result of Measurements at Amplitude(v_{in}) = 100mV.

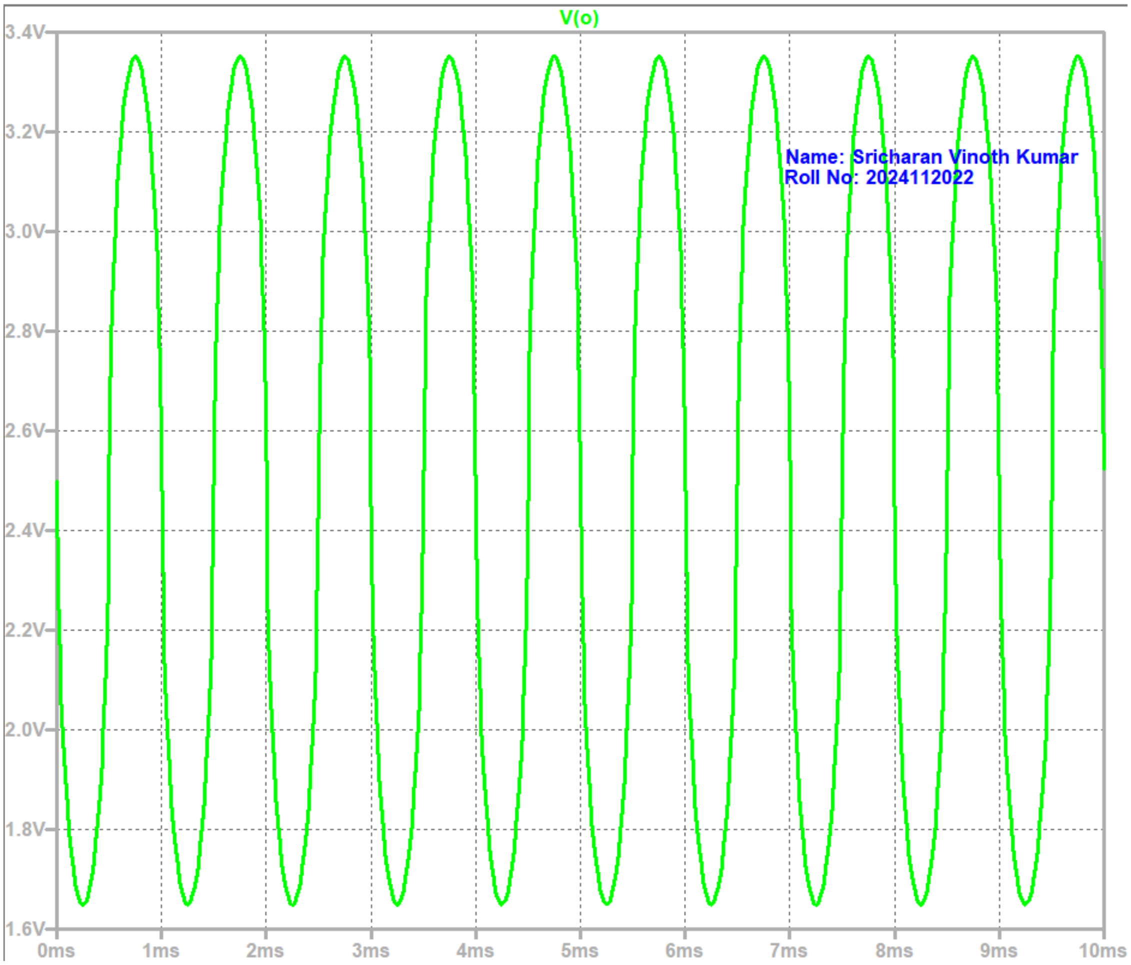


Figure 1.3.6: v_{out} waveform at Amplitude(v_{in}) = 200mV.

```
Vpeak: MAX(V(o))=3.35094451904 FROM 0.005 TO 0.01
Vtrou: MIN(V(o))=1.64919734001 FROM 0.005 TO 0.01
Vpp: Vpeak - Vtrou=1.70174717903
```

Figure 1.3.7: Result of Measurements at Amplitude(v_{in}) = 200mV.

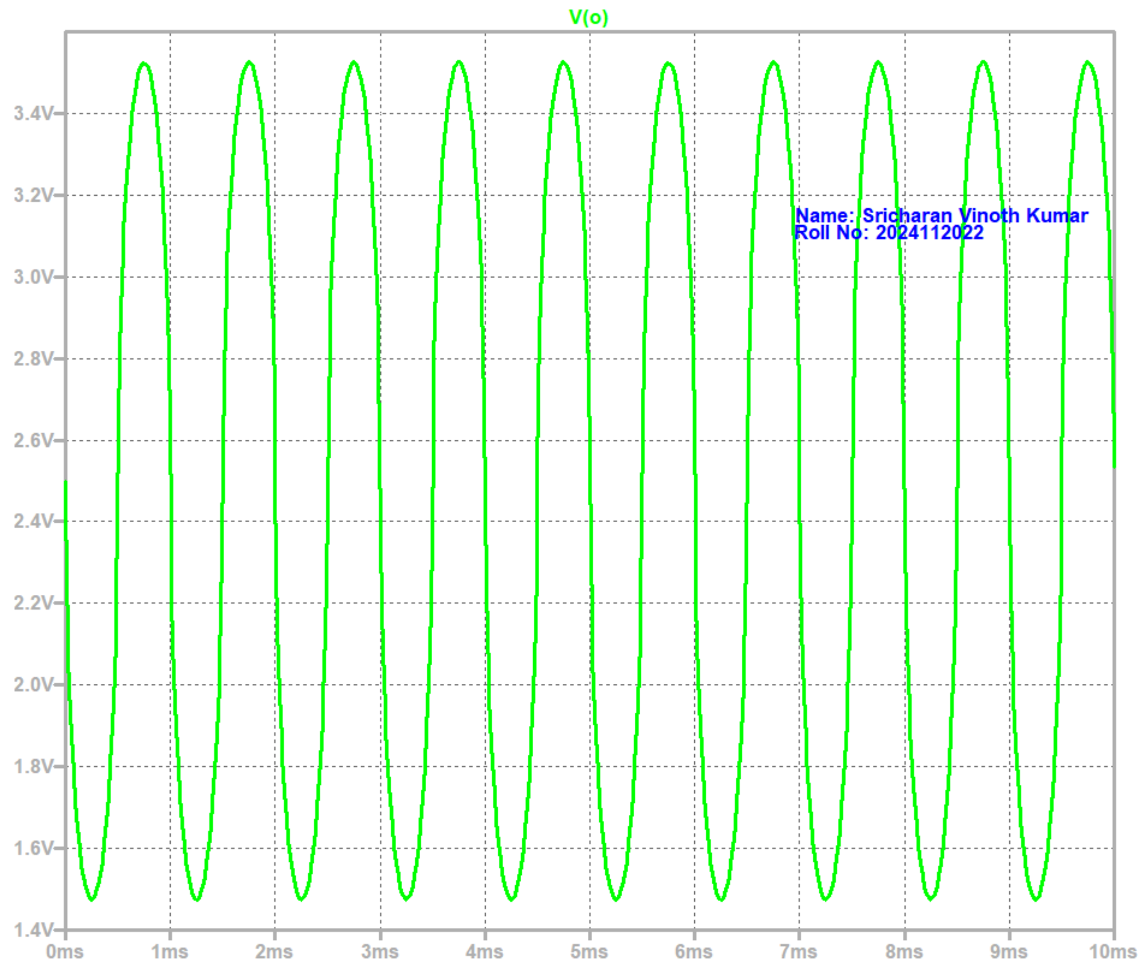


Figure 1.3.8: v_{out} waveform at Amplitude(v_{in}) = 300mV.

```
Vpeak: MAX(V(o))=3.52540278435 FROM 0.005 TO 0.01
Vtrou: MIN(V(o))=1.47473287582 FROM 0.005 TO 0.01
Vpp: Vpeak - Vtrou=2.05066990852
```

Figure 1.3.9: Result of Measurements at Amplitude(v_{in}) = 300mV.

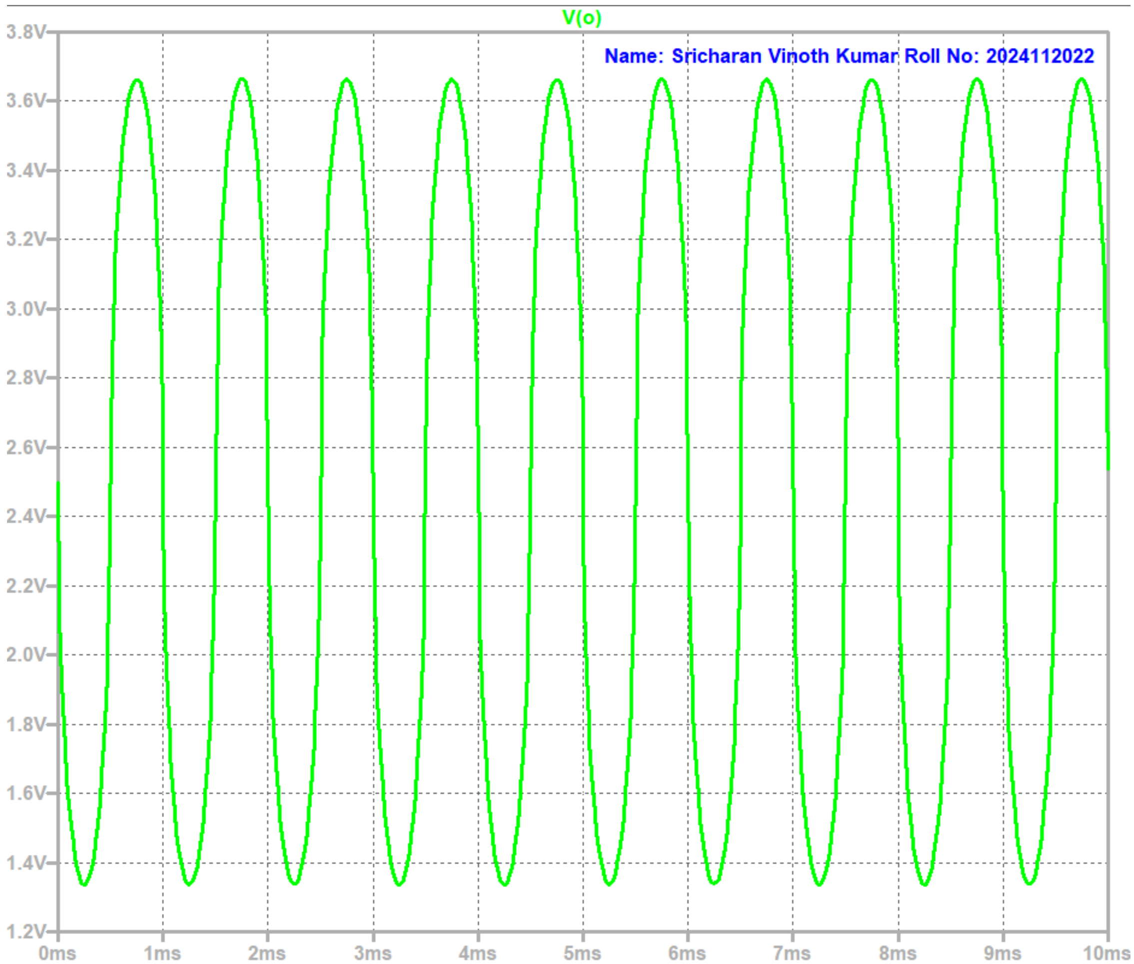


Figure 1.3.10: v_{out} waveform at Amplitude(v_{in}) = 400mV.

```
Vpeak: MAX(V(o))=3.66464757919 FROM 0.005 TO 0.01
Vtrou: MIN(V(o))=1.33546054363 FROM 0.005 TO 0.01
Vpp: Vpeak - Vtrou=2.32918703556
```

Figure 1.3.11: Result of Measurements at Amplitude(v_{in}) = 400mV.

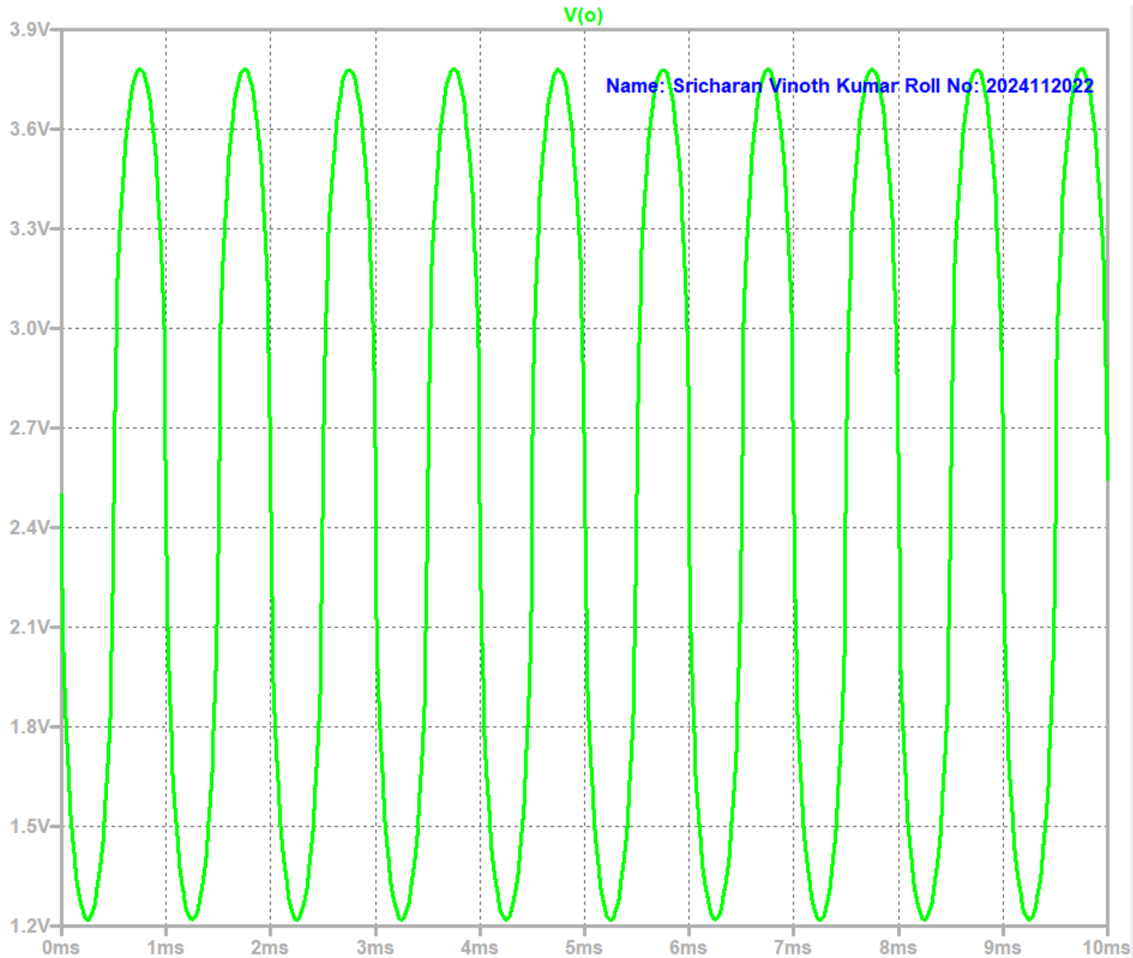


Figure 1.3.12: v_{out} waveform at Amplitude(v_{in}) = 500mV.

```
Vpeak: MAX(V(o))=3.7814643383 FROM 0.005 TO 0.01
Vtrou: MIN(V(o))=1.2186511755 FROM 0.005 TO 0.01
Vpp: Vpeak - Vtrou=2.5628131628
```

Figure 1.3.13: Result of Measurements at Amplitude(v_{in}) = 500mV.

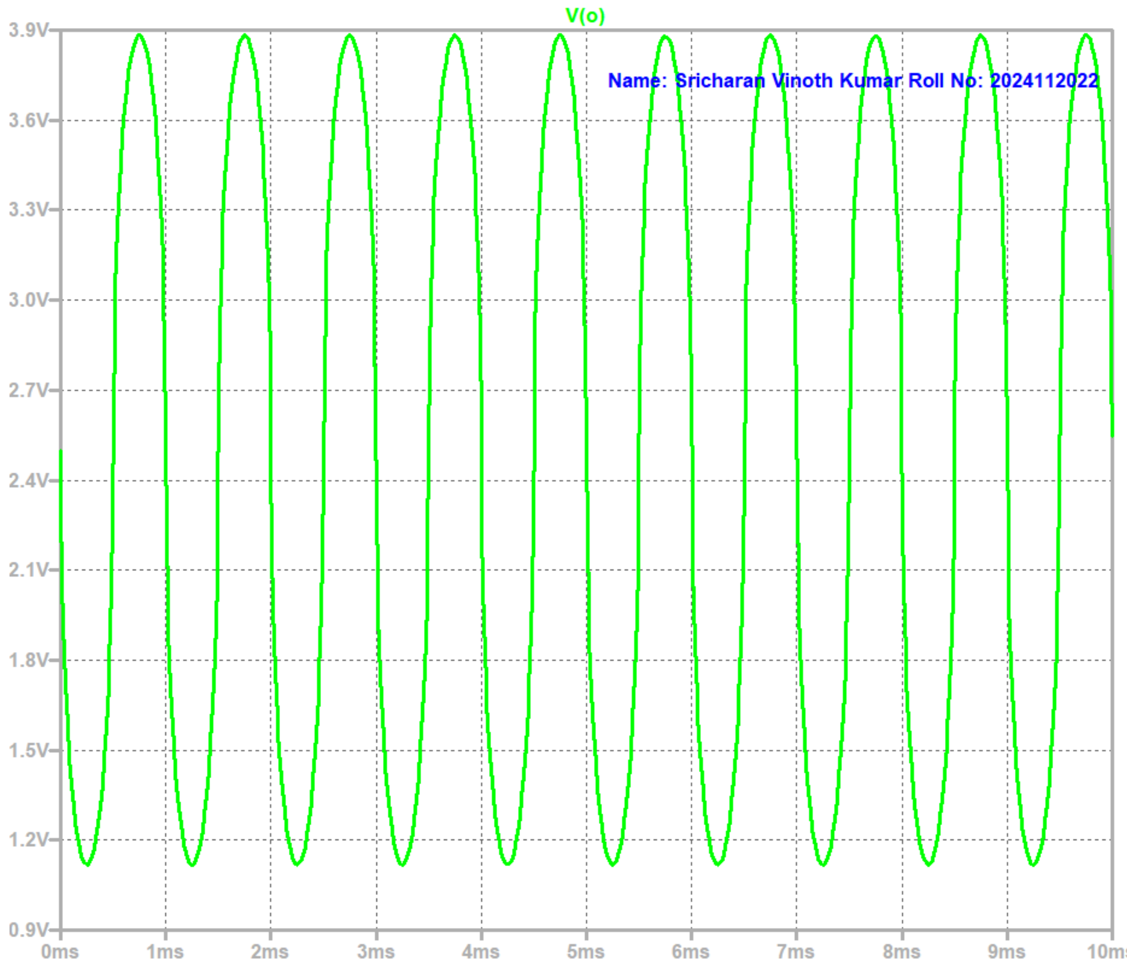


Figure 1.3.14: v_{out} waveform at Amplitude(v_{in}) = 600mV.

```
Vpeak: MAX(V(o))=3.88230371475 FROM 0.005 TO 0.01
Vtrou: MIN(V(o))=1.11785078049 FROM 0.005 TO 0.01
Vpp: Vpeak - Vtrou=2.76445293427
```

Figure 1.3.15: Result of Measurements at Amplitude(v_{in}) = 600mV.

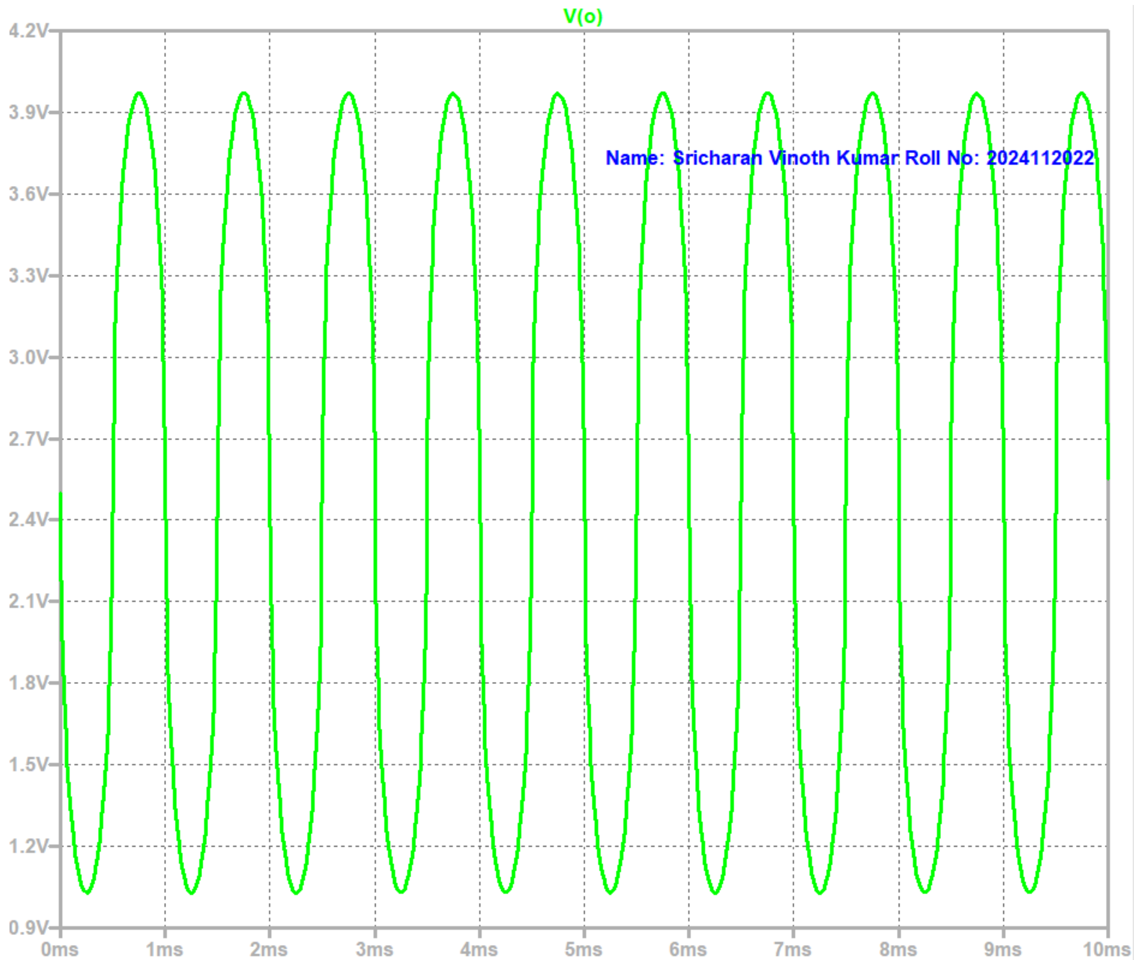


Figure 1.3.16: v_{out} waveform at Amplitude(v_{in}) = 700mV.

```
Vpeak: MAX(V(o))=3.97077202797 FROM 0.005 TO 0.01
Vtrou: MIN(V(o))=1.02910804749 FROM 0.005 TO 0.01
Vpp: Vpeak - Vtrou=2.94166398048
```

Figure 1.3.17: Result of Measurements at Amplitude(v_{in}) = 700mV.

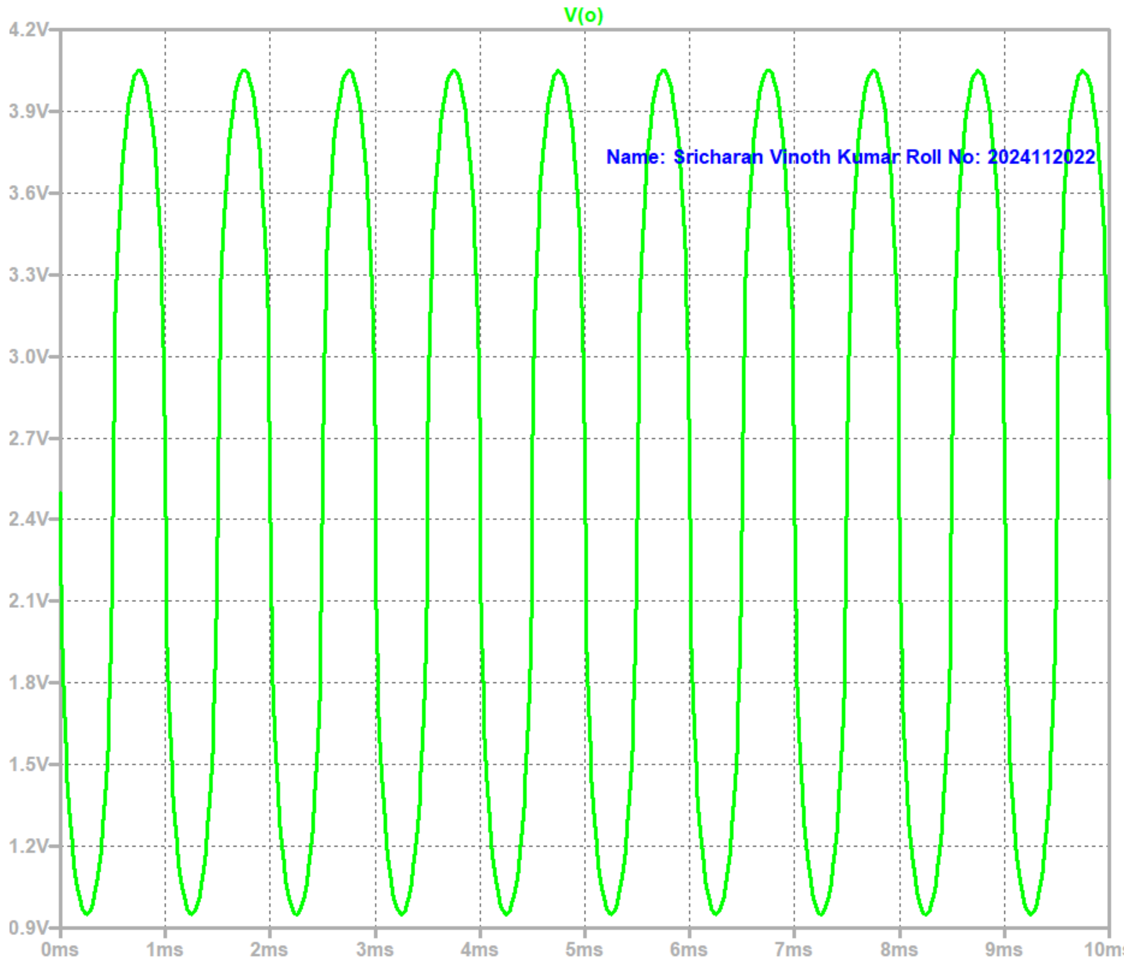
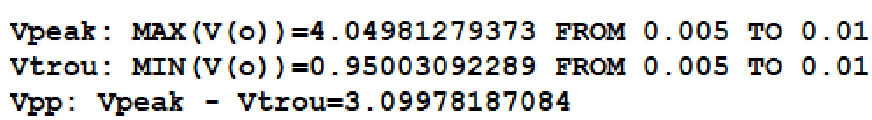


Figure 1.3.18: v_{out} waveform at Amplitude(v_{in}) = 800mV.



```
Vpeak: MAX(V(o))=4.04981279373 FROM 0.005 TO 0.01
Vtrou: MIN(V(o))=0.95003092289 FROM 0.005 TO 0.01
Vpp: Vpeak - Vtrou=3.09978187084
```

Figure 1.3.19: Result of Measurements at Amplitude(v_{in}) = 800mV.

1.4 Observations

To find a valid input range,

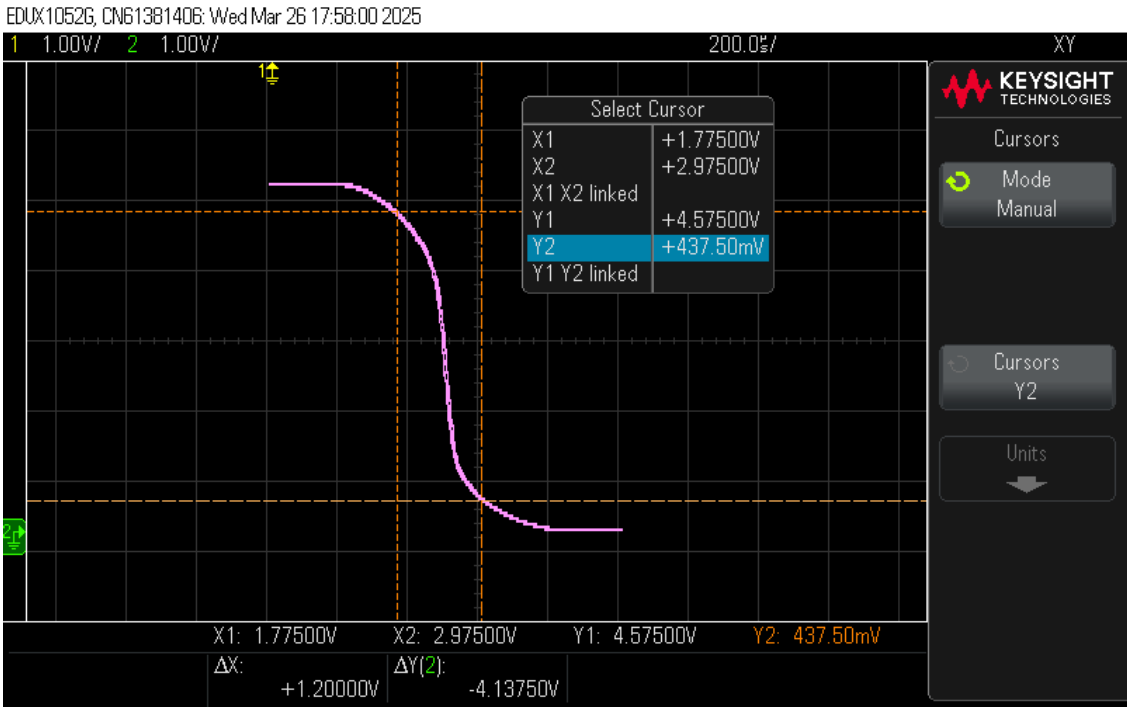


Figure 1.4.1: Obtained VTC (v_{out} vs v_{in}) Plot in DSO

Obtained range,

$$v_{in} \in (1.775V, 2.975V) \tag{1.4.1}$$

To observe Amplifying behaviour,

The DC voltages at the gate and drain terminals were approximately 2.6V. The values observed are (the voltages mentioned are the amplitudes of the respective voltage responses):

v_{in}	v_{out}	Gain $A_v = \frac{v_{out}}{v_{in}}$
0.1	1.25	12.5
0.2	2.21	11.05
0.3	2.77	9.233333333
0.4	3.06	7.65
0.5	3.3	6.6
0.6	3.5	5.833333333

Table 2: Observed Values

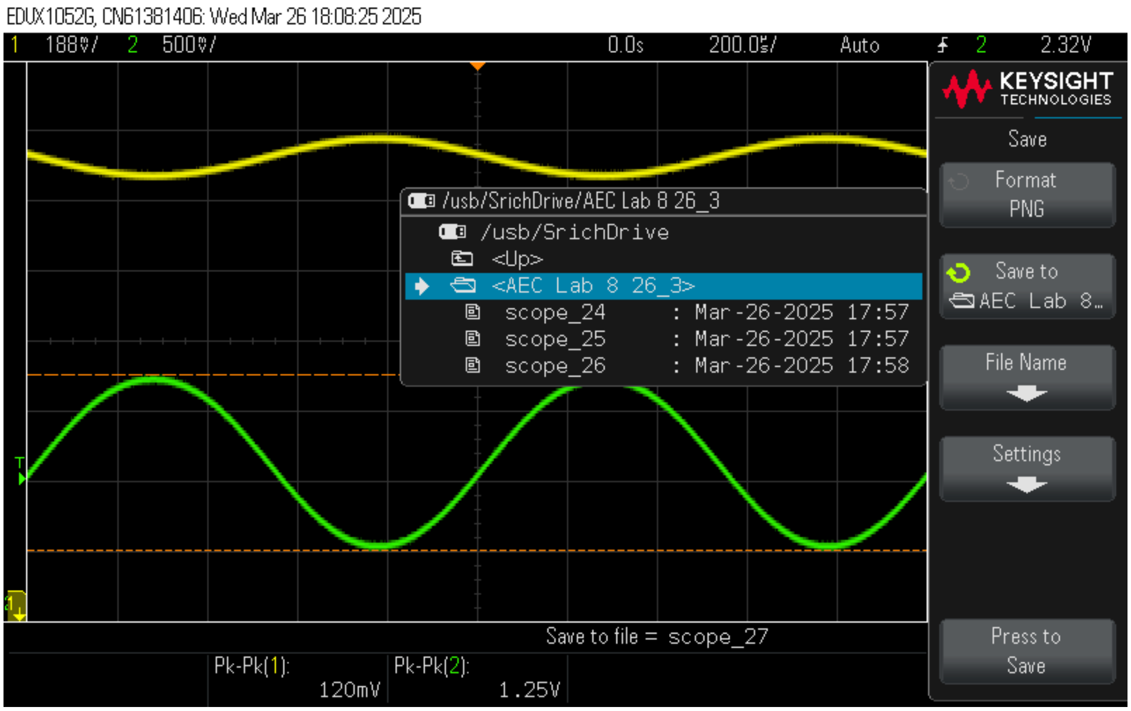


Figure 1.4.2: v_{out} waveform at Amplitude(v_{in}) = 100mV

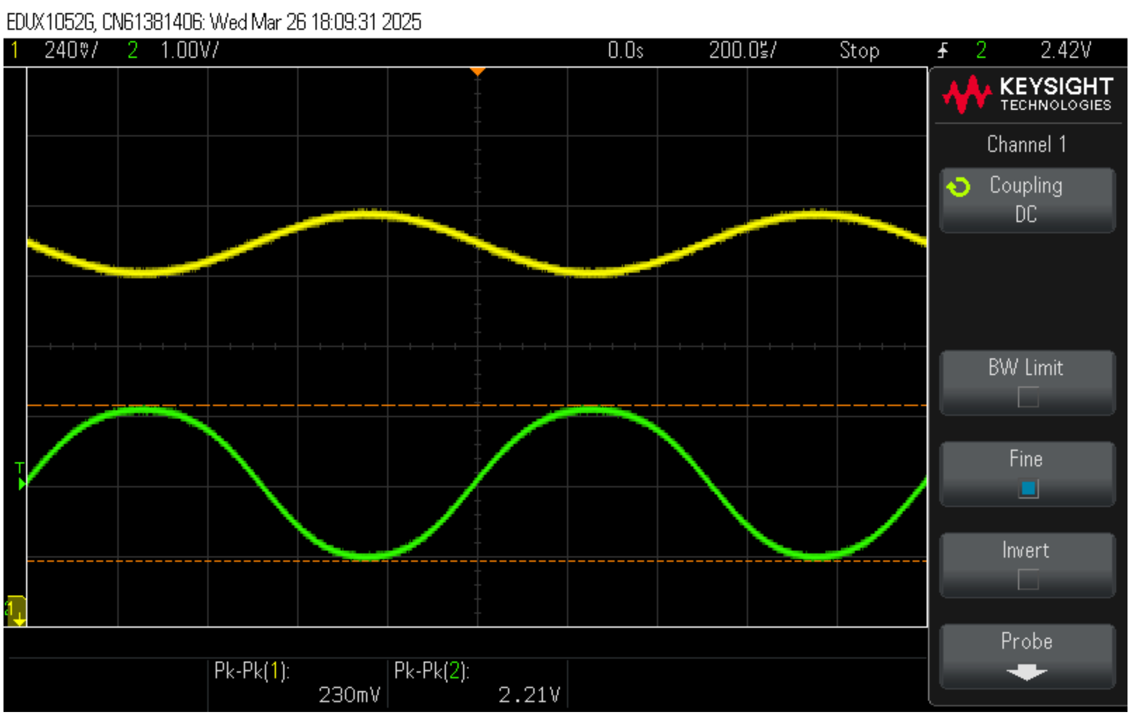


Figure 1.4.3: v_{out} waveform at Amplitude(v_{in}) = 200mV

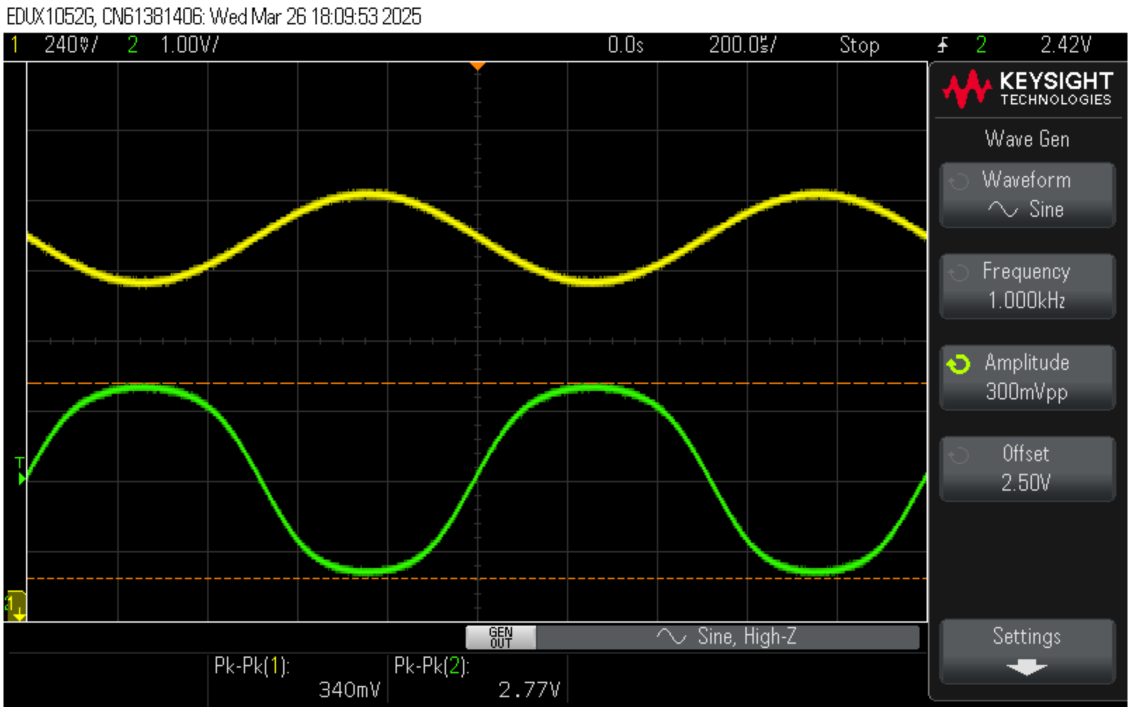


Figure 1.4.4: v_{out} waveform at Amplitude(v_{in}) = 300mV

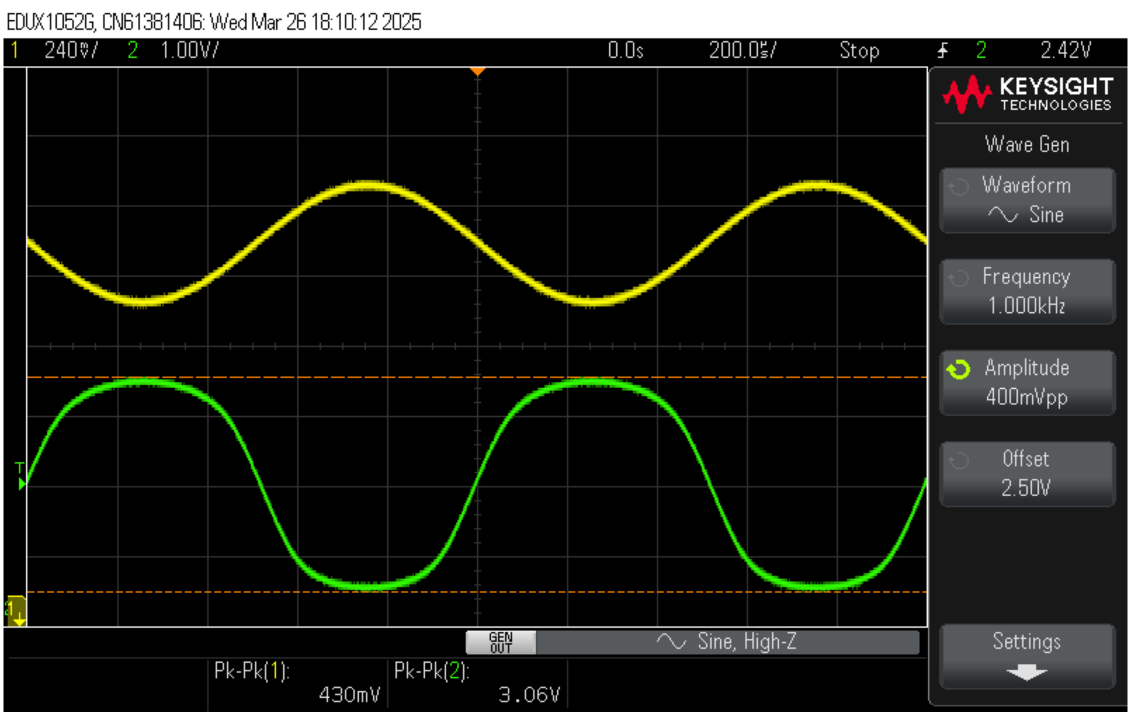


Figure 1.4.5: v_{out} waveform at Amplitude(v_{in}) = 400mV

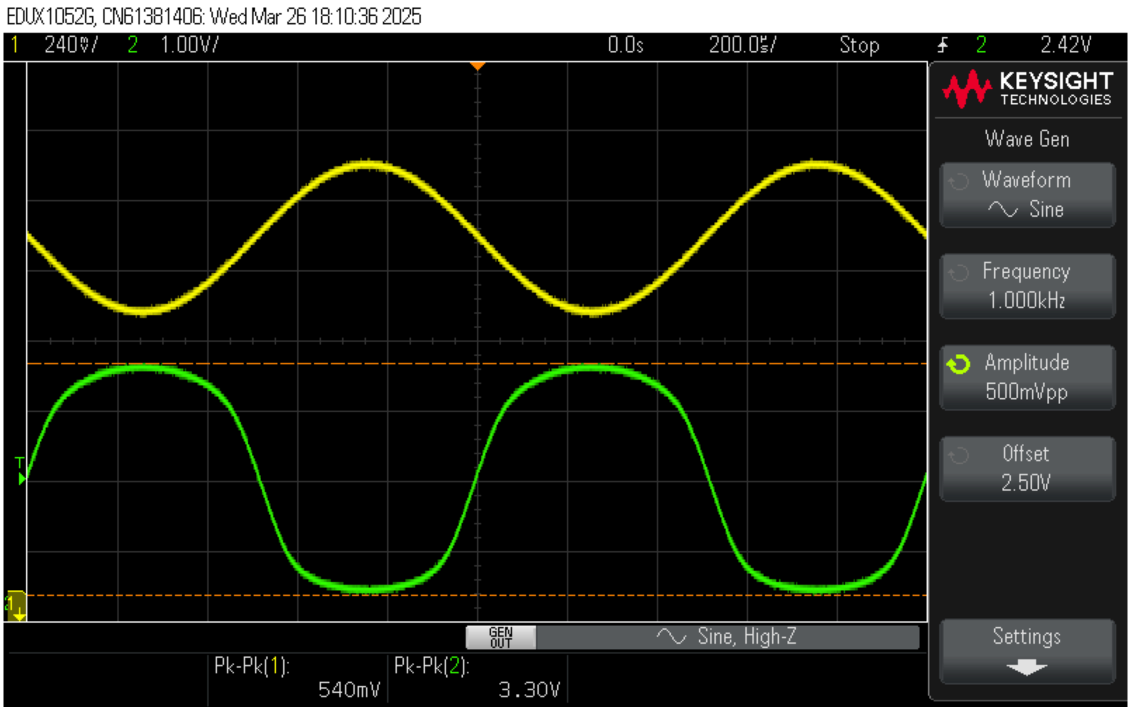


Figure 1.4.6: v_{out} waveform at Amplitude(v_{in}) = 500mV

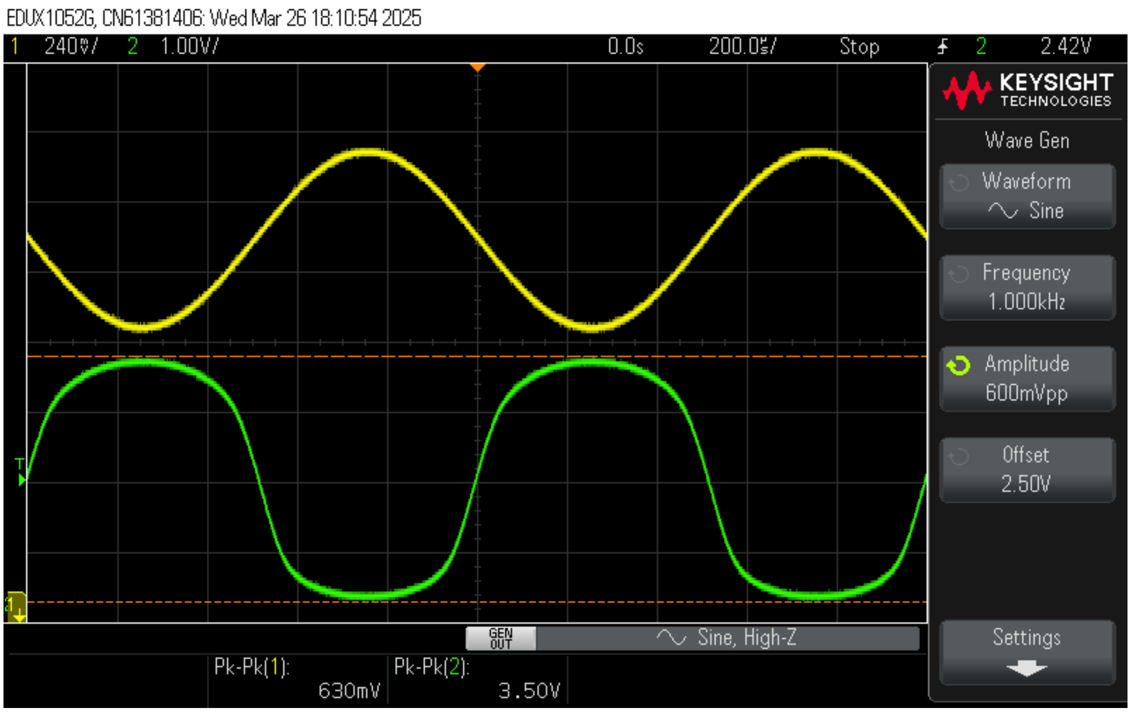


Figure 1.4.7: v_{out} waveform at Amplitude(v_{in}) = 600mV

1.5 Inference

In the LTSpice Simulation and the Observations, we see that there is a significant reduction in gain at around $v_{in} = 600mV$. We can attribute this to the **clipping of the output waveform.**

Reason For Clipping: We know that the valid input region for the Amplifier (in Observations, Equation 1.4.1) is (1.775V, 2.975V). Since the Operating Point voltage at the gate terminal is 2.4V, the allowed amplitude of v_{in} such that the gate voltage stays within the range is,

$$\begin{aligned} Max\ Amplitude &= min\{2.6 - 1.775, 2.975 - 2.6\} \\ &= min\{0.925, 0.375\} \\ &= 375mV \end{aligned}$$

This matches with what we observe, since we get significant clipping and reduction in gain at Amplitude(v_{in}) ≈ 400mV.
Therefore, we can conclude that the cause of the clipping is due to the input voltage leaving the Amplification region.

2 Characterization of Operational Amplifier

2.1 Objective:

To observe the Open Loop Voltage Transfer Characteristic, and the DC offset of the given Operational Amplifier.

2.2 Circuit Diagram:

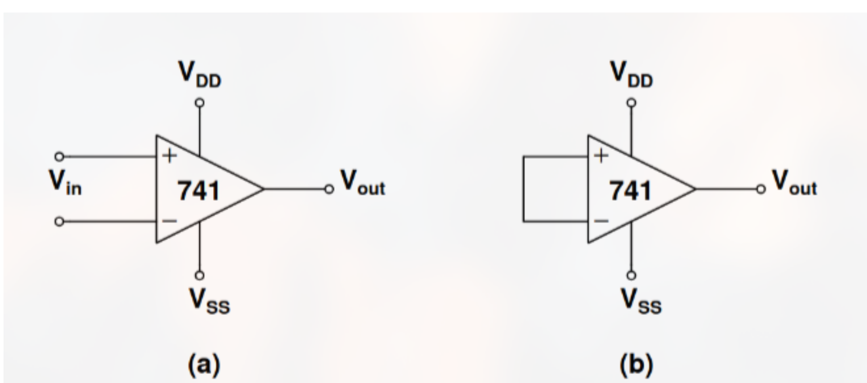


Figure 2.2.1: (a)-To determine Open Loop VTC, (b)-To determine DC Offset

2.3 Common Parameters Used

- $V_{DD} = 10V$
- $V_{SS} = -10V$
- v_{in} : $12V\ peak\ to\ peak,\ 100Hz\ frequency$ (For VTC only)

2.4 LTSpice Simulation

To determine Open Loop VTC,

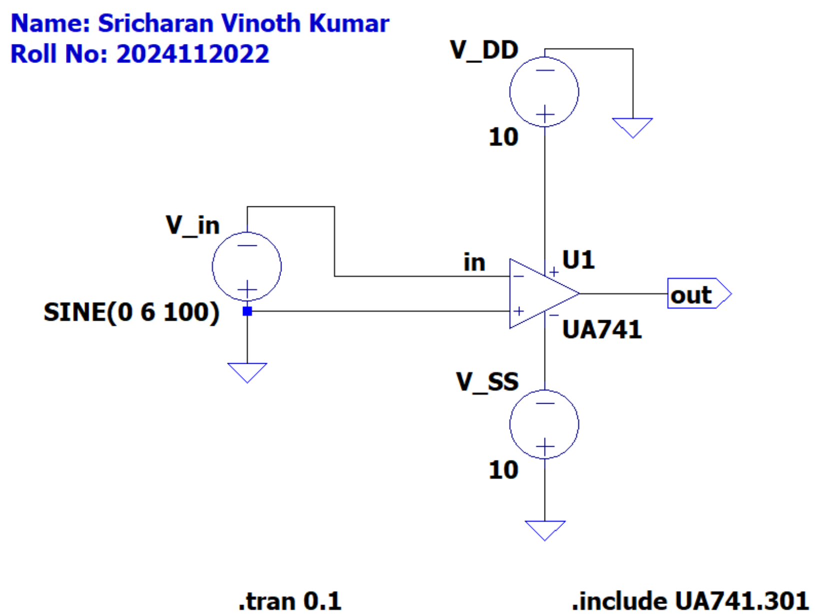


Figure 2.4.1: LTSpice Schematic to determine Open Loop VTC

Obtained VTC:

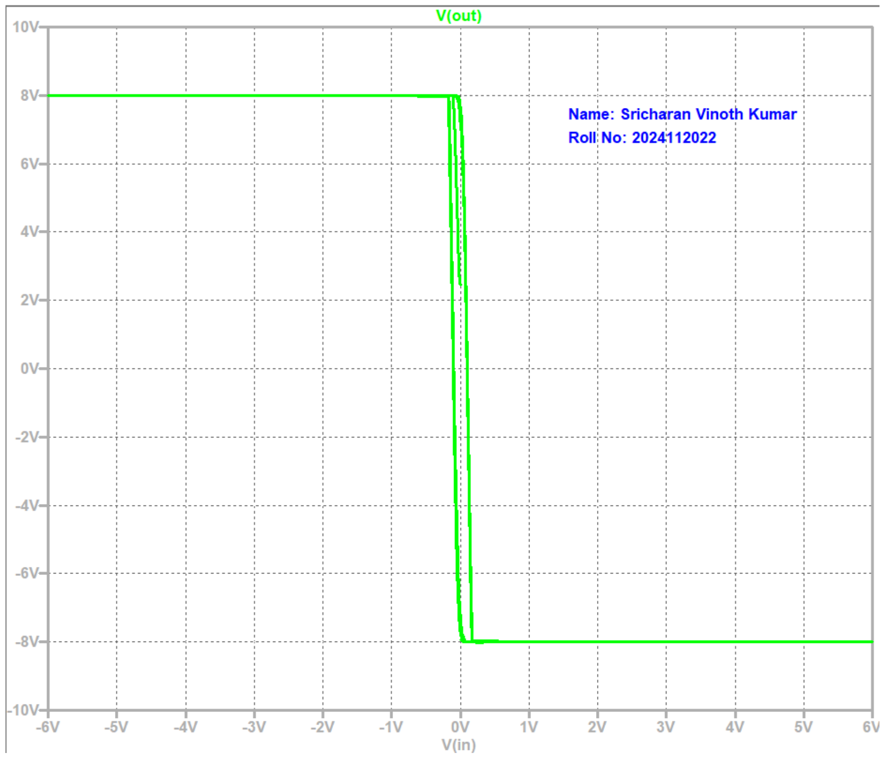


Figure 2.4.2: Obtained VTC: Plot of v_{out} vs v_{in}

To observe DC offset,

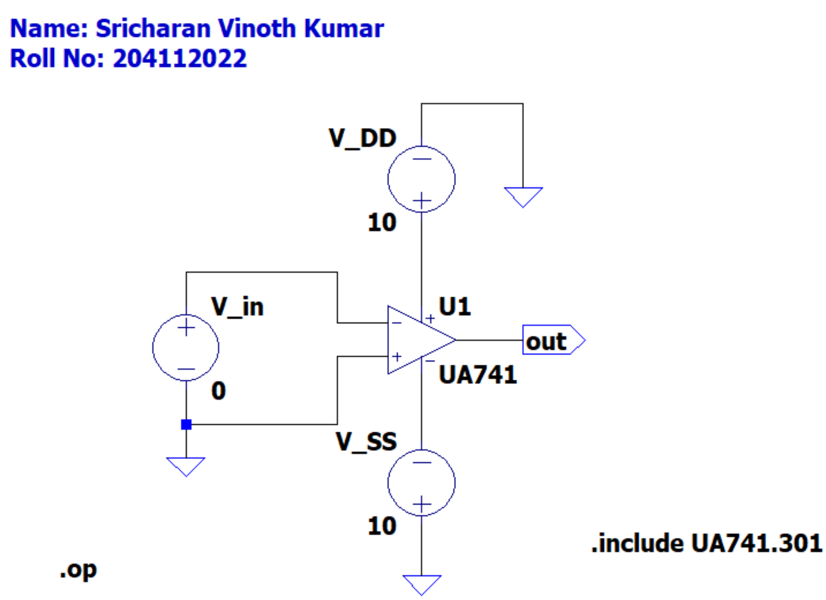


Figure 2.4.3: LTSpice Schematic to observe DC Offset

Observed DC Offset:

```
--- Operating Point ---

V(n002):      10            voltage
V(out):       2.43915       voltage
V(n001):      0             voltage
V(n003):      -10           voltage
I(V_SS):      -0.00111452   device_current
I(V_DD):      -0.00111433   device_current
I(V_in):      -7.97518e-08  device_current
Ix(u1:1):     7.97518e-08   subckt_current
Ix(u1:2):     7.97518e-08   subckt_current
Ix(u1:3):     0.00111433    subckt_current
Ix(u1:4):     -0.00111452   subckt_current
Ix(u1:5):     -1.27929e-18  subckt_current
```

Figure 2.4.4: Result of Operating Point Analysis in LTSpice

Based on the result of the OP analysis, in Figure 2.4.4, we can determine the DC offset to be 2.43915V. Input DC voltage required to negate this DC Offset is:

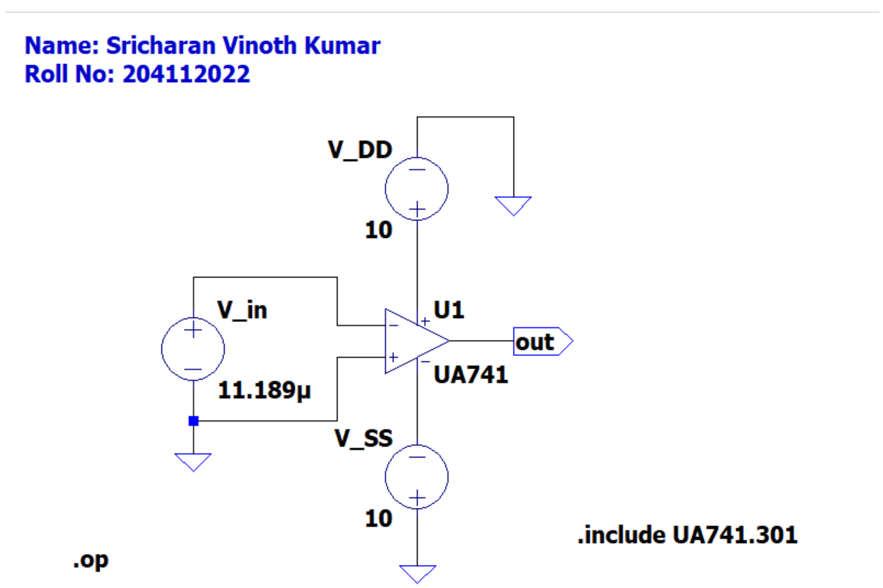


Figure 2.4.5: LTSpice Schematic to negate DC Offset of Op-Amp

New Result of Operating Point analysis:

```
        --- Operating Point ---

V(n002):        10              voltage
V(out):         -0.00090451     voltage
V(n001):        1.1189e-05      voltage
V(n003):        -10             voltage
I(V_SS):        -0.00111452     device_current
I(V_DD):        -0.00111433     device_current
I(V_in):        -7.9763e-08     device_current
Ix(u1:1):       7.97406e-08     subckt_current
Ix(u1:2):       7.9763e-08      subckt_current
Ix(u1:3):       0.00111433      subckt_current
Ix(u1:4):       -0.00111452     subckt_current
Ix(u1:5):       6.57523e-22     subckt_current
```

Figure 2.4.6: New result of Operating Point Analysis

In the above result, we can see that the output DC offset is negligible. Therefore, the approximate DC voltage required to negate the DC offset is **11.189**μV

2.5 Observations

Open Loop VTC:

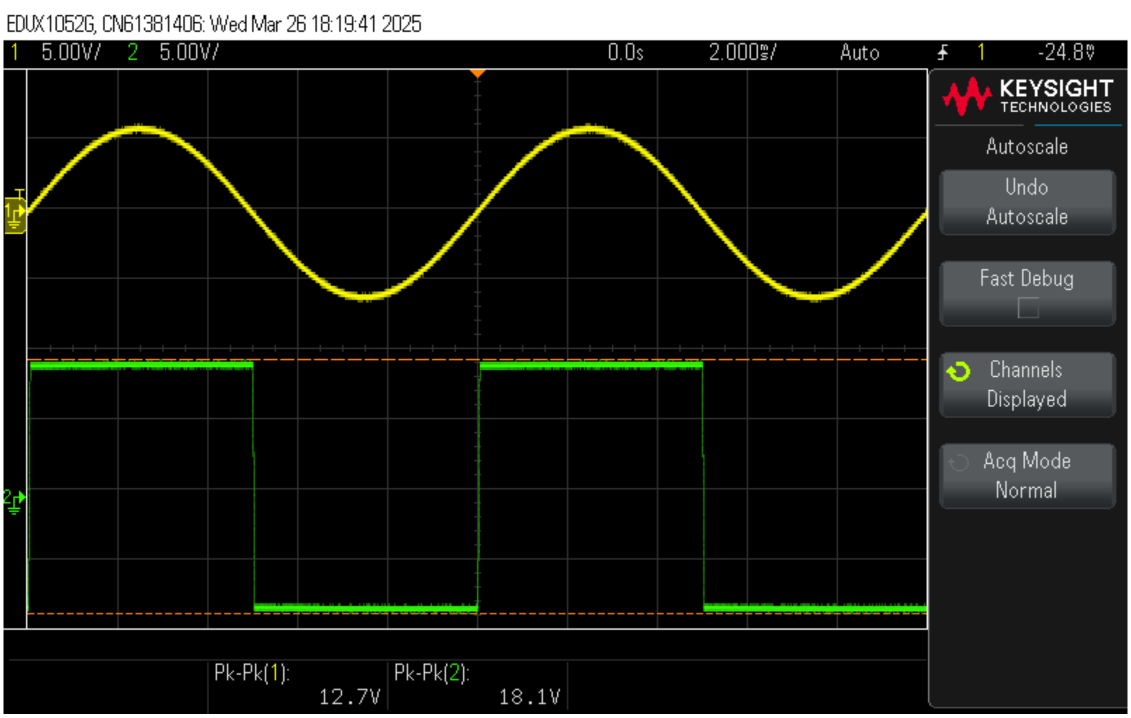


Figure 2.5.1: Plot of v_{in}(Yellow) and v_{out}(Green) vs time

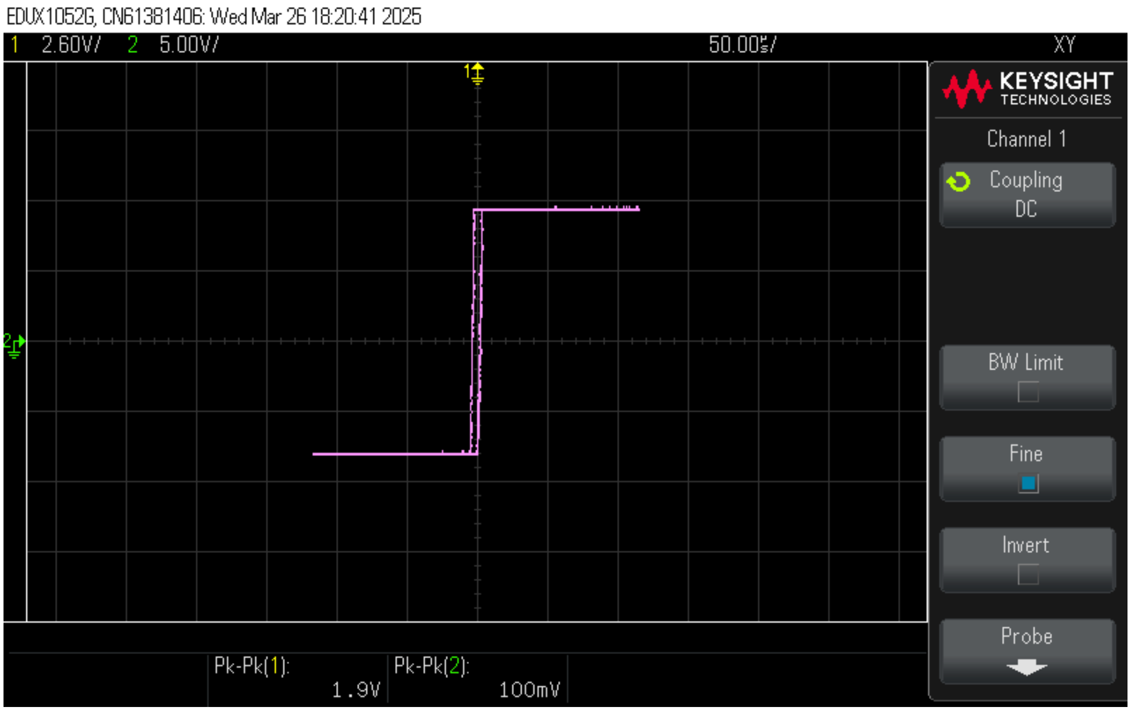


Figure 2.5.2: Obtained VTC: Plot of v_{out} vs v_{in}

Observed DC Offset:

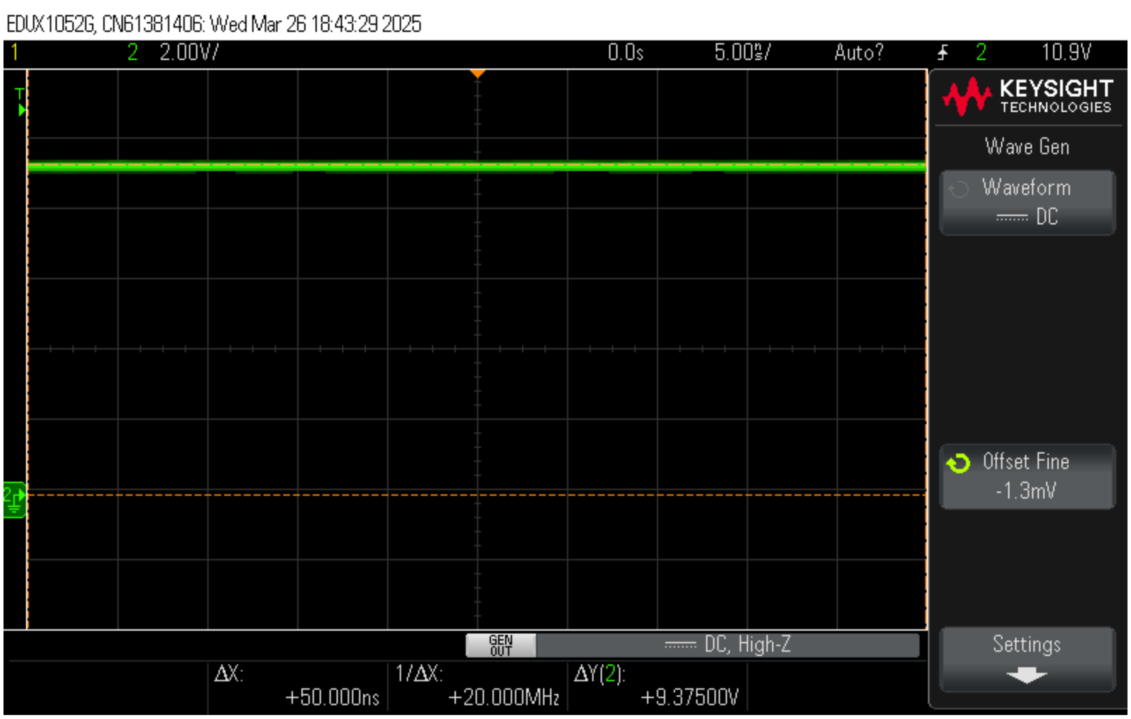


Figure 2.5.3: Observed DC Offset of the Op-Amp

The DC Offset observed is 9.375V. To negate the DC offset

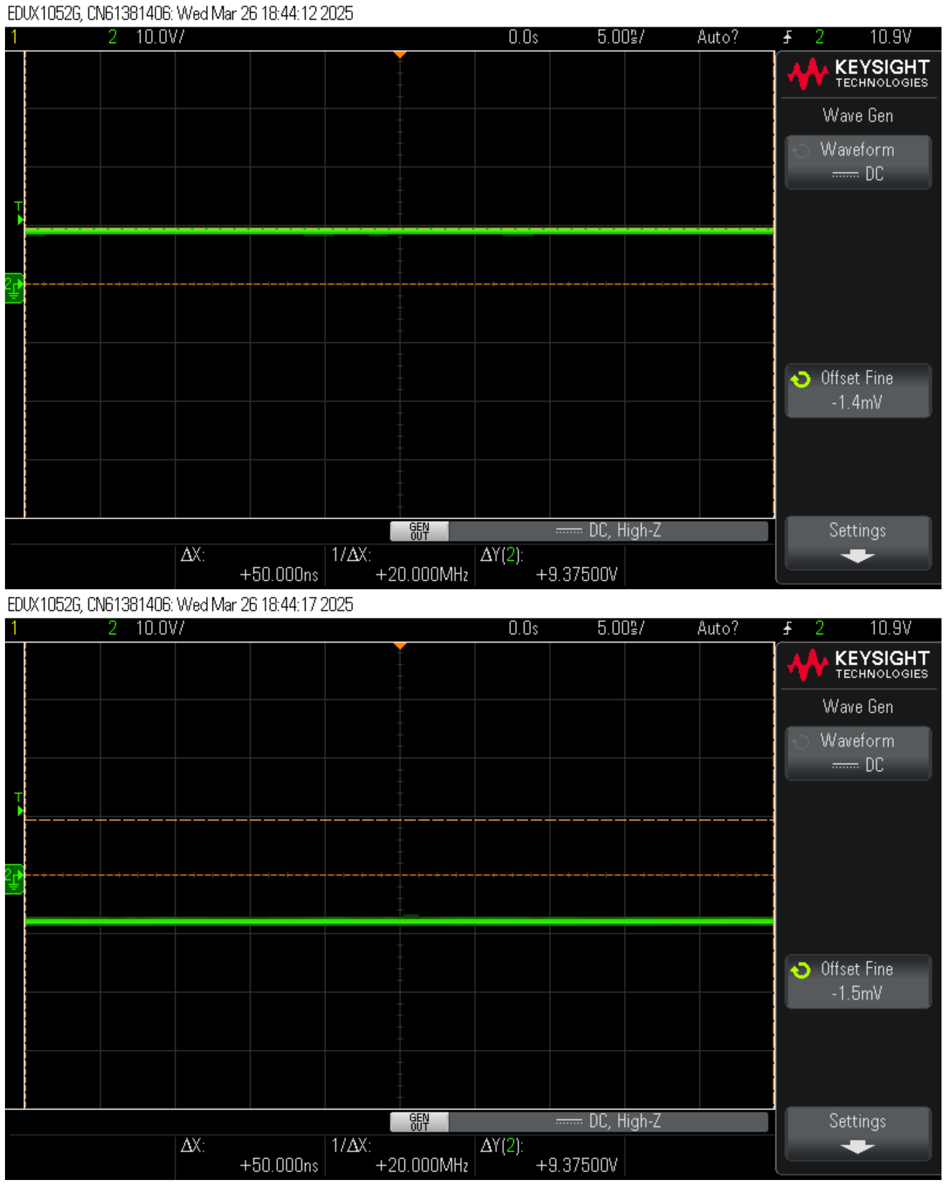


Figure 2.5.4: Observed DC Offset of the Op-Amp at $V_{in} = 1.4mV$(Above) and $V_{in} = 1.5mV$(Below)

Since the offset is positive at 1.4mV and negative at 1.5mV, we can conclude that the voltage required to negate the DC offset is between 1.4 and 1.5mV.

2.6 Inference

The voltage required to offset the DC offset was observed to be between 1.4mV and 1.5mV. The exact value cannot be observed due to the inadequate precision of the Wave Generator of the given DSO.

3 Non-Inverter Amplifier

3.1 Objective

To construct and analyze the working and the gain of a Op-Amp based Non-Inverting Amplifier.

3.2 Circuit Diagram

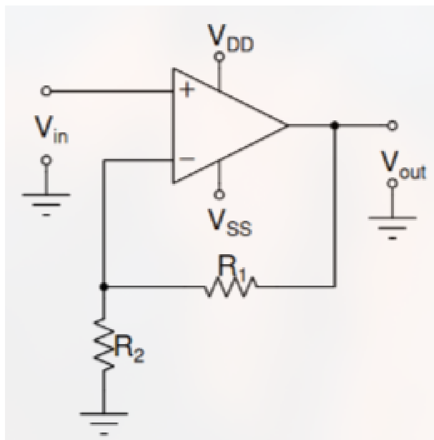


Figure 3.2.1: Circuit Diagram of a Non-Inverting Amplifier

3.3 Common Parameters Used

- $V_{DD} = 12V$
- $V_{SS} = -12V$
- $v_{in} = 250mV peak\ to\ peak,\ 5kHz\ frequency$

3.4 LTSpice Simulations

To derive an expression for the Gain of the Amplifier,

$$v_{in} = v_{out}\left(\frac{R_2}{R_1 + R_2}\right)$$

$$\frac{v_{in}}{v_{out}} = \left(\frac{R_2}{R_1 + R_2}\right) \tag{3.4.1}$$

$$\therefore A_v = 1 + \frac{R_1}{R_2}$$

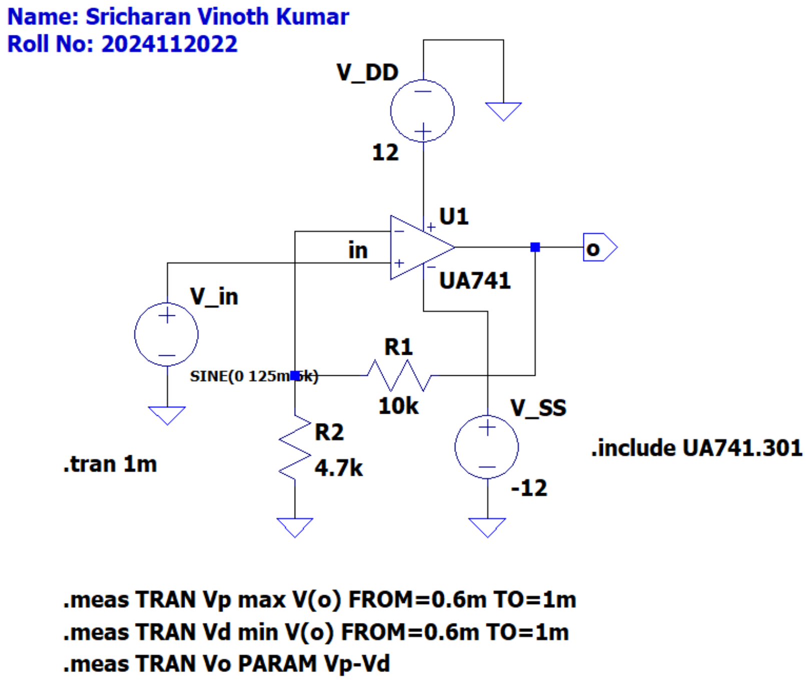


Figure 3.4.1: LTSpice Schematic of Non-Inverting Amplifier

Observed Values,

R_1	R_2	v_{out}	Calculated Gain $= 1 + \frac{R_2}{R_1}$	Observed Gain
$10k\Omega$	$10k\Omega$	0.49927V	2	1.99708
$10k\Omega$	$4.7k\Omega$	0.78086V	3.1276	3.12344

Expected Gain	R_1	R_2	v_{out}	Observed Gain
4	$30k\Omega$	$10k\Omega$	0.99858	3.99432
5	$40k\Omega$	$10k\Omega$	1.24823	4.99292

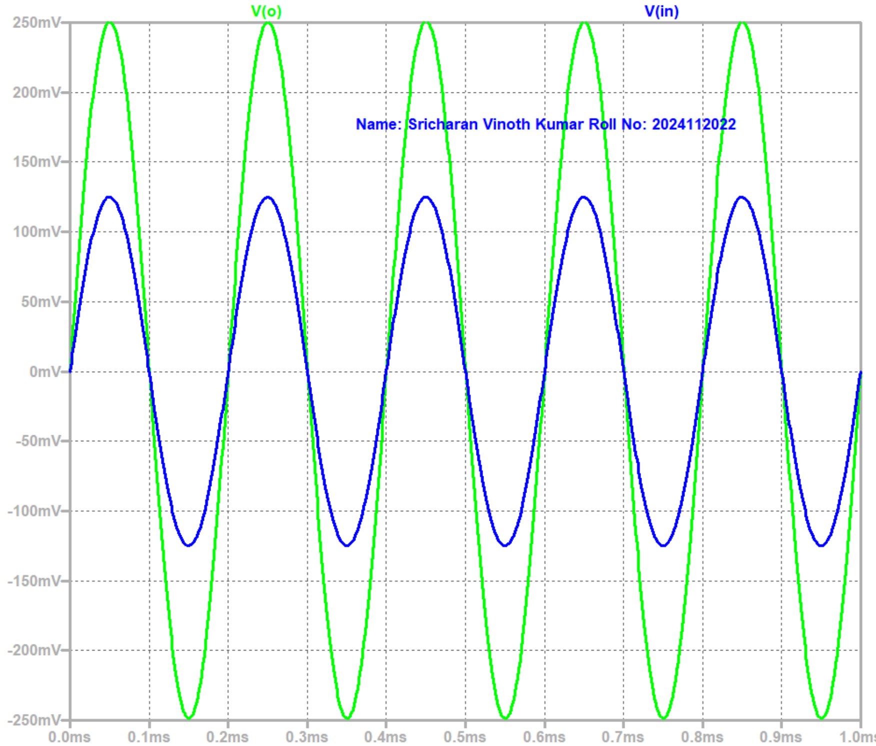


Figure 3.4.2: Plot of v_{in}(Blue) and v_{out}(Green) vs time at $R_1 = R_2 = 10k\Omega$

```
Vp: MAX(V(o))=0.250437216588 FROM 0.0006 TO 0.001
Vd: MIN(V(o))=-0.248835107981 FROM 0.0006 TO 0.001
Vo: Vp-Vd=0.49927232457
```

Figure 3.4.3: Measurement of Amplitude of v_{out}

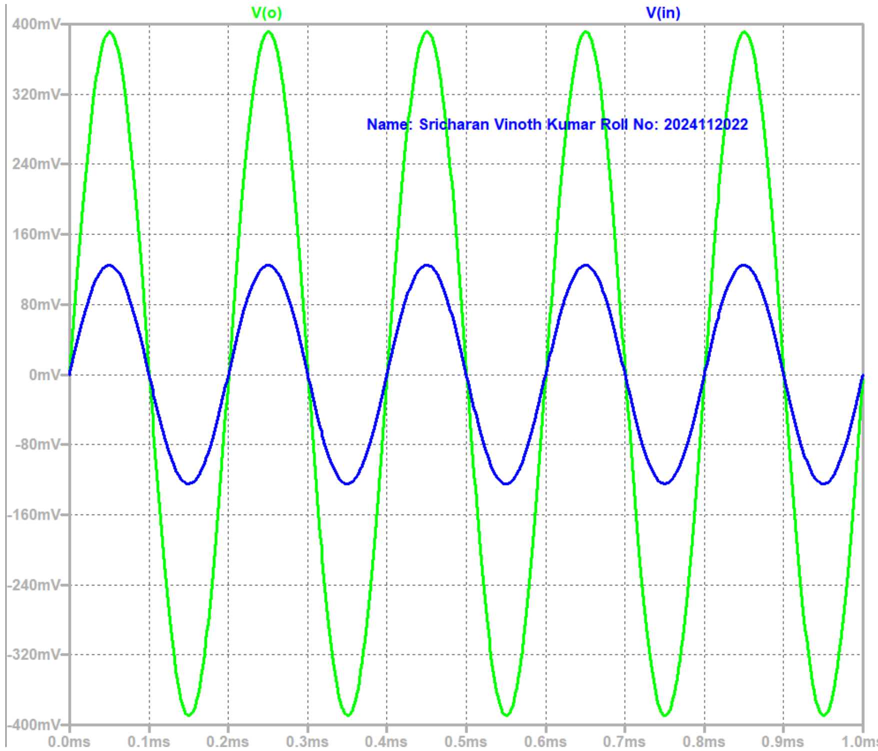


Figure 3.4.4: Plot of v_{in}(Blue) and v_{out}(Green) vs time at $R_1 = 10k\Omega, R_2 = 4.7k\Omega$

```
Vp: MAX(V(o))=0.39123942599 FROM 0.0006 TO 0.001
Vd: MIN(V(o))=-0.389620878386 FROM 0.0006 TO 0.001
Vo: Vp-Vd=0.780860304376
```

Figure 3.4.5: Measurement of Amplitude of v_{out}

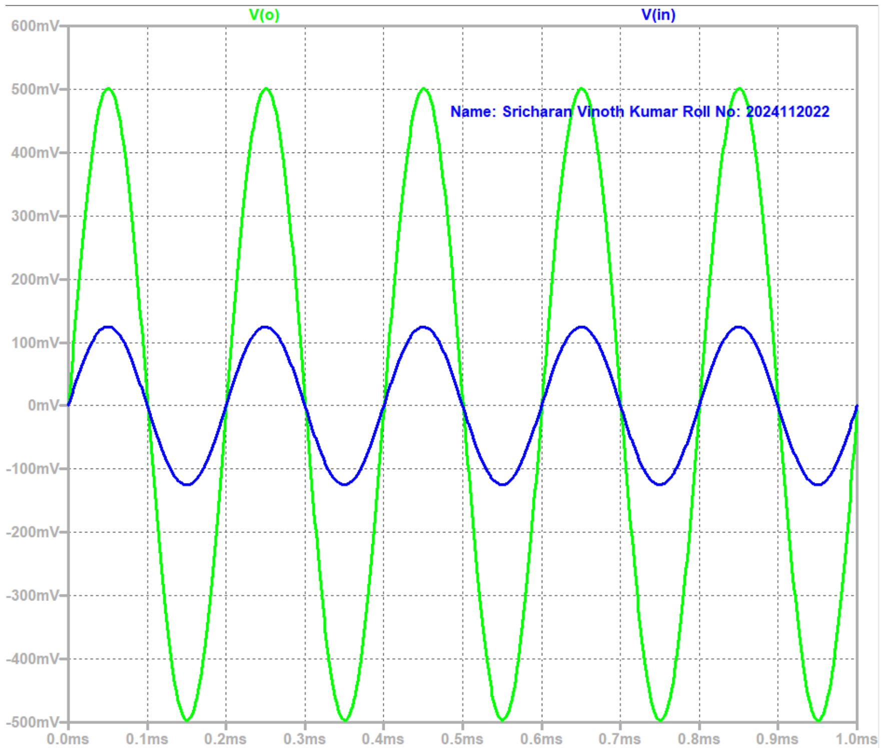


Figure 3.4.6: Plot of v_{in}(Blue) and v_{out}(Green) vs time for Expected Gain = 4

```
Vp: MAX(V(o))=0.501705982168 FROM 0.0006 TO 0.001
Vd: MIN(V(o))=-0.496874362784 FROM 0.0006 TO 0.001
Vo: Vp-Vd=0.998580344952
```

Figure 3.4.7: Measurement of Amplitude of v_{out}

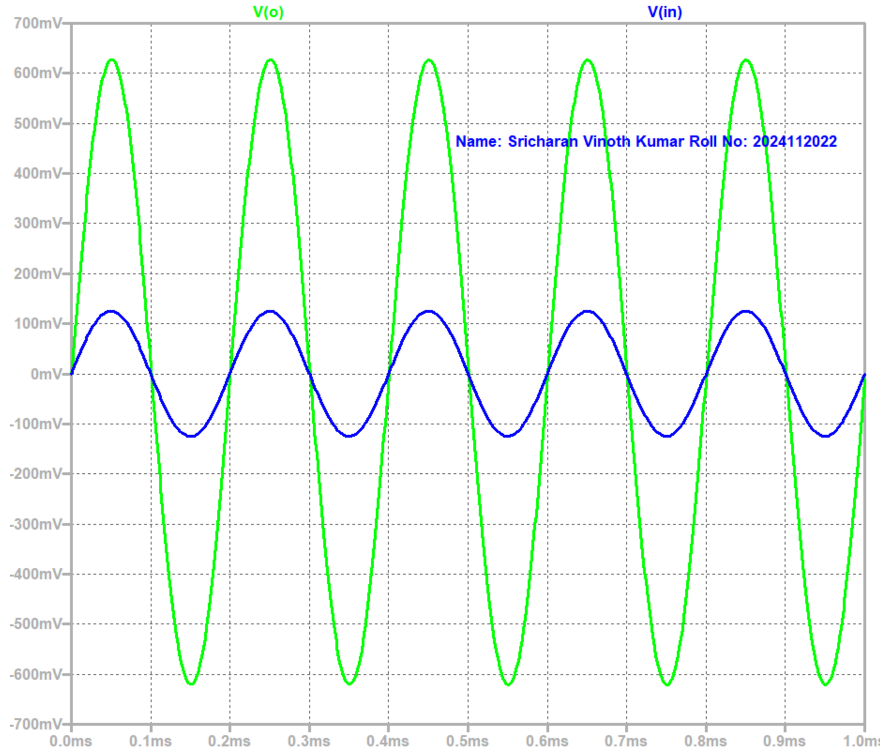


Figure 3.4.8: Plot of v_{in}(Blue) and v_{out}(Green) vs time for Expected Gain = 5

```
Vp: MAX(V(o))=0.627396074804 FROM 0.0006 TO 0.001
Vd: MIN(V(o))=-0.62083900004 FROM 0.0006 TO 0.001
Vo: Vp-Vd=1.24823507484
```

Figure 3.4.9: Measurement of Amplitude of v_{out}

3.5 Observations

From Equation 3.4.1, we know that,

$$A_v = 1 + \frac{R_1}{R_2} \tag{3.5.1}$$

Observed Values:

R_1	R_2	v_{out}	Calculated Gain $= 1 + \frac{R_2}{R_1}$	Observed Gain
$10k\Omega$	$10k\Omega$	0.52	2	2.08
$10k\Omega$	$4.7k\Omega$	0.8	3.1276	3.2

Expected Gain	R_1	R_2	v_{out}	Observed Gain
4	$30k\Omega$	$10k\Omega$	1.05	4.2
5	$40k\Omega$	$10k\Omega$	1.29	5.16

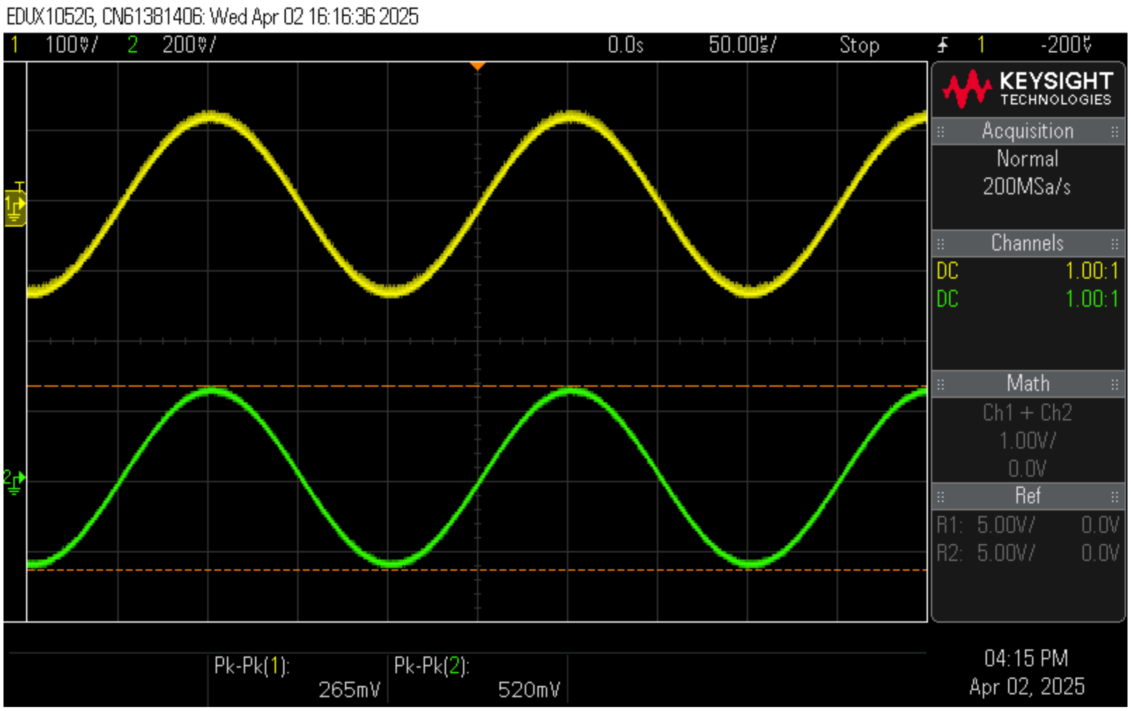


Figure 3.5.1: Response of v_{out} at $R_1 = R_2 = 10k\Omega$

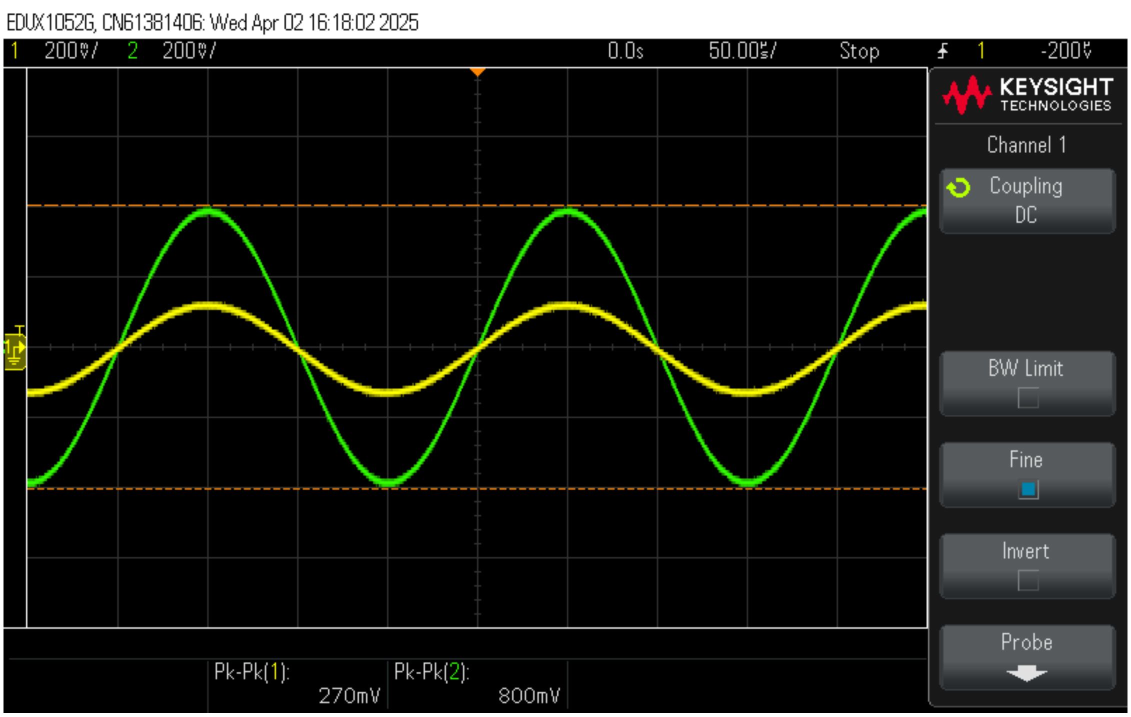


Figure 3.5.2: Response of v_{out} at $R_1 = 10k\Omega, R_2 = 4.7k\Omega$

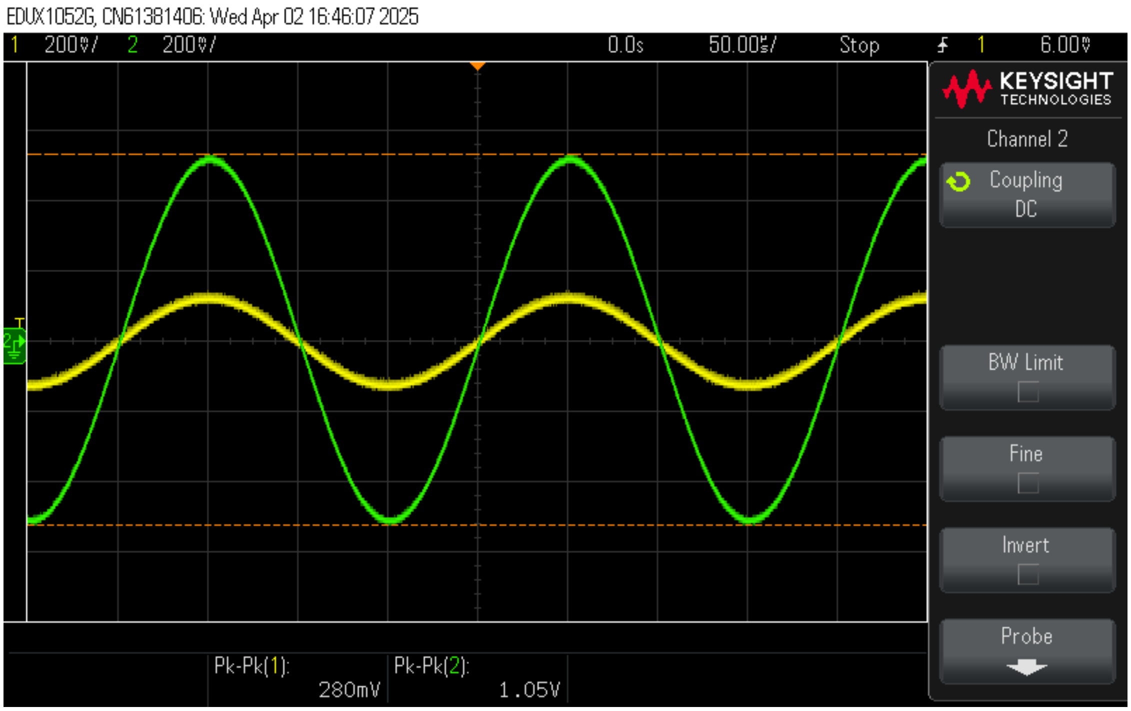


Figure 3.5.3: Response of v_{out} at Expected Gain = 4

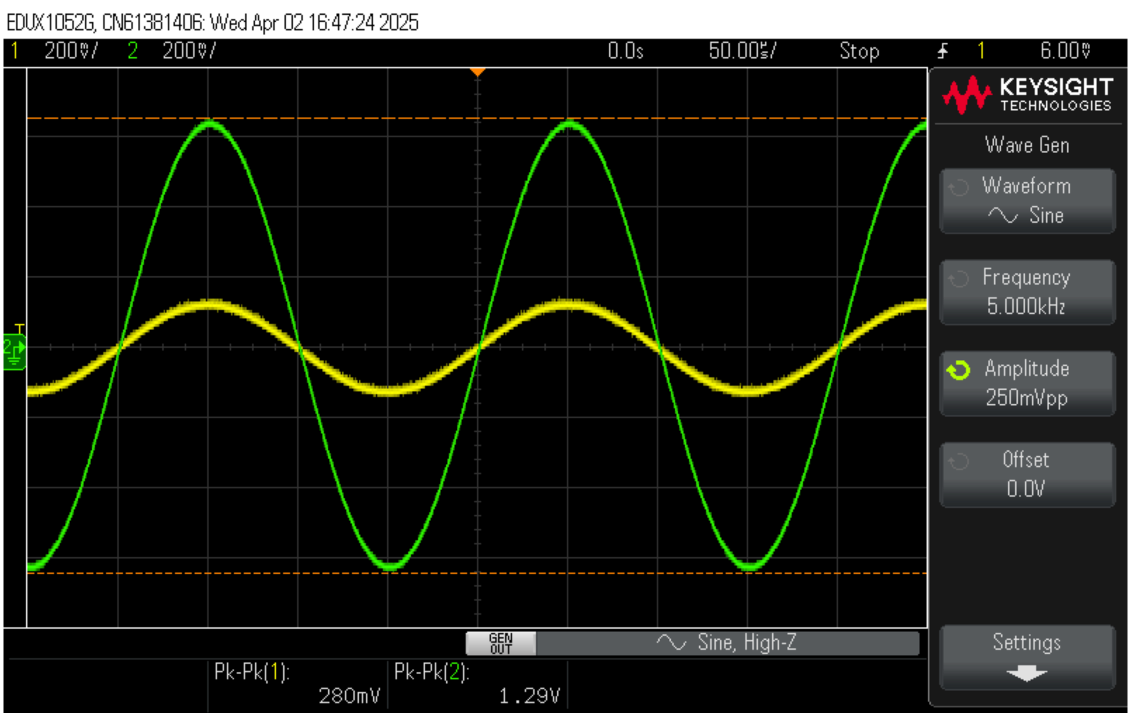


Figure 3.5.4: Response of v_{out} at Expected Gain = 5

3.6 Questions Asked

What happens if we directly connect V_{out} to the Inverting terminal directly?
If that connection happens, the Op-Amp will be in Negative feedback mode. Since, in negative feedback, the voltage at the Output terminal will try to match the voltage in the Inverting terminal. Therefore,

$$v_{out} = v_{in} \implies Gain = 1$$

Negative feedback is used to stabilize the signal, and make it less sensitive to changes in external factors.

4 Inverting Amplifier

4.1 Objective

To construct and analyze the working and gain of an Op-Amp based Inverting Amplifier

4.2 Circuit Diagram

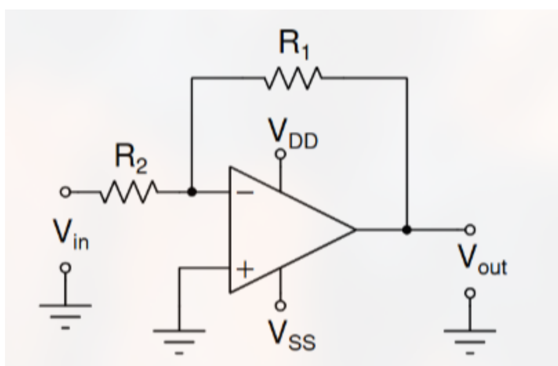


Figure 4.2.1: Circuit Diagram of an Inverting Amplifier

4.3 Common Parameters Used

- $V_{DD} = 12V$
- $V_{SS} = -12V$
- $v_{in} = 250mV peak\ to\ peak,\ 5kHz\ frequency$

4.4 LTSpice Simulation

To derive an expression for the Gain of the Amplifier, We know that for an Op-Amp in Negative feedback,

$$\begin{aligned} V_- &= V_+ \\ \implies V_- &= 0 \\ \implies \frac{v_{out}}{R_1} &= -\frac{v_{in}}{R_2} \\ \therefore A_v &= -\frac{R_1}{R_2} \end{aligned} \tag{4.4.1}$$

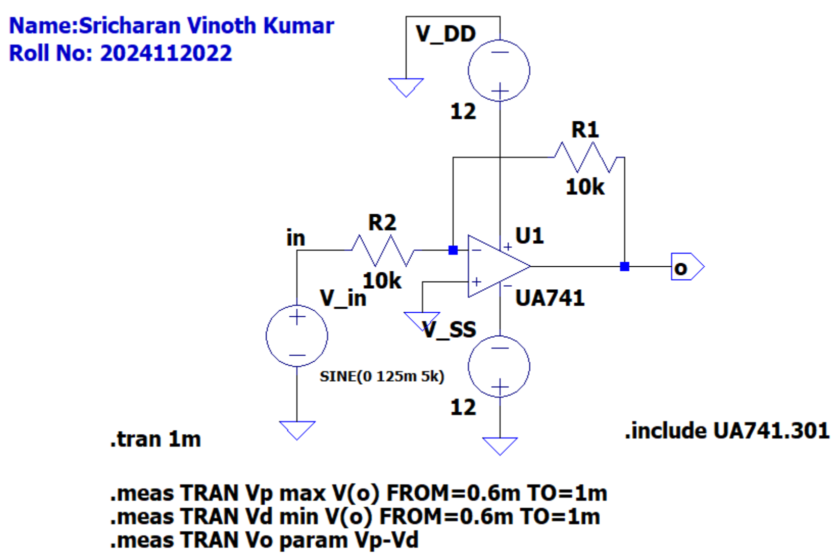


Figure 4.4.1: LTSpice Schematic Of an Inverting Amplifier

Observed Values:

R_1	R_2	v_{out}	Calculated Gain = -$\frac{R_1}{R_2}$	Observed Gain
$10k\Omega$	$10k\Omega$	-0.24978V	-1	-0.99912
$10k\Omega$	$4.7k\Omega$	-0.53145V	-2.12765	-2.1258

Expected Gain	R_1	R_2	v_{out}	Observed Gain
4	$40k\Omega$	$10k\Omega$	-0.99926	-3.99704
5	$50k\Omega$	$10k\Omega$	-1.24885	-4.9954

Values are negative due to the inverted nature of the output

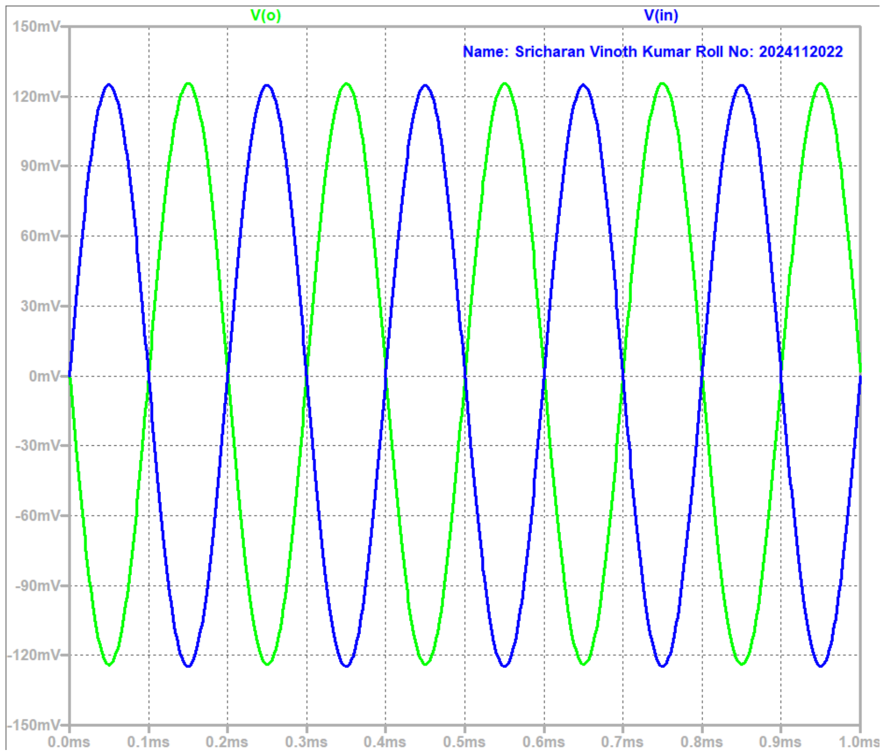


Figure 4.4.2: Plot of v_{in}(Blue) and v_{out}(Green) vs time at $R_1 = R_2 = 10k\Omega$

```
Vp: MAX(V(o))=0.125698358367 FROM 0.0006 TO 0.001
Vd: MIN(V(o))=-0.124083823676 FROM 0.0006 TO 0.001
Vo: Vp-Vd=0.249782182043
```

Figure 4.4.3: Measurement of Amplitude of v_{out}

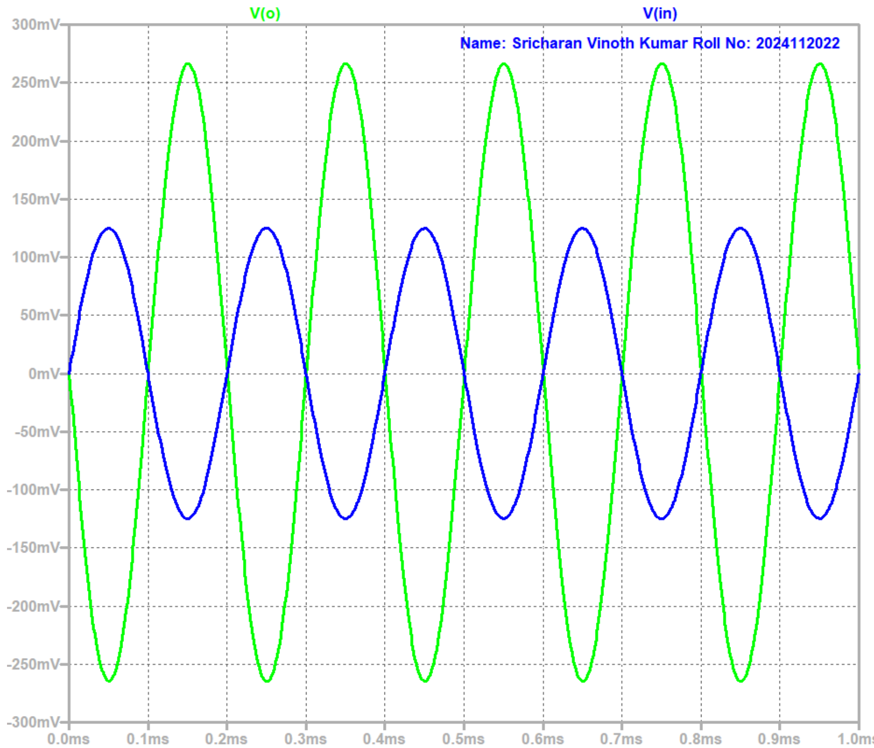


Figure 4.4.4: Plot of v_{in}(Blue) and v_{out}(Green) vs time at $R_1 = 10k\Omega, R_2 = 4.7k\Omega$

```
Vp: MAX(V(o))=0.266523515405 FROM 0.0006 TO 0.001
Vd: MIN(V(o))=-0.264932723125 FROM 0.0006 TO 0.001
Vo: Vp-Vd=0.53145623853
```

Figure 4.4.5: Measurement of Amplitude of v_{out}

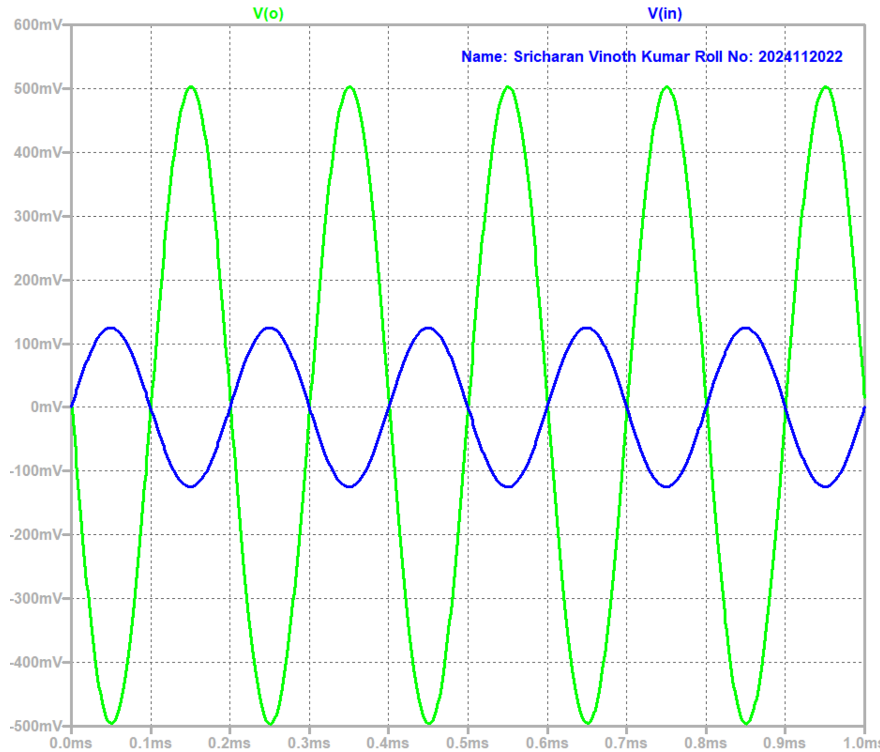


Figure 4.4.6: Plot of v_{in}(Blue) and v_{out}(Green) vs time for Expected Gain = 4

```
Vp: MAX(V(o))=0.5028528435 FROM 0.0006 TO 0.001
Vd: MIN(V(o))=-0.496515601873 FROM 0.0006 TO 0.001
Vo: Vp-Vd=0.999368445374
```

Figure 4.4.7: Measurement of Amplitude of v_{out}

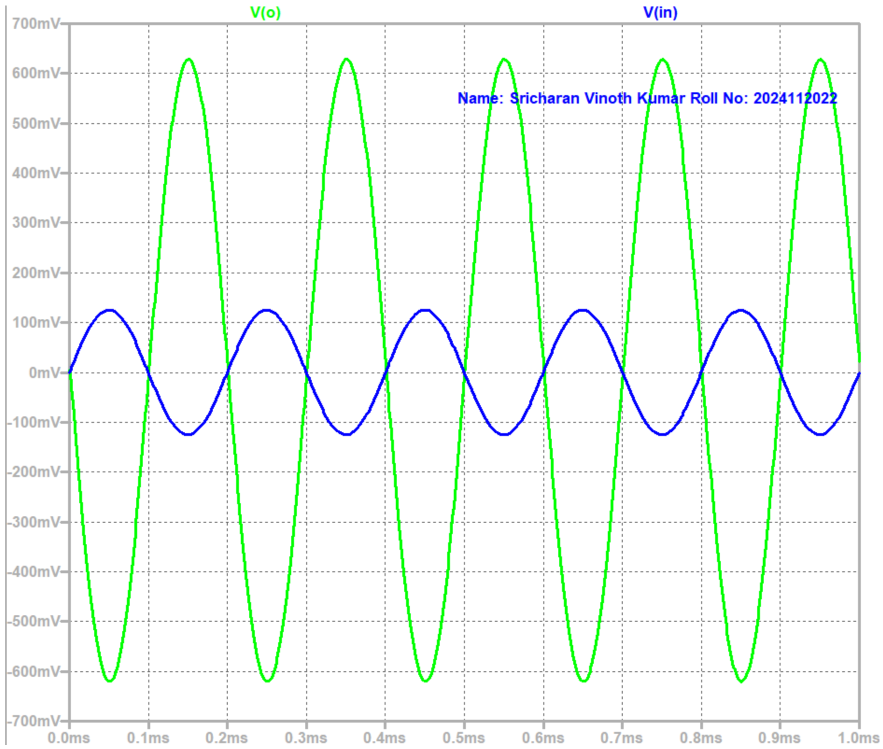


Figure 4.4.8: Plot of v_{in}(Blue) and v_{out}(Green) vs time for Expected Gain = 5

```
Vp: MAX(V(o))=0.628366259625 FROM 0.0006 TO 0.001
Vd: MIN(V(o))=-0.62048667507 FROM 0.0006 TO 0.001
Vo: Vp-Vd=1.2488529347
```

Figure 4.4.9: Measurement of Amplitude of v_{out}

4.5 Observations

From Equation 4.4.1, we know that,

$$A_v = -\frac{R_1}{R_2} \tag{4.5.1}$$

Observed Values:

R_1	R_2	v_{out}	Calculated Gain = -$\frac{R_1}{R_2}$	Observed Gain
$10k\Omega$	$10k\Omega$	-0.253	-1	-1.012
$10k\Omega$	$4.7k\Omega$	-0.535	-2.12765	-2.14

Expected Gain	R_1	R_2	v_{out}	Observed Gain
4	$40k\Omega$	$10k\Omega$	-1.04	-4.16
5	$50k\Omega$	$10k\Omega$	-1.28	-5.12

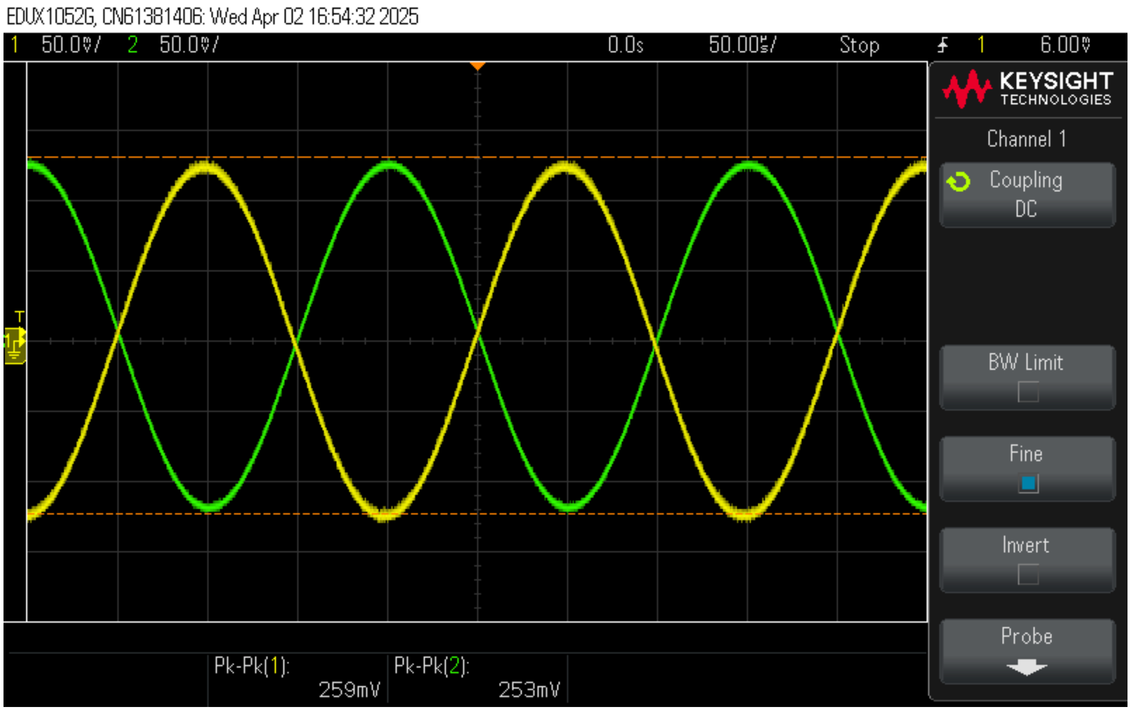


Figure 4.5.1: Response of v_{out} at $R_1 = R_2 = 10k\Omega$

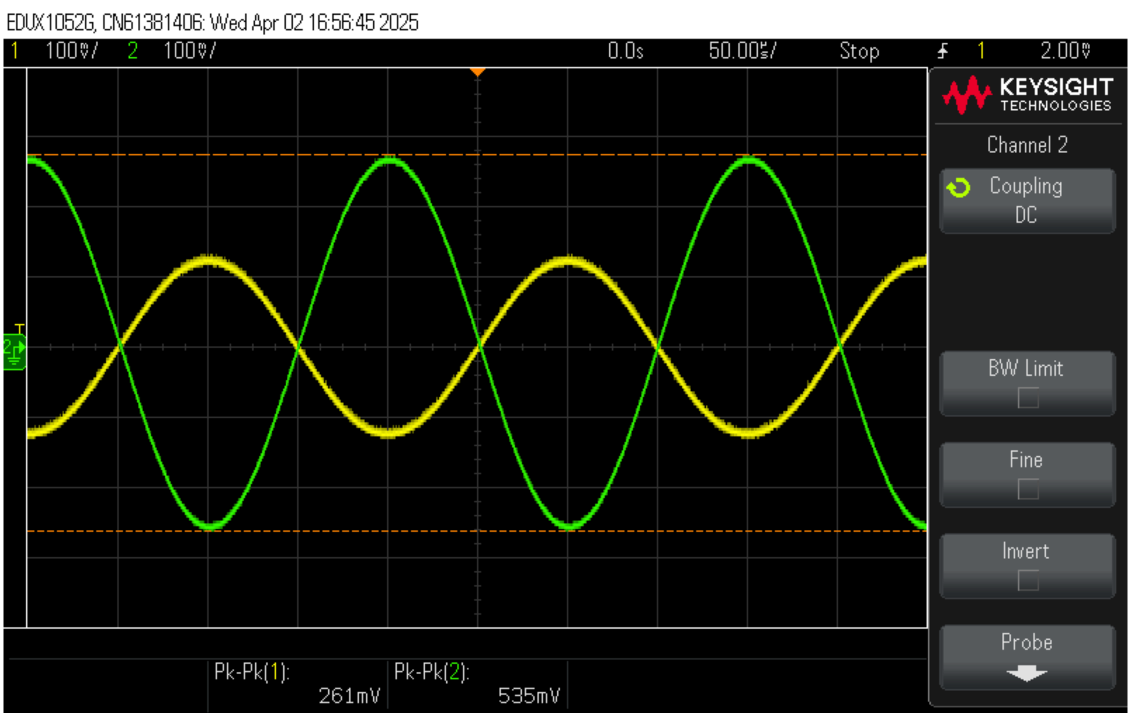


Figure 4.5.2: Response of v_{out} at $R_1 = 10k\Omega, R_2 = 4.7k\Omega$

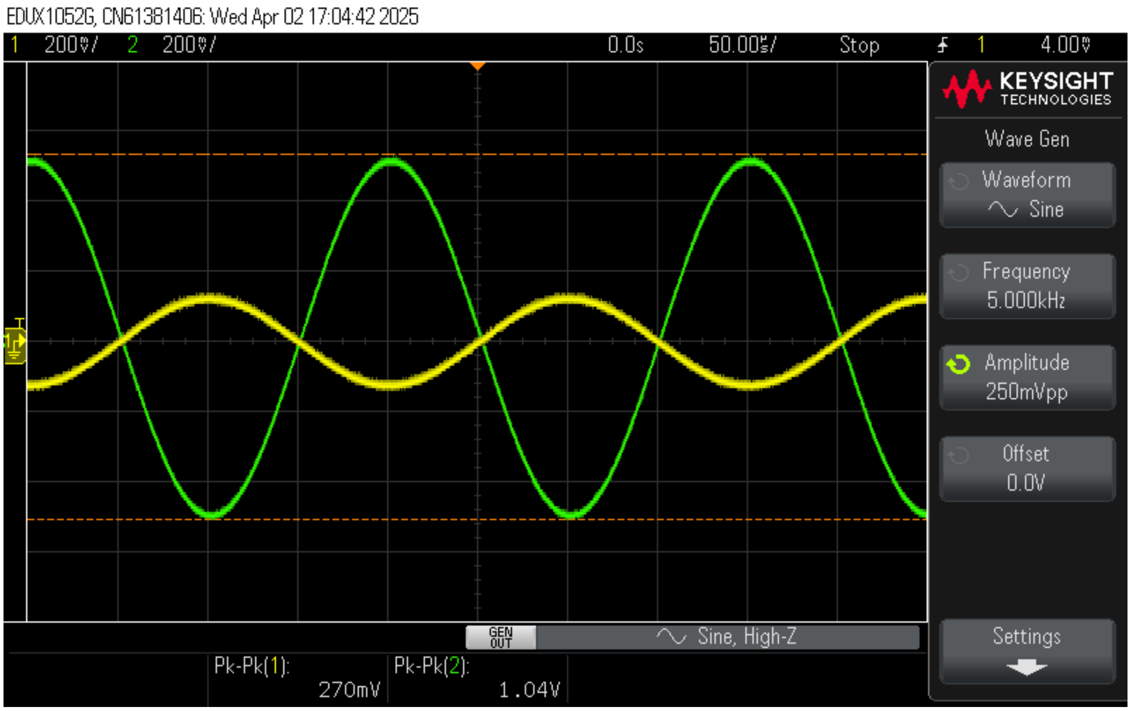


Figure 4.5.3: Response of v_{out} at Expected Gain = 4

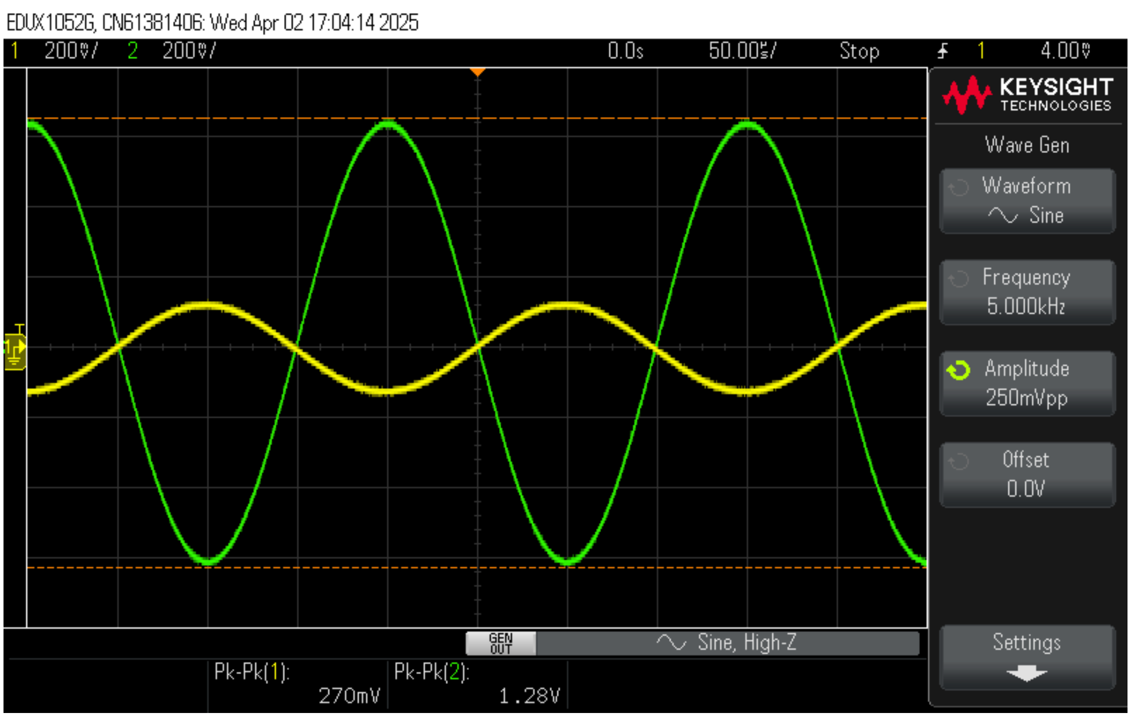


Figure 4.5.4: Response of v_{out} at Expected Gain = 5