Julia Frothingham

Lab 14

Figure 1. Wiring specifications for a non-inverting amplifier.

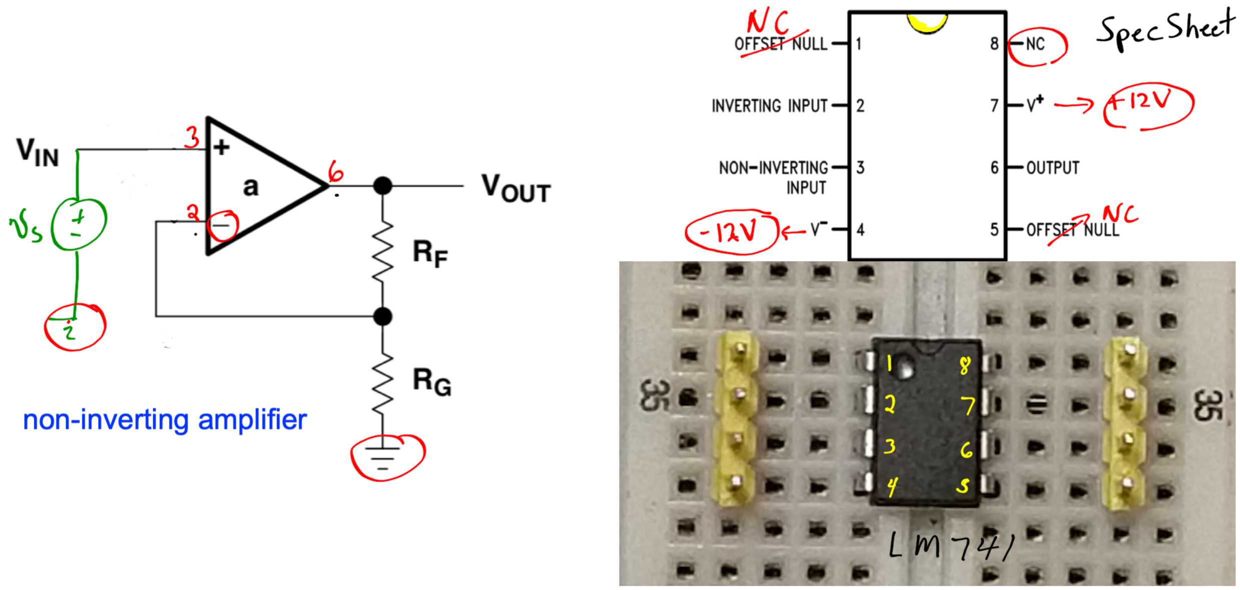
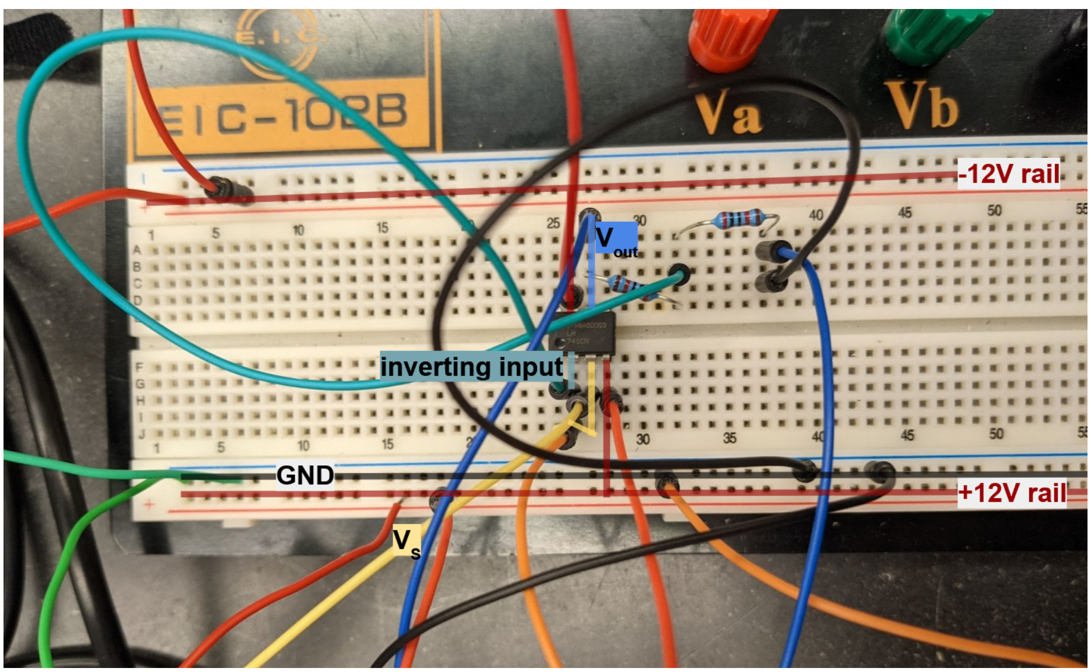


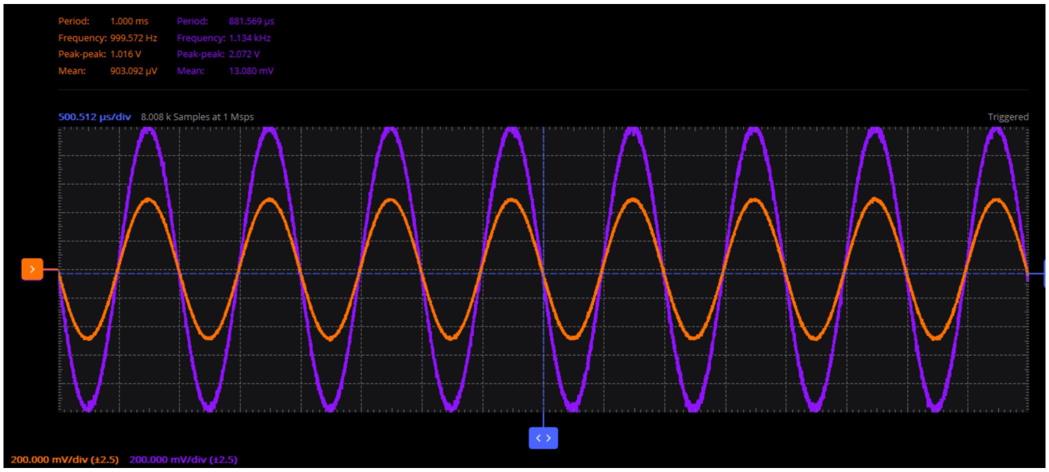
Figure 2. Built circuit for a non-inverting amplifier.



Gain ≅ 2; **$R_F = R_G = 20k\Omega$;** **V_S = 1V p-p sine wave at 1kHz**

Channel 1 of Scopy's wave generator was used to supply a source voltage V_S. Channel 1 of Scopy's oscilloscope (orange wires) was used to measure V_S. Channel 2 of Scopy's oscilloscope (blue wires) was used to measure V_{out}.

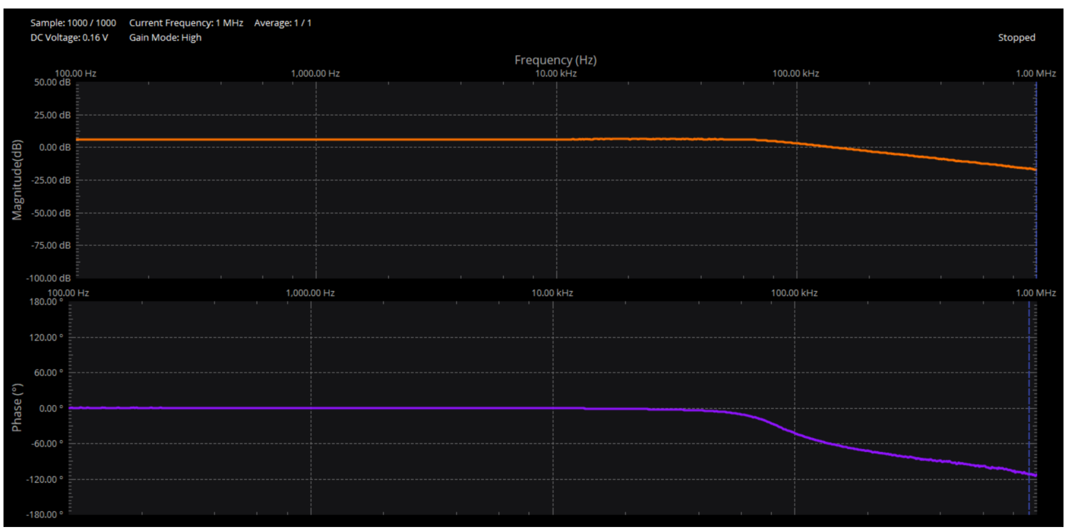
Figure 3. V_S (orange) and V_{out} (purple) over time. Gain=2.



This looks as would be expected from a non-inverting op amp with a gain of 2. The output voltage is approximately twice the amplitude of the input voltage, and the two voltages are in phase with each other.

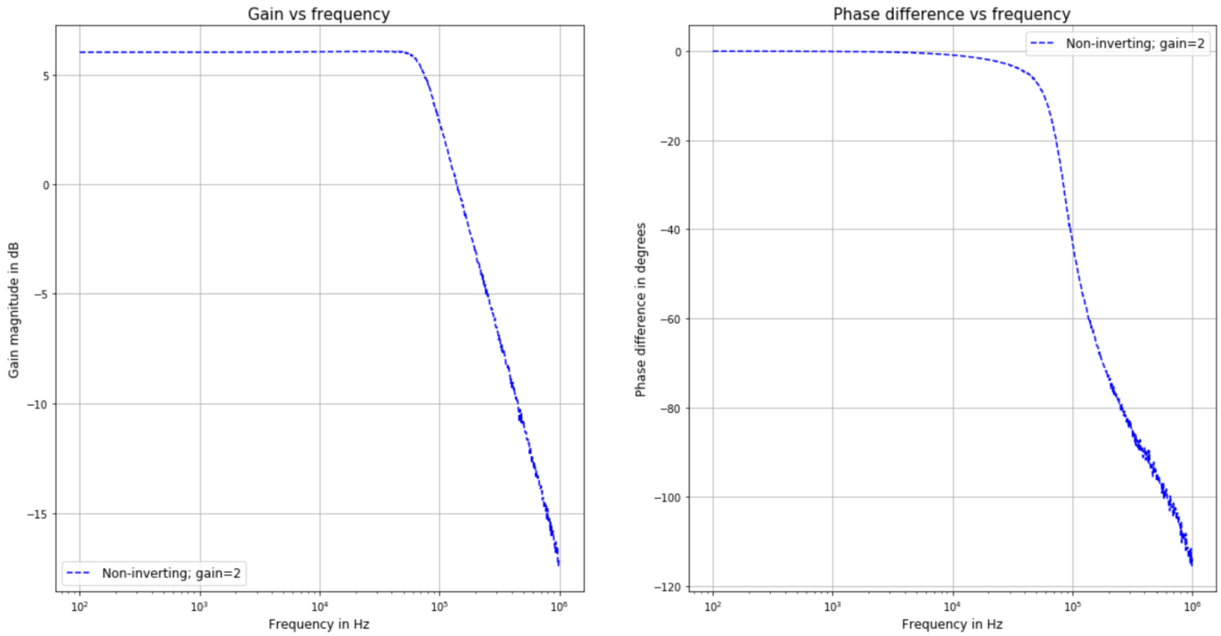
Scopy's network analyzer revealed that the circuit response is essentially identical for most low frequencies. However, the response changes at higher frequencies.

Figure 4. Measured frequency response 100Hz to 1MHz with Scopy network analyzer.



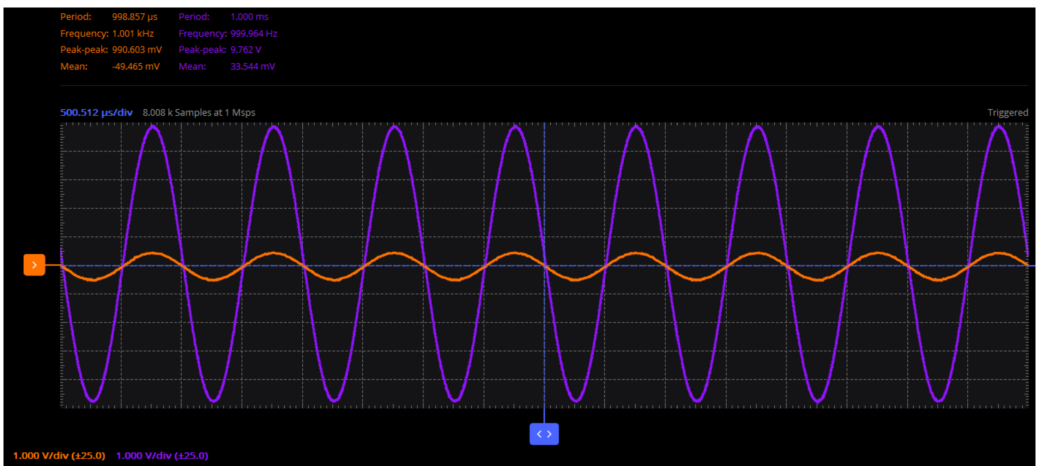
Plotting the gain and phase difference in Python shows the same pattern.

Figure 5. Gain and phase difference vs frequency.



Changing the resistance values in the circuit changes the gain. Building an op amp circuit for which $R_F \cong 91k\Omega$ and $R_G \cong 10k\Omega$ produces a gain of 10.

Figure 6. V_S (orange) and V_{out} (purple) over time. Gain=10.



This looks as would be expected from a non-inverting op amp with a gain of 10. The output voltage is approximately ten times the amplitude of the input voltage, and the two voltages are in phase with each other.

Scopy's network analyzer revealed that the circuit response is essentially identical for most low frequencies. However, the response changes at higher frequencies.

Figure 7. Measured frequency response 100Hz to 1MHz with Scopy network analyzer.

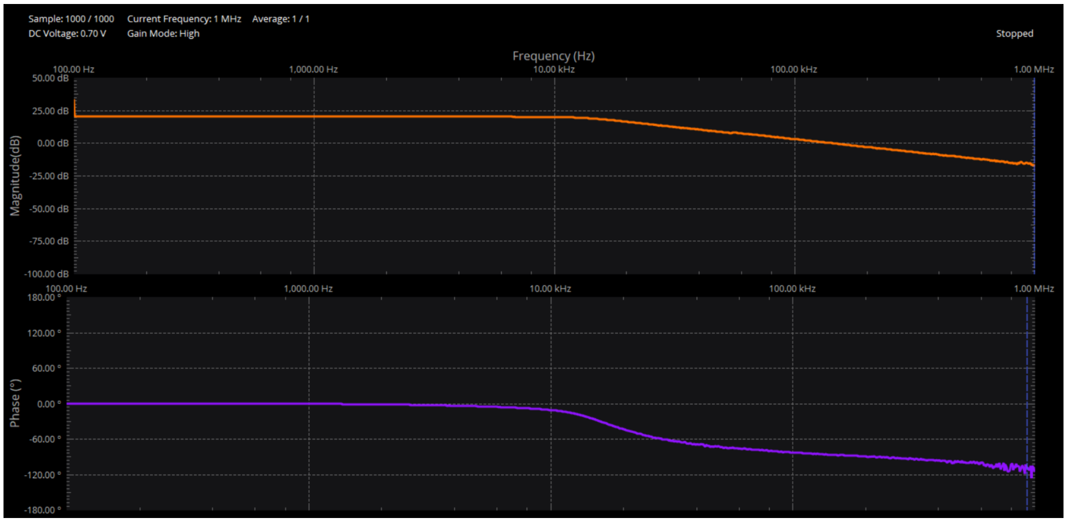
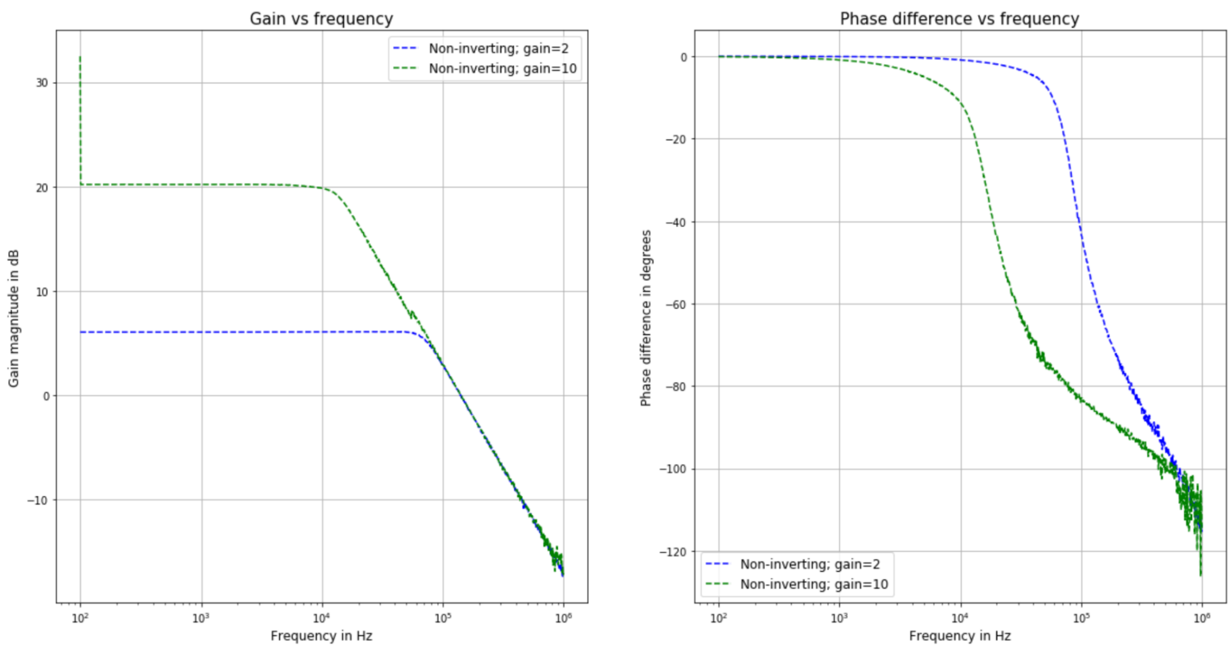


Figure 8. Gain and phase difference vs frequency.



The python plots of the non-inverting op amps with different gains show the same general trends. The gain vs frequency plot shows constant gain values for low frequencies, then decreasing gain for higher frequencies. On a logarithmic scale, the region of decrease is linear. The frequency at which the decrease occurs is lower for the circuit with higher gain, but the rate of decrease is the same for each circuit, and the decreasing gain response appears almost identical at high frequencies (greater than about 10^5 Hz). On the phase difference vs frequency plot, both circuits display a phase difference of 0 degrees at low frequencies and then decrease. The circuit with higher gain displays decreasing phase difference at lower frequency. The change in phase difference occurs about 1KHz before the change in gain for each circuit.

Figure 9. Python code to calculate the gain-bandwidth product.

```
# GAIN-BANDWIDTH PRODUCT CALCULATIONS

# figure out gain in flat portion and convert to ratio
print('GAIN IN FLAT PORTION')

g2length = int(np.size(g2mag)/2)
g2_flat = np.average(g2mag[0:g2length])
g2flat_ratio = 10**(g2_flat/20)
print('Non-inverting; gain=2 --> flat =', g2flat_ratio)

g10length = int(np.size(g10mag)/2)
g10_flat = np.average(g10mag[0:g10length])
g10flat_ratio = 10**(g10_flat/20)
print('Non-inverting; gain=10 --> flat =', g10flat_ratio)

ig10length = int(np.size(ig10mag)/2)
ig10_flat = np.average(ig10mag[0:ig10length])
ig10flat_ratio = 10**(ig10_flat/20)
print('Inverting; gain=10 --> flat =', ig10flat_ratio)
print('\n')

# find bandwidth
# bandwidth is the frequency at which the gain falls to 3db below the flat region
print('BANDWIDTH')

g2_threshold = g2_flat - 3
g2_bw_index = np.asarray(np.where(np.abs(g2mag - g2_threshold) < 0.095))
g2_bw = float(g2freq[g2_bw_index[[0]]])
print('Non-inverting; gain=2 --> bandwidth =', g2_bw, 'Hz')

g10_threshold = g10_flat - 3
g10_bw_index = np.asarray(np.where(np.abs(g10mag - g10_threshold) < 0.09))
g10_bw = float(g10freq[g10_bw_index[[0]]])
print('Non-inverting; gain=10 --> bandwidth =', g10_bw, 'Hz')

ig10_threshold = ig10_flat - 3
ig10_bw_index = np.asarray(np.where(np.abs(ig10mag - ig10_threshold) < 0.04))
ig10_bw = float(ig10freq[ig10_bw_index[[0]]])
print('Inverting; gain=10 --> bandwidth =', ig10_bw, 'Hz')
print('\n')

# calculate gain-bandwidth product
print('GAIN-BANDWIDTH PRODUCT')

g2_gbp = g2flat_ratio * g2_bw
print('Non-inverting; gain=2 --> gain-bandwidth product =', np.round(g2_gbp,2), 'Hz')

g10_gbp = g10flat_ratio * g10_bw
print('Non-inverting; gain=10 --> gain-bandwidth product =', np.round(g10_gbp,2), 'Hz')

ig10_gbp = ig10flat_ratio * ig10_bw
print('Inverting; gain=10 --> gain-bandwidth product =', np.round(ig10_gbp,2), 'Hz')
print('\n')

avg_gbp = (g2_gbp + g10_gbp + ig10_gbp)/3
print('AVERAGE GAIN-BANDWIDTH PRODUCT =', np.round(avg_gbp,2), 'Hz')
```

Figure 10. Calculated gain, bandwidth, and gain-bandwidth products.

```
GAIN IN FLAT PORTION
Non-inverting; gain=2 --> flat = 2.0044698673275776
Non-inverting; gain=10 --> flat = 10.214068591780174
Inverting; gain=10 --> flat = 9.219885124942309


BANDWIDTH
Non-inverting; gain=2 --> bandwidth = 97947.0 Hz
Non-inverting; gain=10 --> bandwidth = 17957.8 Hz
Inverting; gain=10 --> bandwidth = 19511.5 Hz


GAIN-BANDWIDTH PRODUCT
Non-inverting; gain=2 --> gain-bandwidth product = 196331.81 Hz
Non-inverting; gain=10 --> gain-bandwidth product = 183422.2 Hz
Inverting; gain=10 --> gain-bandwidth product = 179893.79 Hz


AVERAGE GAIN-BANDWIDTH PRODUCT = 186549.27 Hz
```

Figure 11. Percent difference calculations.

```python
# percent difference in gain-bandwidth product between non-inverting op amp circuits

percent_diff_noniverting = 100 * (np.abs(g2_gbp-g10_gbp)/g2_gbp)
percent_diff_noninverting2 = 100 * (np.abs(g2_gbp-g10_gbp)/g10_gbp)

print(np.round(percent_diff_noniverting,2),'percent difference from non-inverting gain=2')
print(np.round(percent_diff_noninverting2,2),'percent difference from non-inverting gain=10')
```

```
6.58 percent difference from non-inverting gain=2
7.04 percent difference from non-inverting gain=10
```

Figure 12. Wiring specifications for a non-inverting amplifier.

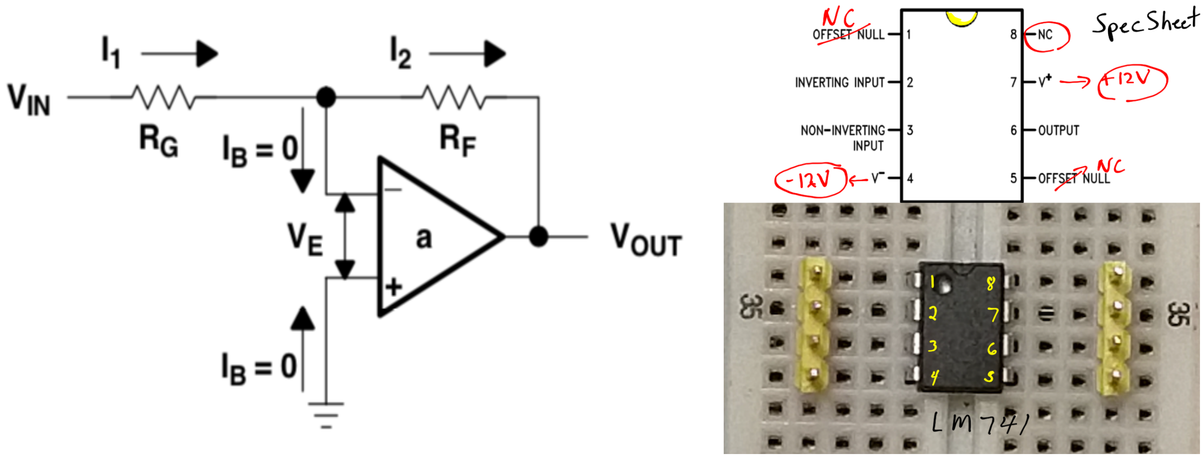
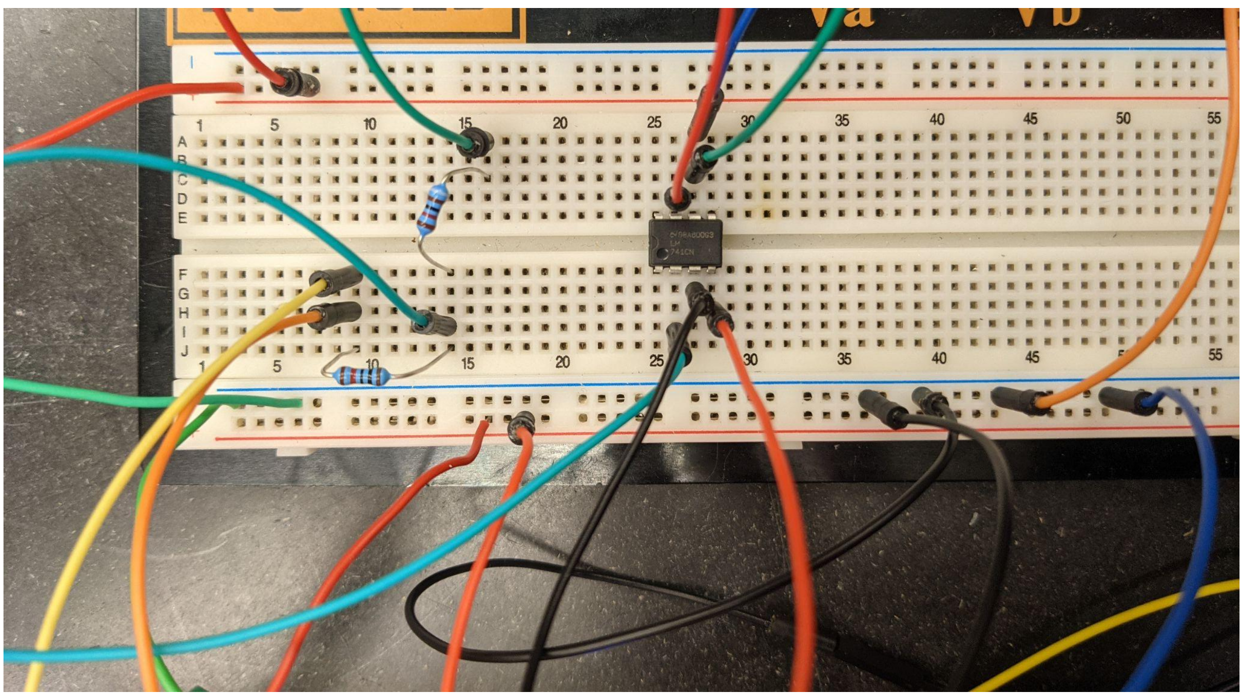


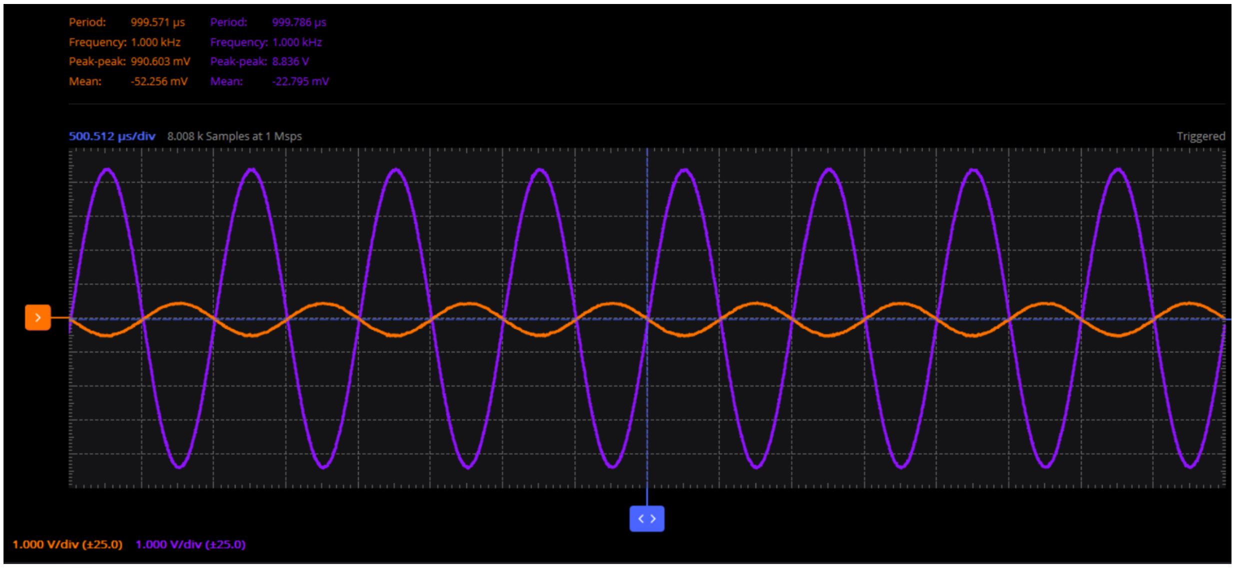
Figure 13. Built circuit for an inverting amplifier.



Gain ≅ 10; R_F ≅ 91kΩ and R_G ≅ 10kΩ; V_S = 1V p-p sine wave at 1kHz

Channel 1 of Scopy's wave generator was used to supply a source voltage V_S. Channel 1 of Scopy's oscilloscope (orange wires) was used to measure V_S. Channel 2 of Scopy's oscilloscope (blue wires) was used to measure V_{out}.

Figure 14. V_S (orange) and V_{out} (purple) over time. Gain=10.



This looks as would be expected from an inverting op amp with a gain of 10. The output voltage is approximately ten times the amplitude of the input voltage, and the two voltages are 180 degrees out of phase with each other.

Scopy's network analyzer revealed that the circuit response is essentially identical for most low frequencies. However, the response changes at higher frequencies.

Figure 15. Measured frequency response 100Hz to 1MHz with Scopy network analyzer.

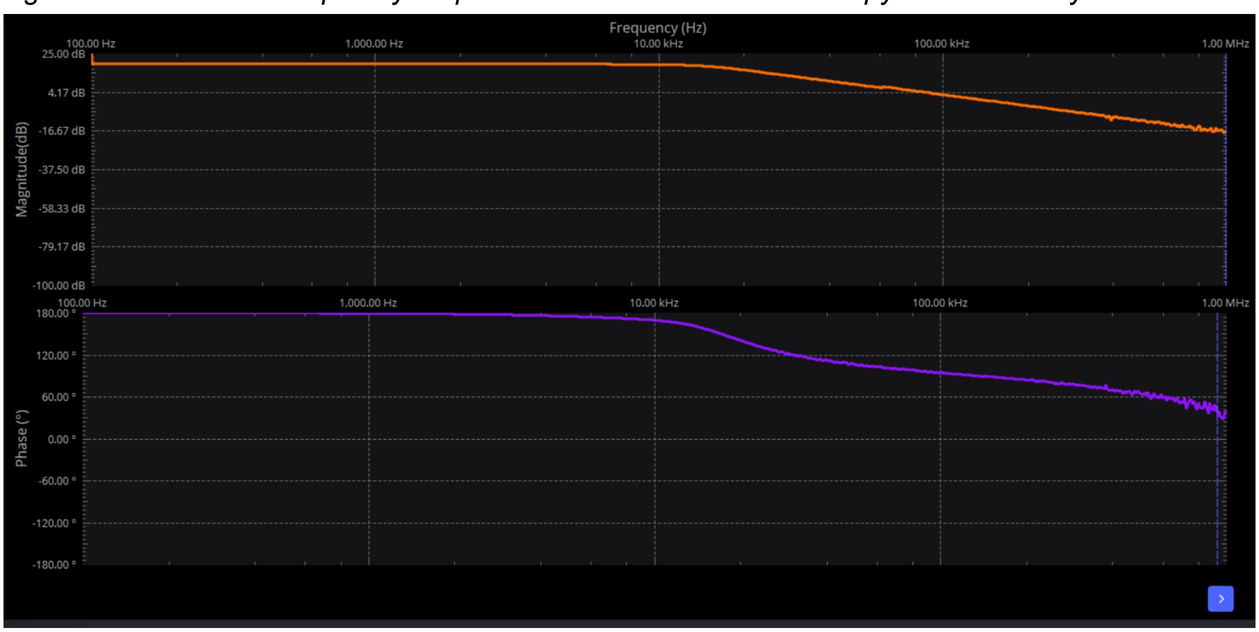
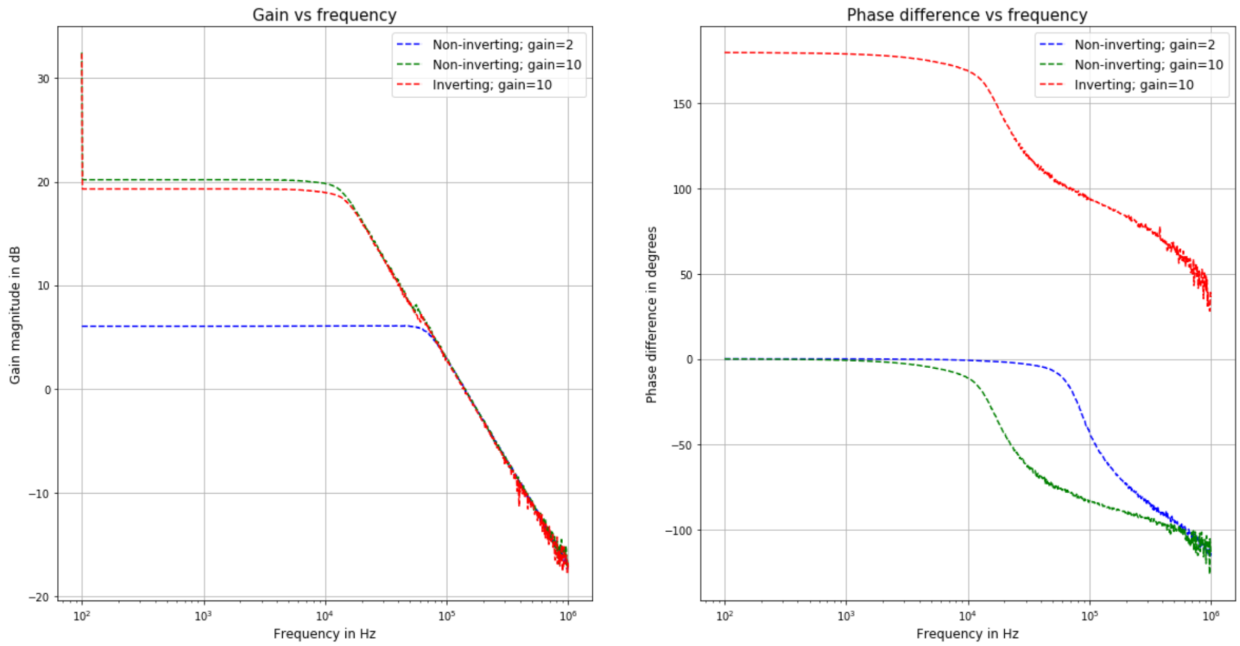


Figure 16. Gain and phase difference vs frequency.



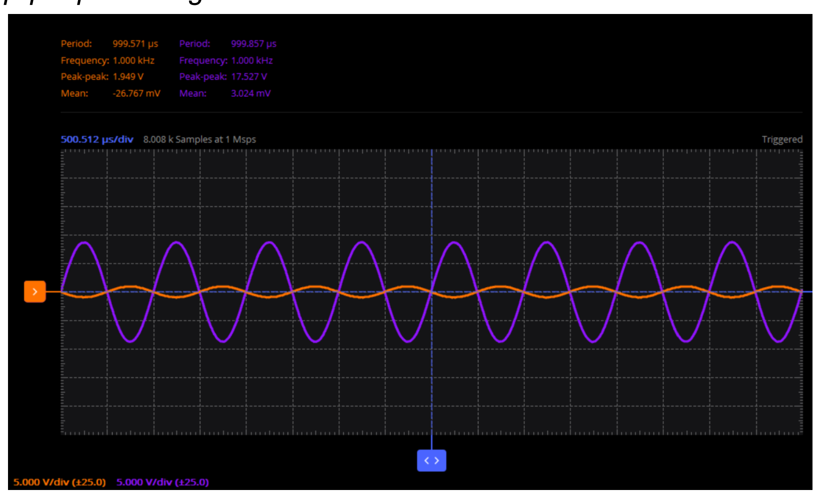
The inverting op amp circuit is very similar to the non-inverting op amp circuits in terms of gain vs frequency. The phase difference vs frequency for the inverting op amp circuit is very similar in shape to the plot for the non-inverting op amp circuit with the same gain, but with a vertical shift of 180 degrees.

Figure 16. (repeat of Figure 10).

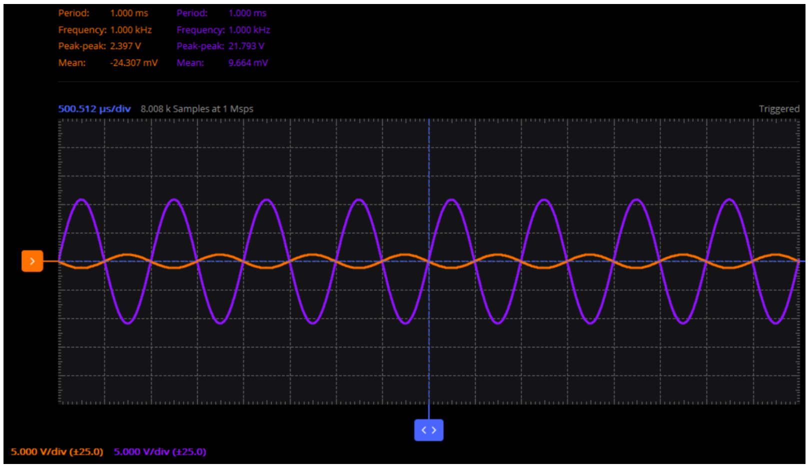
```
GAIN IN FLAT PORTION
Non-inverting; gain=2 --> flat = 2.0044698673275776
Non-inverting; gain=10 --> flat = 10.214068591780174
Inverting; gain=10 --> flat = 9.219885124942309


BANDWIDTH
Non-inverting; gain=2 --> bandwidth = 97947.0 Hz
Non-inverting; gain=10 --> bandwidth = 17957.8 Hz
Inverting; gain=10 --> bandwidth = 19511.5 Hz


GAIN-BANDWIDTH PRODUCT
Non-inverting; gain=2 --> gain-bandwidth product = 196331.81 Hz
Non-inverting; gain=10 --> gain-bandwidth product = 183422.2 Hz
Inverting; gain=10 --> gain-bandwidth product = 179893.79 Hz


AVERAGE GAIN-BANDWIDTH PRODUCT = 186549.27 Hz
```

Raising the amplitude of V_S can cause distortion in V_{out}. The distortion becomes noticeable for an input voltage with amplitude between 2.5V p-p and 2.7V p-p. The distortion flattens the rounded peaks of the sinusoids, starting with negative peaks. As the p-p amplitude increases, the effect becomes more noticeable.

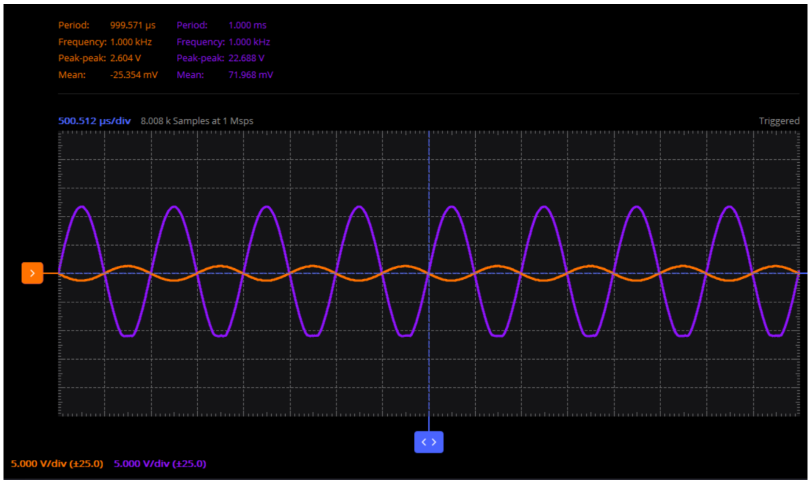
Figure 17. Oscilloscope plots of V_S (orange) and V_{out} (purple) over time for different amplitude p-p input voltages.



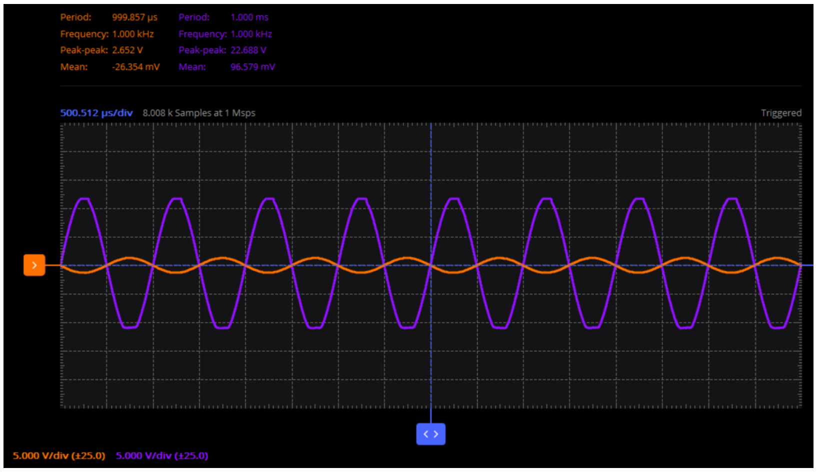
2V


Period: 1.000 ms
Frequency: 1.000 kHz
Peak-peak: 2.397 V
Mean: -24.307 mV
Period: 1.000 ms
Frequency: 1.000 kHz
Peak-peak: 21.793 V
Mean: 9.664 mV
500.512 µs/div
8.008 k Samples at 1 Msps
Triggered
5.000 V/div (±25.0)
5.000 V/div (±25.0)

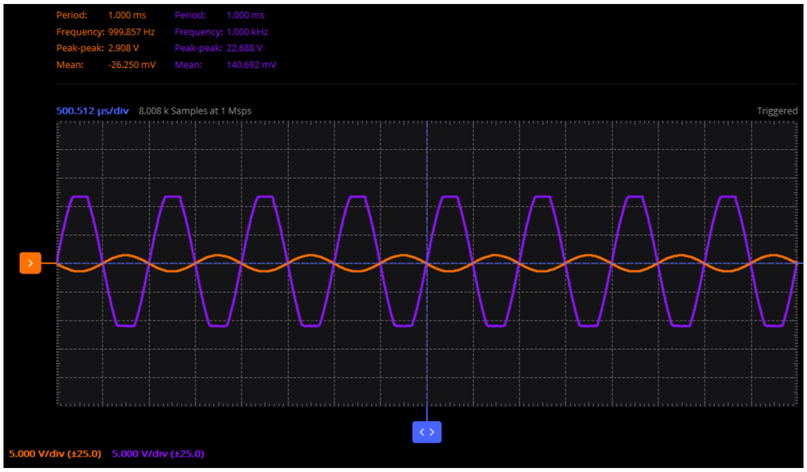
2.5V


Period: 999.571 µs
Frequency: 1.000 kHz
Peak-peak: 2.604 V
Mean: -25.354 mV
Period: 1.000 ms
Frequency: 1.000 kHz
Peak-peak: 22.688 V
Mean: 71.968 mV
500.512 µs/div
8.008 k Samples at 1 Msps
Triggered
5.000 V/div (±25.0)
5.000 V/div (±25.0)

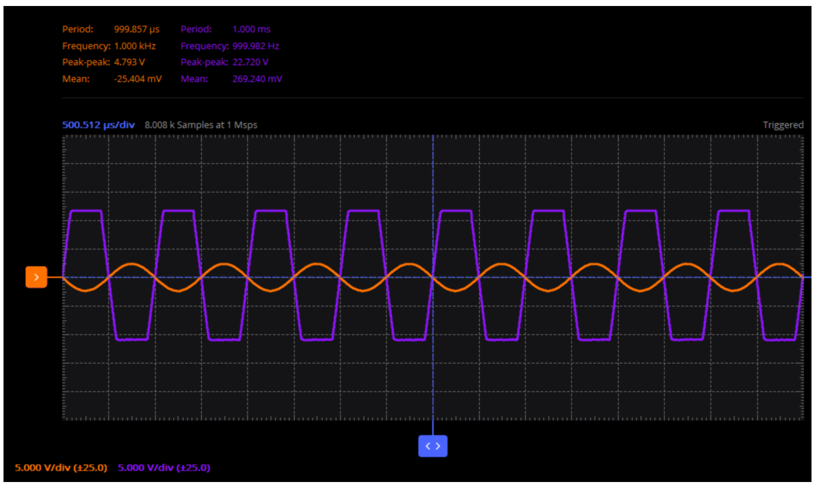
2.7V


Period: 999.857 µs
Frequency: 1.000 kHz
Peak-peak: 2.652 V
Mean: -26.354 mV
Period: 1.000 ms
Frequency: 1.000 kHz
Peak-peak: 22.688 V
Mean: 96.579 mV
500.512 µs/div
8.008 k Samples at 1 Msps
Triggered
5.000 V/div (±25.0)
5.000 V/div (±25.0)

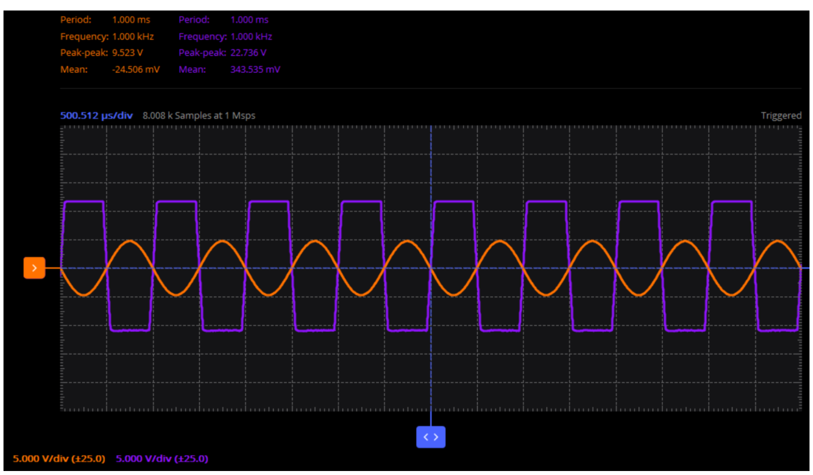
2.75V



3V



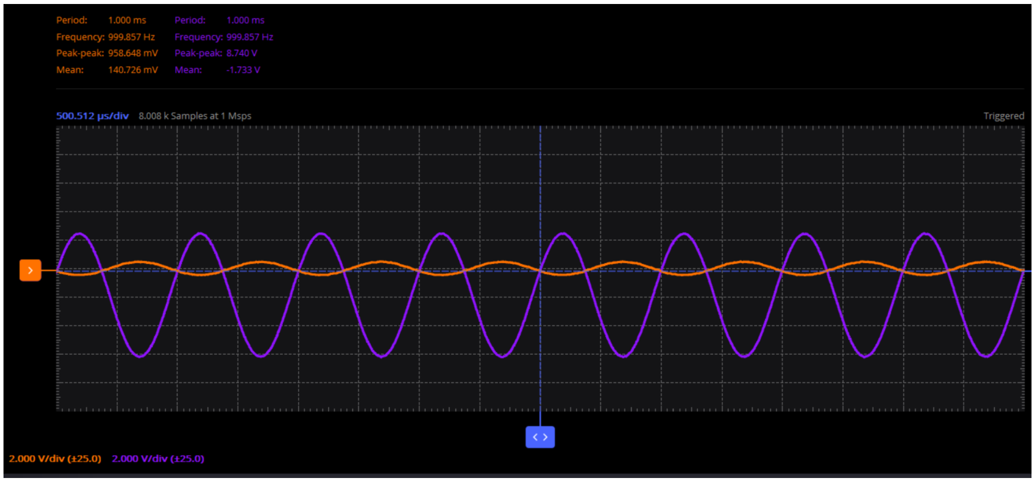
5V



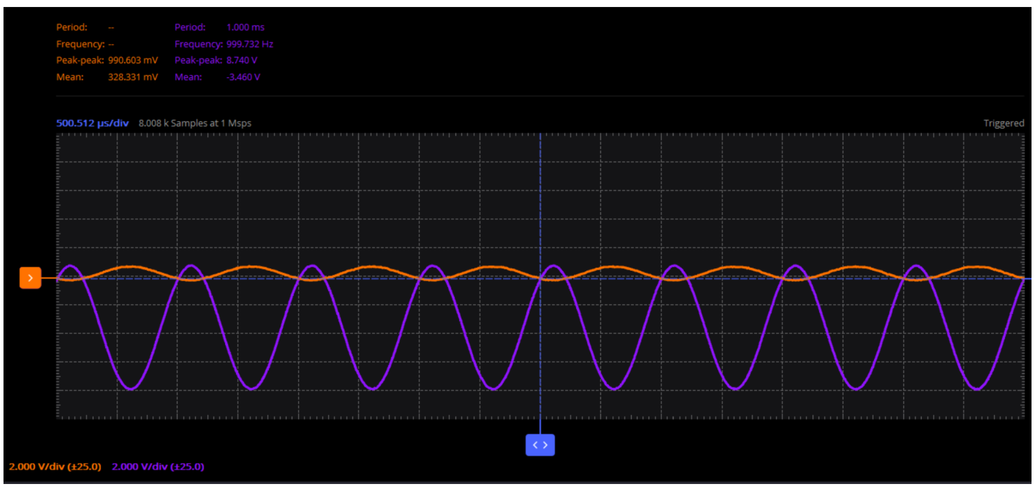
10V

Adding an offset to the input sine wave can also cause distortion. Offsets up to 500mV don't noticeably distort the output voltage, just shift it down. Offsets above 500mV begin to distort the output voltage by flattening the negative peaks until the signal looks like the output of a half-wave rectifier circuit.

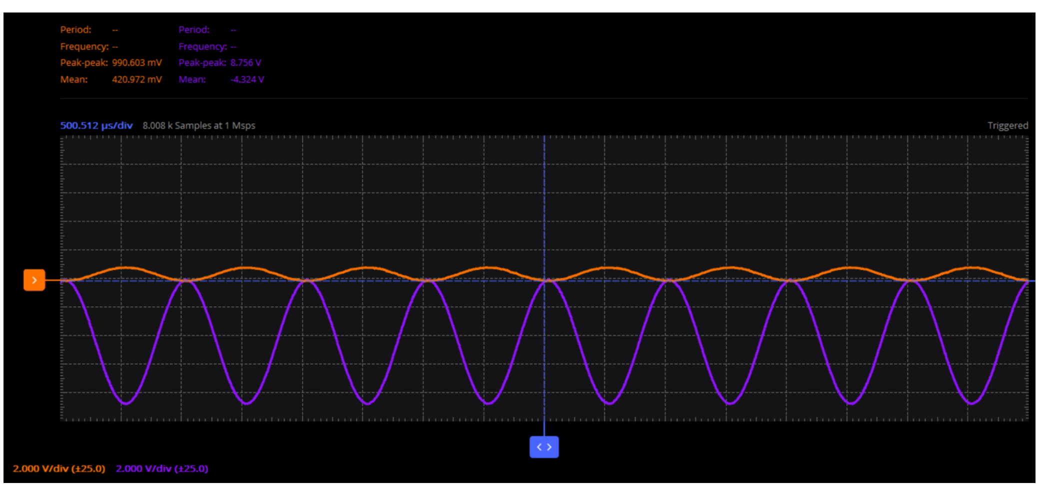
Figure 18. Oscilloscope plots and FFTs of V_S (orange) and V_{out} (purple) over time for different offsets applied to the input voltages.



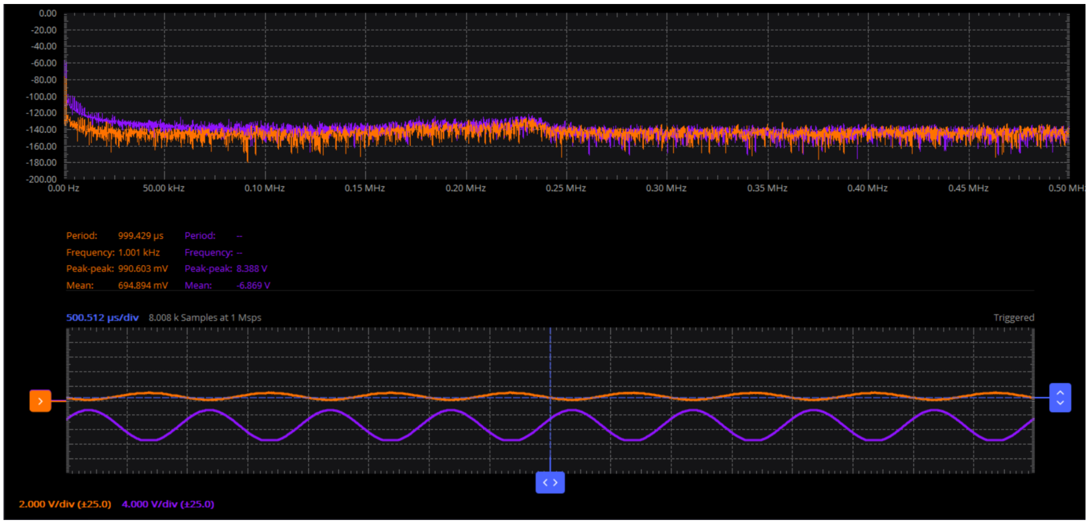
200mV



400mV

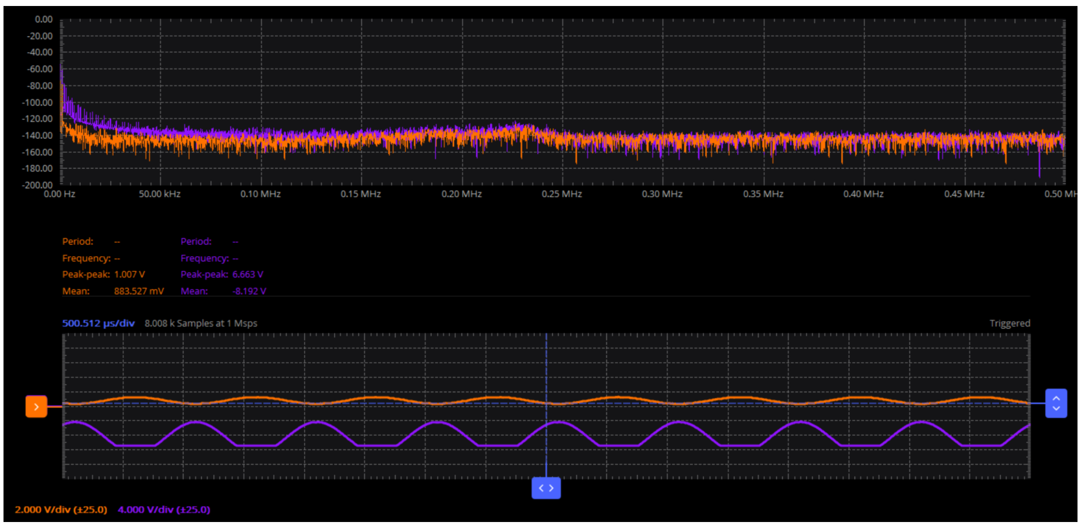


500mV



Period: 999.429 µs
Frequency: 1.001 kHz
Peak-peak: 990.603 mV
Mean: 694.894 mV
Period: --
Frequency: --
Peak-peak: 8.388 V
Mean: -6.869 V
500.512 µs/div
8.008 k Samples at 1 Msps
Triggered
2.000 V/div (±25.0)
4.000 V/div (±25.0)

800mV



Period: --
Frequency: --
Peak-peak: 1.007 V
Mean: 883.527 mV
Period: --
Frequency: --
Peak-peak: 6.663 V
Mean: -8.192 V
500.512 µs/div
8.008 k Samples at 1 Msps
Triggered
2.000 V/div (±25.0)
4.000 V/div (±25.0)

1V