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Op-amps are versatile elements used to implement various circuits such as amplifiers, comparators, filters, and son on. In this experiment, you become familiar with a typical op-amp and its common applications.

MANDATORY EXPERIMENTS

Experiment 1

Build the circuit shown in Fig. 1 using an op-amp comparator module. Create a pair of ± 18 V voltages and connect them to the supply connectors of the module.

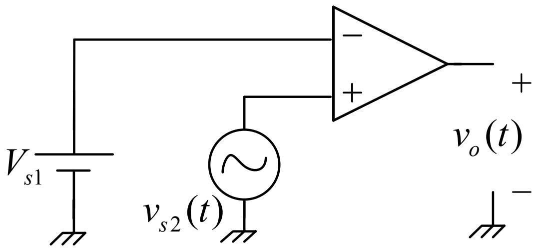

Figure 1: An op-amp as a comparator.

(a) Set $V_{s1} = 0$ or equivalently, connect the inverting input of the op-amp to the ground. Apply a 1-V 1-kHz sine voltage $v_{s2}(t)$ to the non-inverting input. Watch the the output voltage and the non-inverting input voltage of the op-amp simultaneously on the oscilloscope. Interpret the results. Change the sine wave to a triangle wave and observe the results.

Figure 2: Feeding Op-Amp using $+18V$ and $-18V$.

Experiment 1 continued on next page...

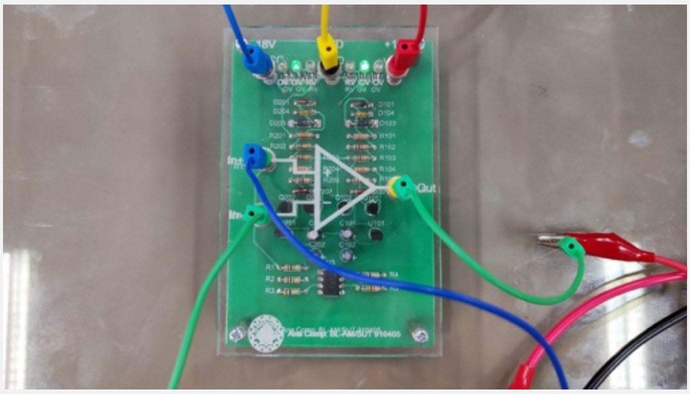

Figure 3: The circuit.

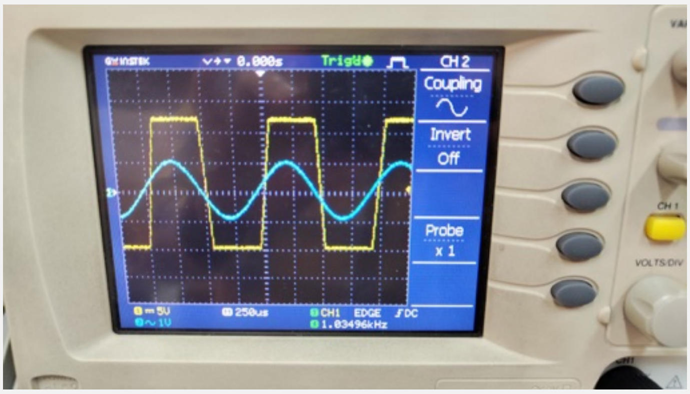

Figure 4: oscilloscope's screen for sine wace.

We know $V_d = V_+ - V_- = V_{\text{sin}} - 0$. The op-amp boosts the input voltage, but since the output voltage exceeds +E at some points, the output voltage does not exceed this number. For the same reason, the output voltage does not decrease from -E.

(b) Set $V_{s1} = \pm 0.5$ V and repeat the previous part.

Figure 5: The circuit used for making $\pm 0.5V$ using potentiometer.

We know $V_d = V_+ - V_- = V_{\text{sin}} - 0.5$. So for +E voltage we have $V_d > 0 \Rightarrow V_{\text{sin}} > 0.5$ and $V_d < 0 \Rightarrow V_{\text{sin}} < 0.5$.

Experiment 1 continued on next page. . .

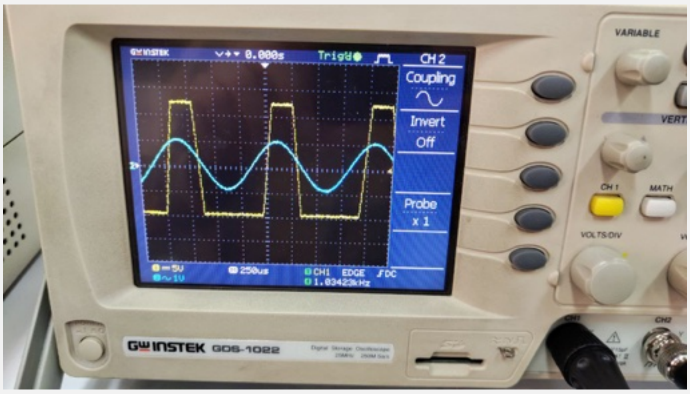

Figure 6: oscilloscope's screen for $+0.5V$.

We know $V_d = V_+ - V_- = V_{\text{sin}} + 0.5$. So for +E voltage we have $V_d > 0 \Rightarrow V_{\text{sin}} > -0.5$ and $V_d < 0 \Rightarrow V_{\text{sin}} < -0.5$.

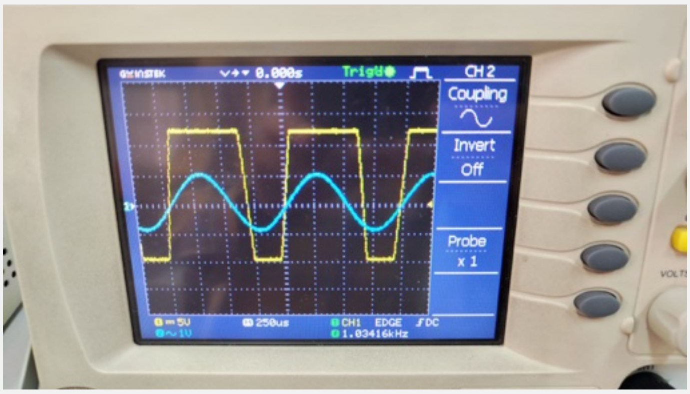

Figure 7: oscilloscope's screen for $-0.5V$.

The above notes also applies to the triangular wave.

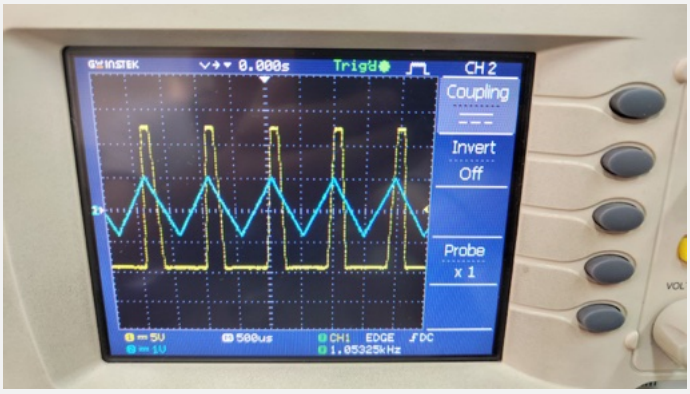

Figure 8: oscilloscope's screen for $+0.5V$ for triangle wave.

Experiment 1 continued on next page...

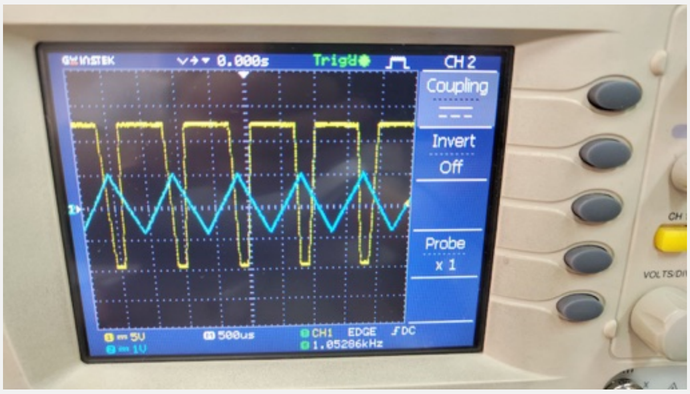

Figure 9: oscilloscope's screen for $-0.5V$ for triangle wave.

(c) Swap the input voltages to the op-amp and redo the previous parts.

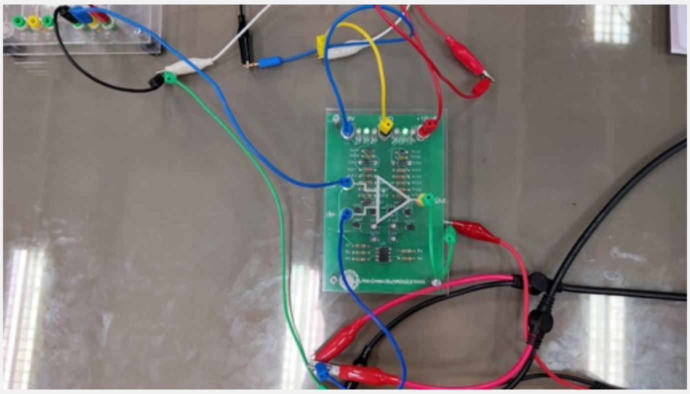

Figure 10: The circuit.

We know $V_d = V_+ - V_- = 0 - V_{\text{sin}}$.

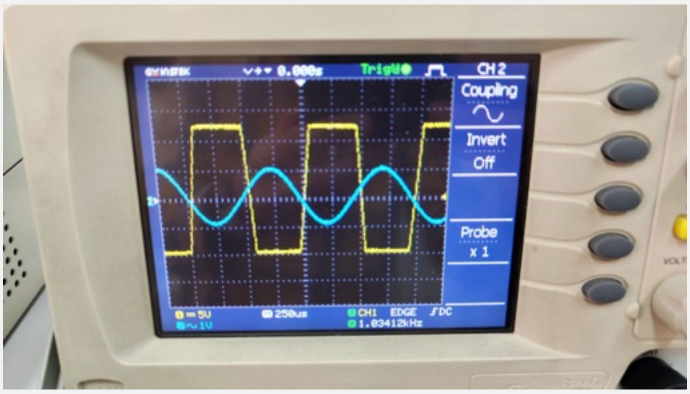

Figure 11: oscilloscope's screen for $0V$.

We know $V_d = V_+ - V_- = 0.5 - V_{\text{sin}}$. So for +E voltage we have $V_d > 0 \Rightarrow V_{\text{sin}} < 0.5$ and $V_d < 0 \Rightarrow V_{\text{sin}} > 0.5$.

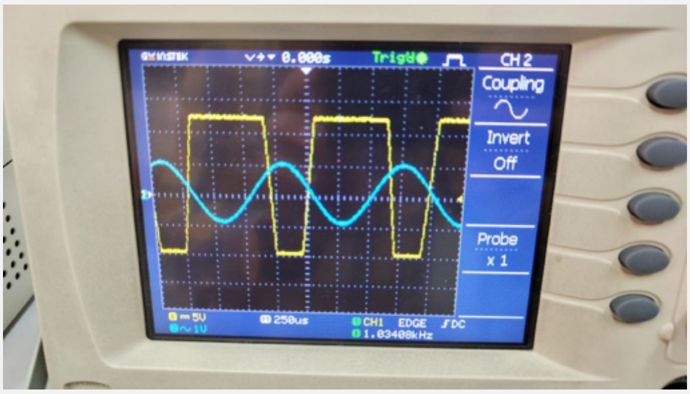

Figure 12: oscilloscope's screen for $+0.5V$.

We know $V_d = V_+ - V_- = -0.5 - V_{\sin}$. So for +E voltage we have $V_d > 0 \Rightarrow V_{\sin} < -0.5$ and $V_d < 0 \Rightarrow V_{\sin} > -0.5$.

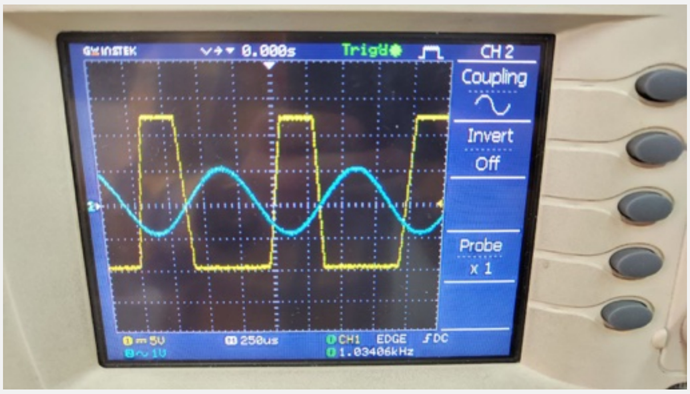

Figure 13: oscilloscope's screen for $-0.5V$.

The above notes also applies to the triangular wave.

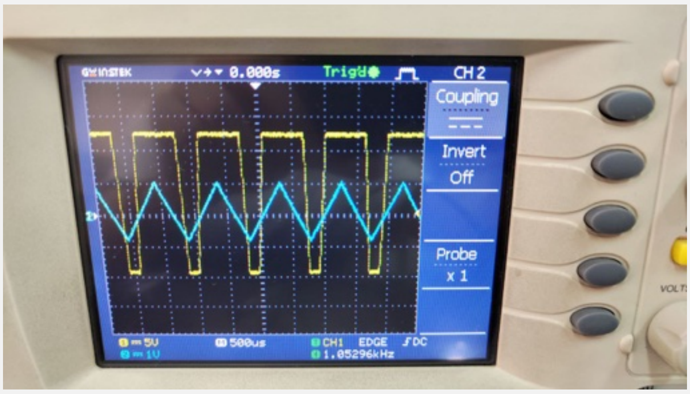

Figure 14: oscilloscope's screen for $0V$ for triangle wave.

Experiment 1 continued on next page. . .

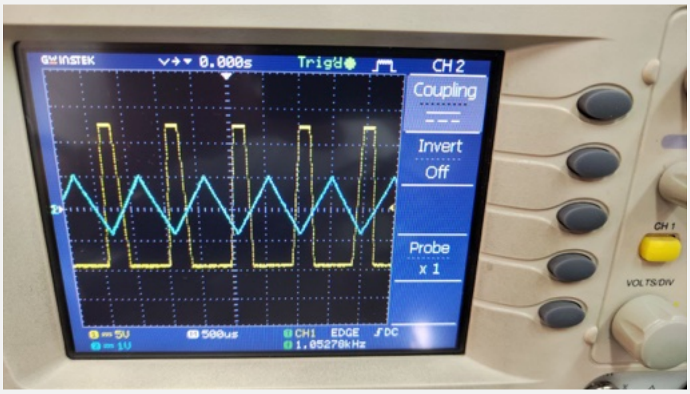

Figure 15: oscilloscope's screen for $+0.5V$ for triangle wave.

Experiment 2

Build the circuit shown in Fig. 16 using an op-amp comparator module. Create a pair of ± 18 V voltages and connect them to the supply connectors of the module as well as to the fixed legs of the potentiometer.

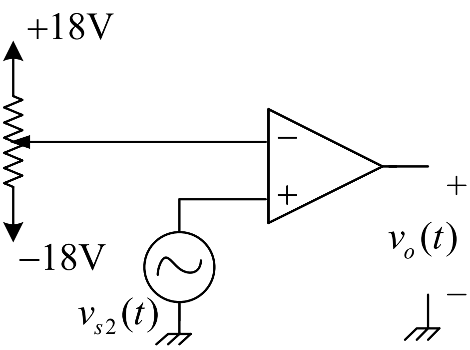

Figure 16: An op-amp as a comparator along with a potentiometer as a voltage divider.

(a) Apply a 1-V 1-kHz sine voltage $v_{s2}(t)$ to the non-inverting input. Watch the the output voltage and the non-inverting input voltage of the op-amp simultaneously on the oscilloscope. Turn the knob of the potentiometer and observe the results.

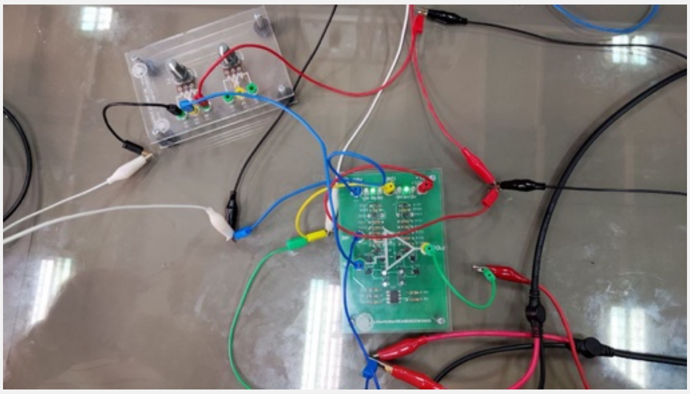

Figure 17: The circuit.

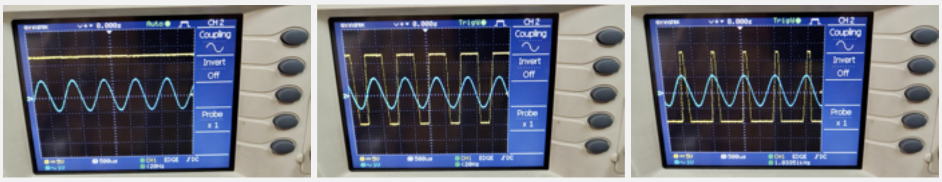

Figure 18: oscilloscope's screen.

As you can see, there is a voltage division between the two output sides of the potentiometer and a variable voltage (adjustable by us) enters the inverting base of the op-amp. We knows $V_d = V_+ - V_- = V_{\sin} - V_{potentiometer}$. As a result, by changing the voltage of the potentiometer and, the output will be the different for each voltage of the potentiometer, which you can see in the above images in three states.

(b) Repeat the previous part for a triangle wave.

Figure 19: oscilloscope's screen.

Experiment 3

Build the circuit shown in Fig. 20 using an op-amp inverting amplifier module. Create a pair of ± 18 V voltages and connect them to the supply connectors of the module.

Experiment 3 continued on next page...

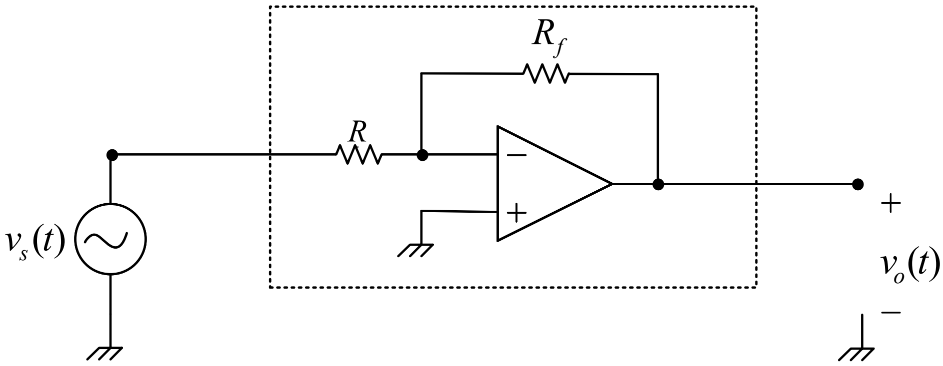

Figure 20: Inverting amplifier.

(a) Apply a 0.5-V 1-kHz sine voltage $v_s(t)$ to the input of the amplifier. Watch the the output and input voltages of the amplifier simultaneously on the oscilloscope. Calculate the gain of the amplifier.

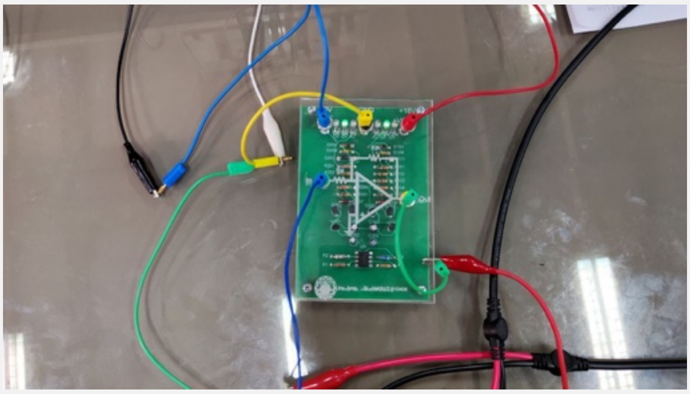

Figure 21: The circuit.

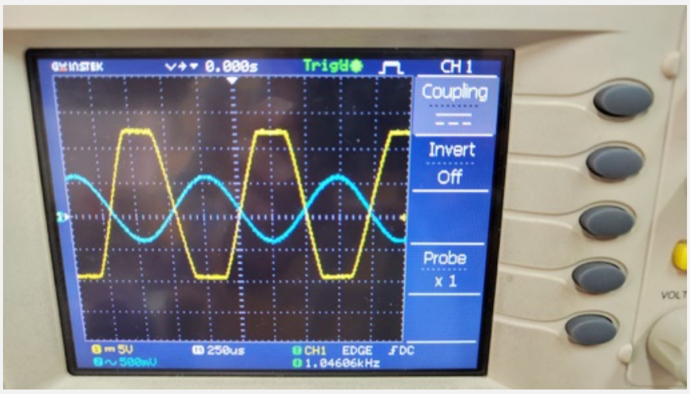

Figure 22: oscilloscope's screen for $0.5V$ voltage.

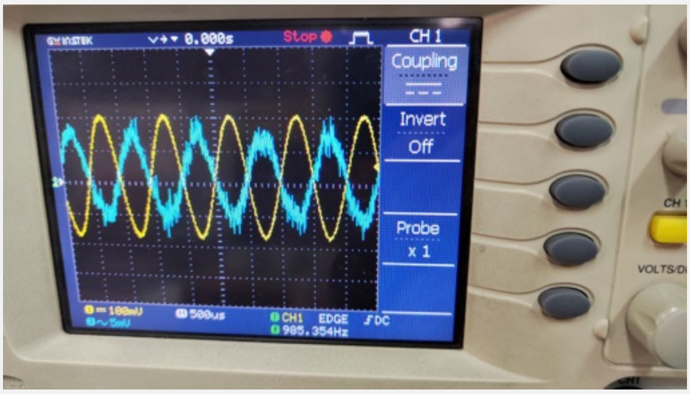

Figure 23: oscilloscope's screen for $5mV$ voltage which used for Calculating Op-Amp's gain.

We use the data from the second picture because the op amp is not saturated.

$$Gain = \frac{V_{out}}{V_{in}} = \frac{2 \times 100mV}{1.5 \times 5mV} = 26.6$$

(b) *Devise an experiment to measure the input and output resistance of the amplifier module.*

For finding R_{in} we connect a R_s after V_s and before V_1, we have:

$$V_1 = \frac{R_{in}}{R_{in} + R_s} V_s$$

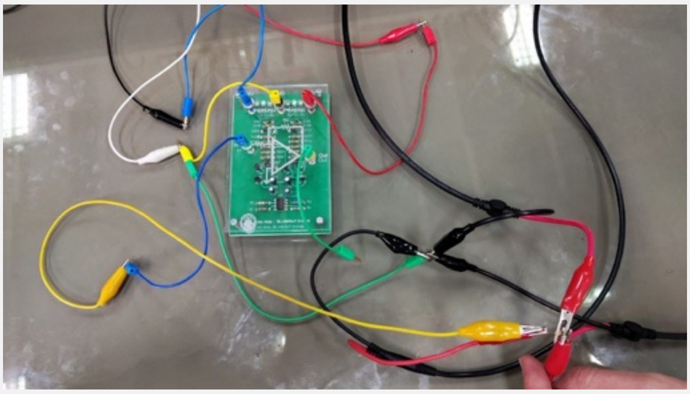

Figure 24: Circuit for R_{in}.

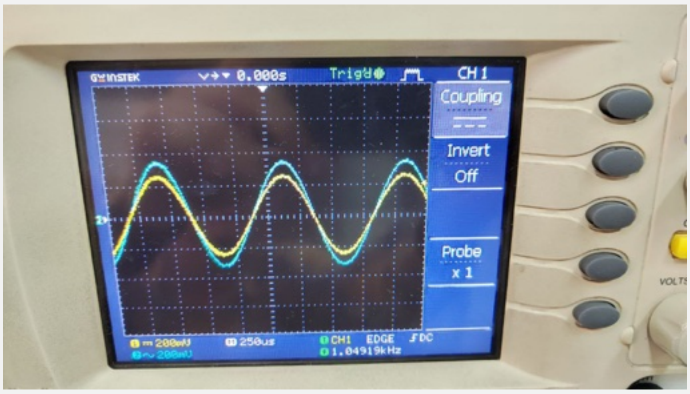

Figure 25: oscilloscope's screen for R_{in}.

$$\frac{R_{in}}{R_{in}+10k} = \frac{13}{17} \Rightarrow R_{in} = 32.5k\Omega$$

For finding R_{out} We connect a resistor R_L. At first $R_L \to \infty$ so we find AV_d and then we set $R_L = xk\Omega$, thus:

$$V_2 = AV_d \frac{R_L}{R_L + R_{out}}$$

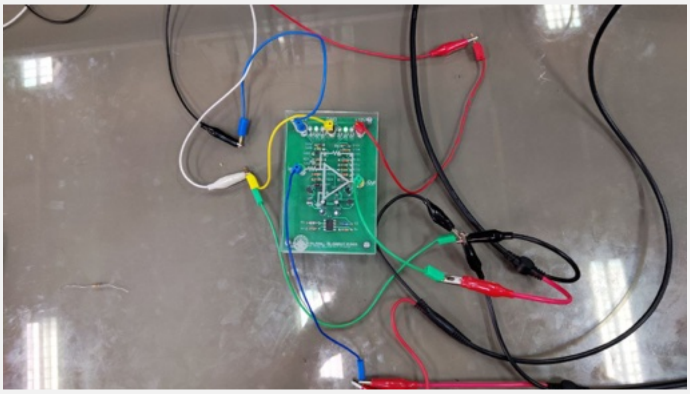

Figure 26: Circuit for R_{out} when $R_L \to \infty$.

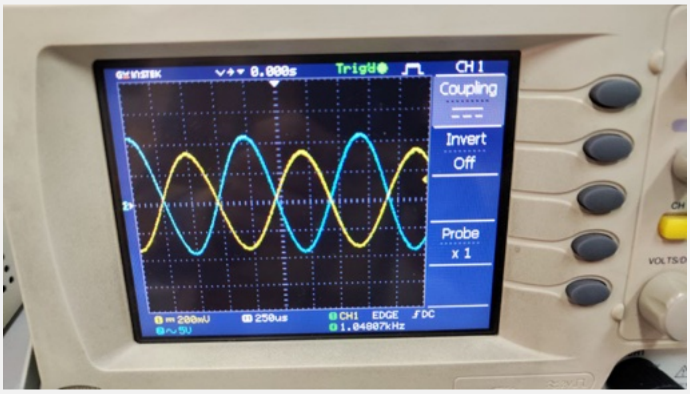

Figure 27: oscilloscope's screen for R_{in} when $R_L \to \infty$.

Experiment 3 continued on next page...

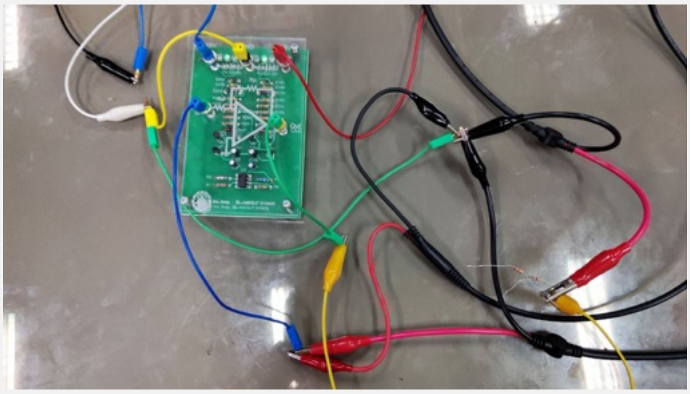

Figure 28: Circuit for R_{out} when $R_L = 1k\Omega$.

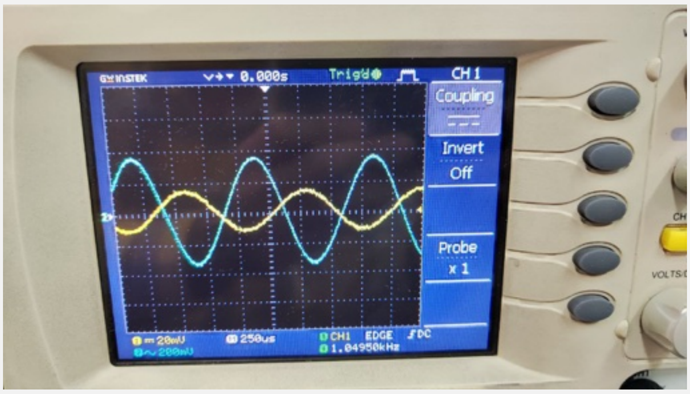

Figure 29: oscilloscope's screen for R_{in} when $R_L = 1k\Omega$.

$$\frac{1k}{1k + R_{out}} = \frac{7}{17} \Rightarrow R_{out} = 1.4k\Omega$$

(c) *Increase the amplitude of the input* 1*-kHz sine wave and record your observations. Interpret and discuss the results.*

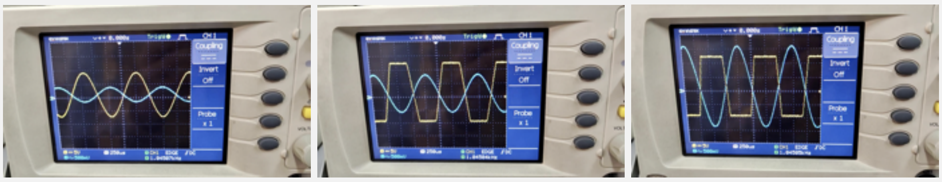

Figure 30: oscilloscope's screen for different input amplitude.

As you can see, the op-amp starts to saturate as the amplitude increases.

Experiment 3 continued on next page...

(d) Increase the frequency of the input 0.5-V sine wave and record your observations. Interpret and discuss the results.

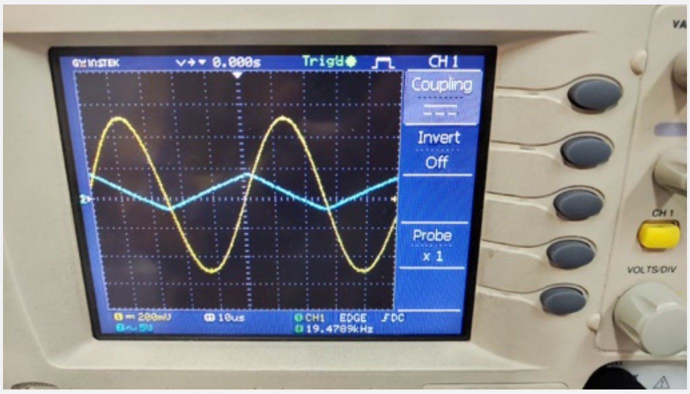

Figure 31: The Op-Amp can't follow input in high-frequency inputs.

Op-amps have limitations in following high-frequency inputs due to several factors.

- Speed limit: Op-amps have a built-in speed limit. They can only change their output so fast.
- Delay: There's a tiny delay between when a signal goes in and when it comes out. For really fast signals, this delay becomes a problem.
- Internal capacitors: Op-amps have tiny capacitors inside them. These act like small batteries that need to charge and discharge, which slows things down at high speeds.
- Gain drop: Op-amps naturally amplify signals less at higher frequencies. It's like turning down the volume as the pitch gets higher.
- Noise: At high frequencies, op-amps start to generate more electrical noise, which can mask the actual signal.

Experiment 4

Build the circuit shown in Fig. 32 using an op-amp non-inverting amplifier module. Create a pair of ± 18 V voltages and connect them to the supply connectors of the module.

Experiment 4 continued on next page. . .

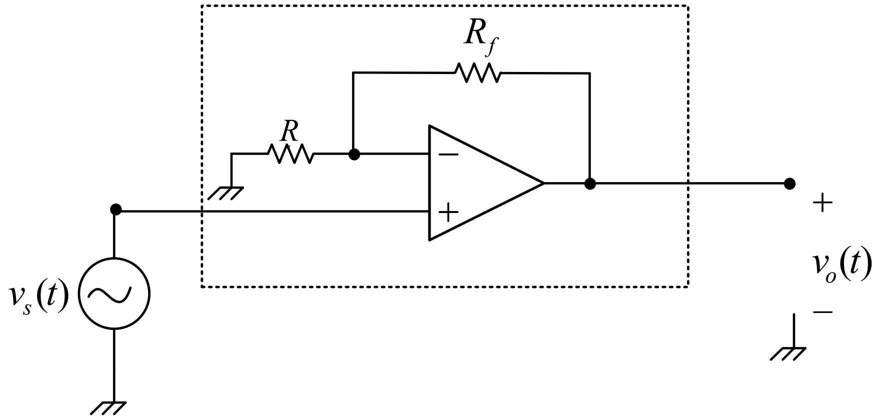

Figure 32: Non-inverting amplifier.

(a) Apply a 0.5-V 1-kHz sine voltage $v_s(t)$ to the input of the amplifier. Watch the the output and input voltages of the amplifier simultaneously on the oscilloscope. Calculate the gain of the amplifier.

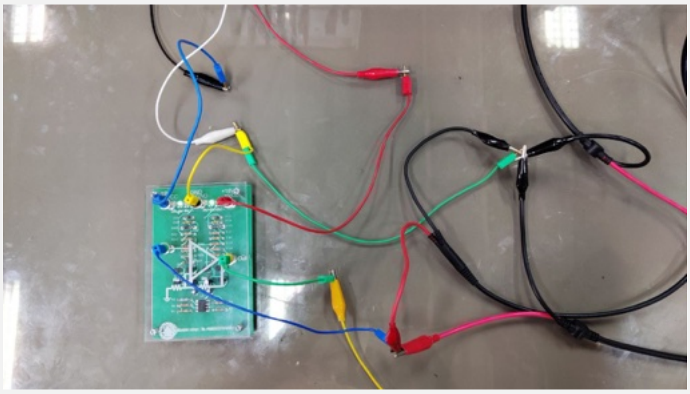

Figure 33: The circuit.

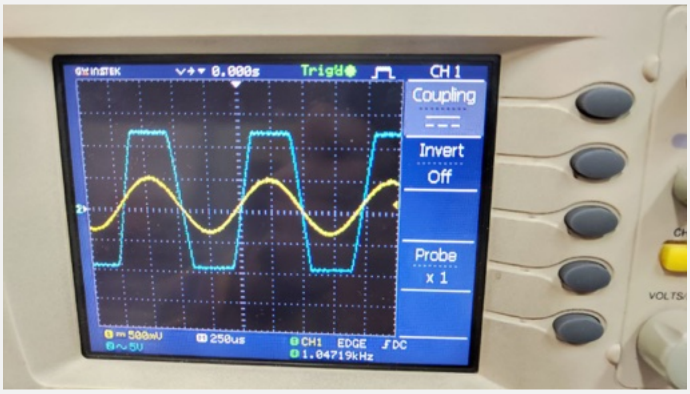

Figure 34: oscilloscope's screen for $0.5V$ voltage.

Experiment 4 continued on next page...

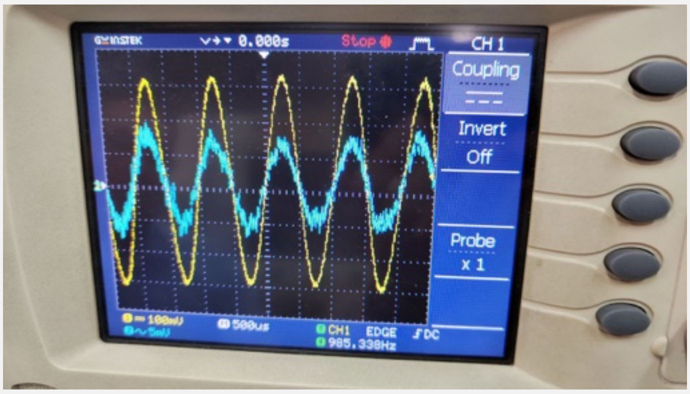

Figure 35: oscilloscope's screen for $5mV$ voltage which used for Calculating Op-Amp's gain.

We use the data from the second picture because the op amp is not saturated.

$$Gain = \frac{V_{out}}{V_{in}} = \frac{3 \times 100mV}{1.5 \times 5mV} = 40$$

(b) Measure the input and output resistance of the amplifier module experimentally.

For finding R_{in} we connect a R_s after V_s and before V_1, we have:

$$V_1 = \frac{R_{in}}{R_{in} + R_s} V_s$$

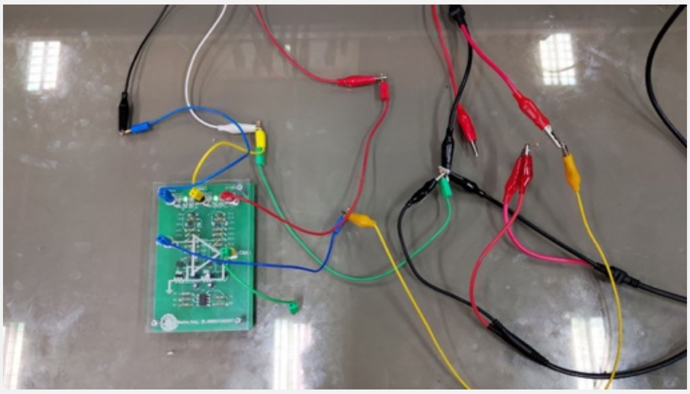

Figure 36: Circuit for R_{in}.

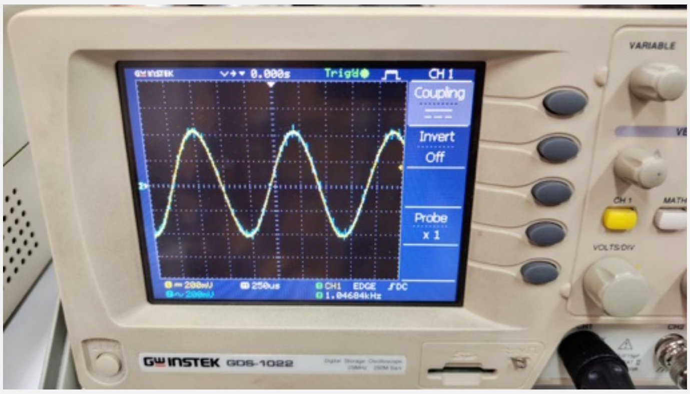

Figure 37: oscilloscope's screen for R_{in}.

Figure 38: voltages measured by multimeter for more accurate number.

$$\frac{R_{in}}{R_{in} + 10k} = \frac{0.2913}{0.2920} \Rightarrow R_{in} = 4.1M\Omega$$

For finding R_{out} We connect a resistor R_L. At first $R_L \to \infty$ so we find AV_d and then we set $R_L = xk\Omega$, thus:

$$V_2 = AV_d \frac{R_L}{R_L + R_{out}}$$

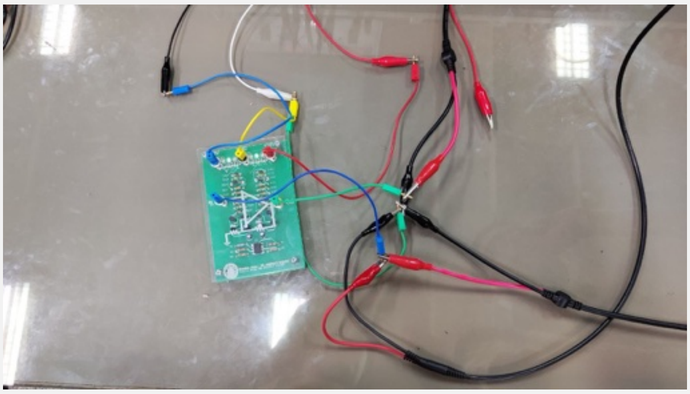

Figure 39: Circuit for R_{out} when $R_L \to \infty$.

Experiment 4 continued on next page...

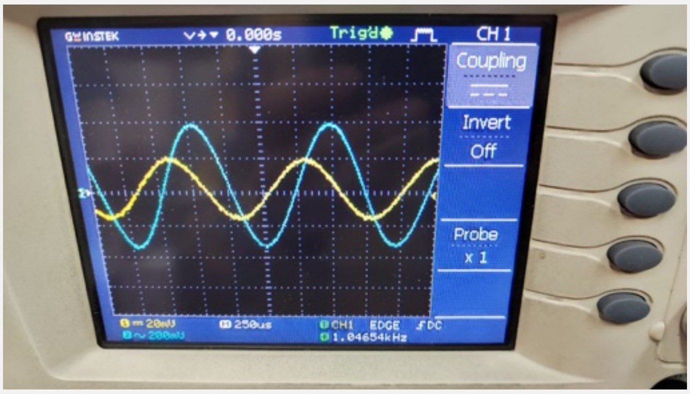

Figure 40: oscilloscope's screen for R_{in} when $R_L \to \infty$.

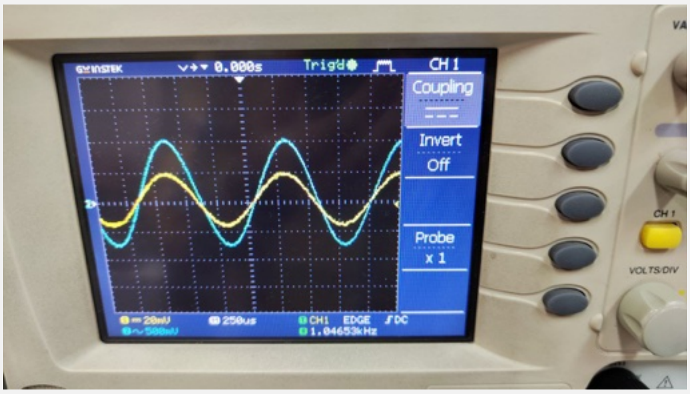

Figure 41: oscilloscope's screen for R_{in} when $R_L = 1k\Omega$.

$$\frac{1k}{1k + R_{out}} = \frac{7}{9} \Rightarrow R_{out} = 0.3k\Omega$$

(c) *Increase the amplitude of the input* 1*-kHz sine wave and record your observations. Interpret and discuss the results.*

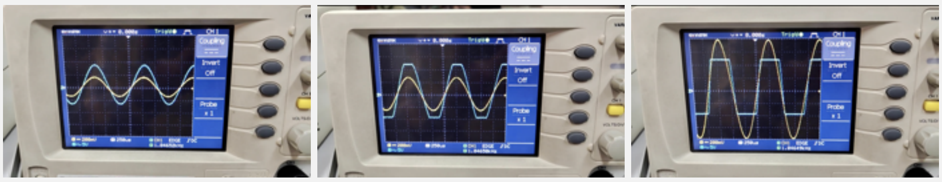

Figure 42: oscilloscope's screen for different input voltages.

As you can see, the op-amp starts to saturate as the amplitude increases.

Experiment 4 continued on next page. . .

(d) Increase the frequency of the input 0.5-V sine wave and record your observations. Interpret and discuss the results.

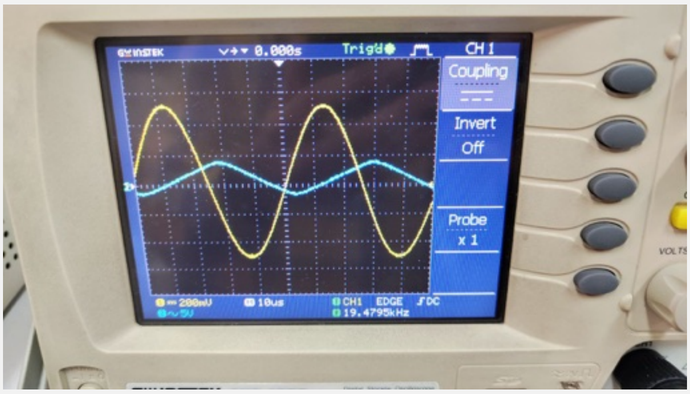

Figure 43: The Op-Amp can't follow input in high-frequency inputs.

As explained in experiment 4 section d, op-amp have limitations over high frequency.

Experiment 5

Cascade an inverting amplifier and a non-inverting amplifier as shown in Fig. 44 .

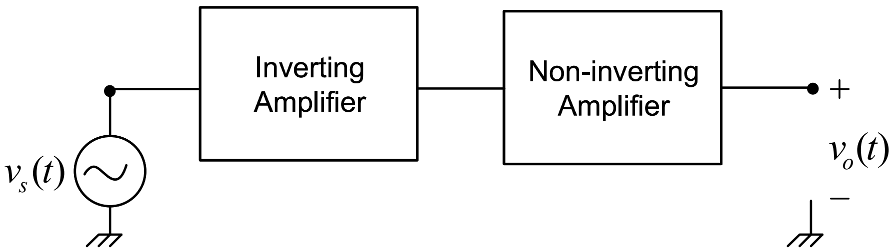

Figure 44: Cascade of two amplifiers.

(a) Apply a 100-mV 1-kHz sine voltage $v_s(t)$ to the input of the cascaded amplifiers. Watch the the output and input voltages of the cascaded amplifiers simultaneously on the oscilloscope. Calculate the overall gain of the cascaded amplifiers.

Experiment 5 continued on next page...

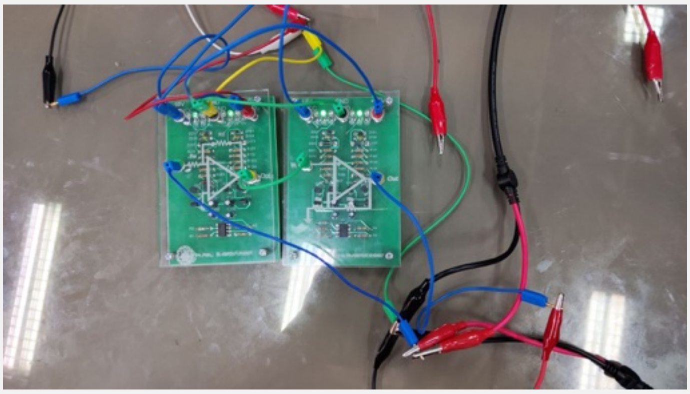

Figure 45: The circuit.

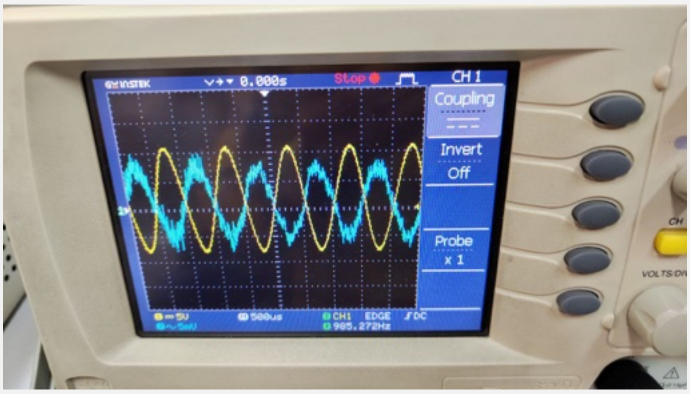

Figure 46: oscilloscope's screen.

$$Gain = \frac{V_{out}}{V_{in}} = \frac{2 \times 5V}{1.5 \times 5mV} = 1333.3$$

We also can Calculate Gain using $G_{tot} = G_{inv}G_{nnv}$.

$$Gain_{total} = 26.6 \times 40 = 1064$$

(b) Swap the order of the amplifiers and repeat the previous part. Is there any difference between the measured gains in the two experiments? Explain.

Experiment 5 continued on next page...

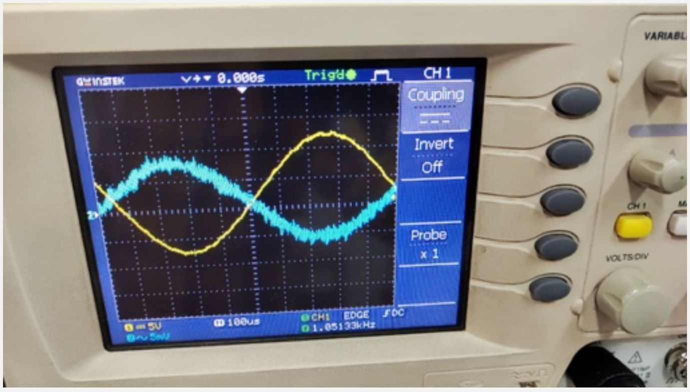

Figure 47: The oscilloscope's screen.

$$Gain = \frac{V_{out}}{V_{in}} = \frac{2 \times 5V}{1.5 \times 5mV} = 1333.3$$

By moving these two amplifiers, there was no noticeable change in the gain of the circuit (of course, we may not have noticed the changes due to the accuracy of the oscilloscope), although it would not be strange if there was a difference (more explanation in experiment b of question 6).

BONUS EXPERIMENTS

Experiment 6

In a circuit design, we need to cascade an inverting and a non-inverting amplifier to get the overall gain of $G_{tot} = G_{inv}G_{nnv}$.

(a) From analytical point of view, is there any difference to change the order of the cascaded amplifiers?

Theoretically, the order of multiplication doesn't change the result. So, mathematically:

$$G_{tot} = G_{inv} \times G_{nnv} = G_{nnv} \times G_{inv}$$

This suggests that the order of cascading shouldn't matter for the overall gain.
An inverting amplifier introduces a $180°$ phase shift, while a non-inverting amplifier doesn't introduce any phase shift $0°$. The total phase shift will be $180°$ regardless of the order:

Experiment 6 continued on next page...

(b) From practical point of view, is there any difference to change the order of the cascaded amplifiers? Justify your answer using PSpice simulation.

Yes, there are some difference.

- Input impedance: Non-inverting amplifiers typically have higher input impedance than inverting amplifiers. Placing the non-inverting amplifier first in the cascade can provide a higher overall input impedance. This is beneficial because:
  - It reduces loading on the signal source
  - It minimizes signal attenuation at the input
  - It can improve the overall signal-to-noise ratio
- Output impedance: The output impedance of the first stage interacts with the input impedance of the second stage. This interaction can affect:
  - Signal transfer between stages
  - Bandwidth of the overall system
  - Potential for oscillations or instability
- Noise considerations: In a cascade, the noise contribution of the first stage is generally more significant. This is because its noise gets amplified by subsequent stages. Therefore:
  - Placing the lower noise amplifier first can improve the overall noise performance
  - This is especially important in low-signal applications where maintaining signal-to-noise ratio is crucial
- Bandwidth: Each amplifier stage has its own bandwidth limitations. In a cascade:
  - The overall bandwidth is typically less than that of individual amplifiers
  - The order of cascading can affect the final bandwidth, especially if the amplifiers have very different bandwidth characteristics
  - Placing the higher bandwidth stage first might help preserve more of the signal's frequency content
- Dynamic range and linearity: The first stage in a cascade is more susceptible to overload from large input signals.
  - Placing the lower gain stage first can help prevent early saturation
  - This can improve the overall linearity of the system
  - It's particularly important when dealing with signals that have a wide dynamic range
- DC offset: Any DC offset present at the output of the first stage gets amplified by the second stage.

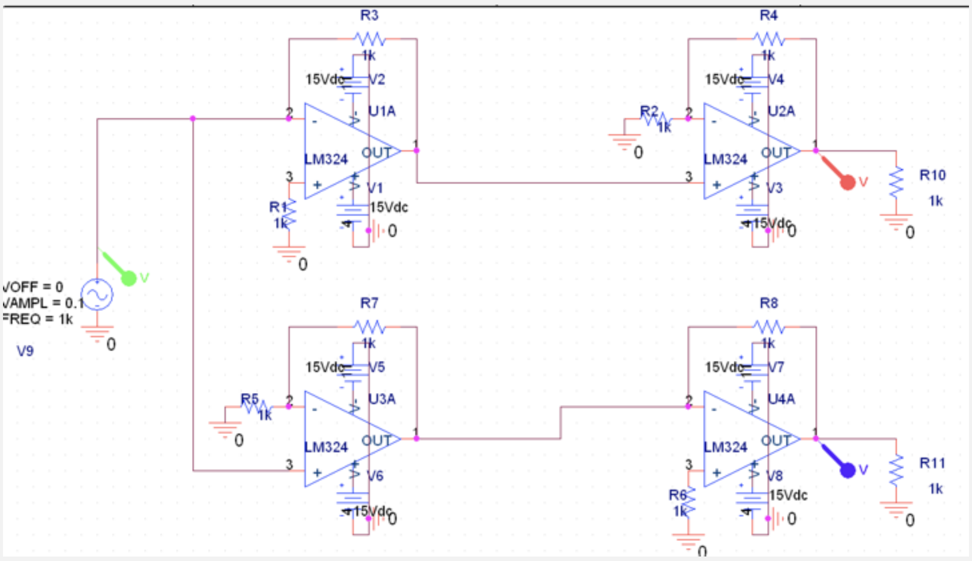

Figure 48: A simple circuit to check the effect of the order of the amplifiers on the final output.

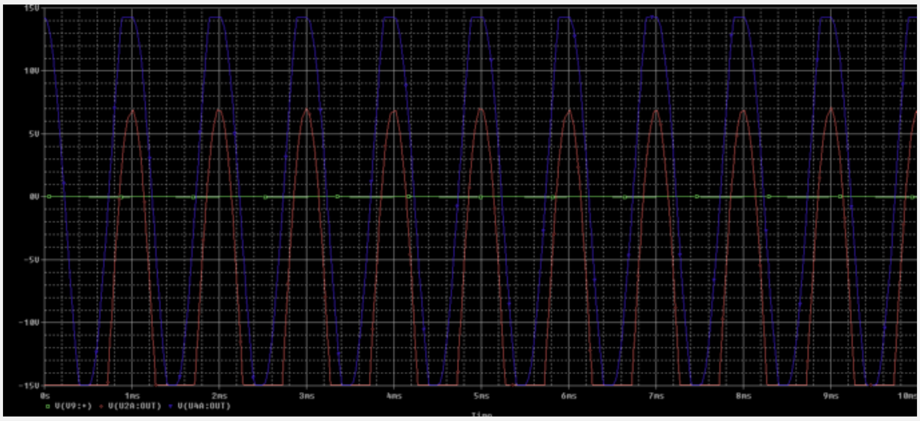

Figure 49: The input diagram (which is multiplied by 10 to be visible on the diagram) and the output of two modes.

As you can see, there is a phase difference between the two modes and there is a difference between their output voltage.

Experiment 7

Op-amps usually need a pair of positive and negative DC supply voltages $\pm V_s$.

Experiment 7 continued on next page...

(a) What happens if the absolute values of the supply voltages differ?

When the absolute values of these supply voltages differ, it affects the op-amp's performance in several ways:

- Output swing: The maximum output voltage swing will be limited by the smaller of the two supply voltages. For example, if you have $+12V$ and $-5V$ supplies, the output swing will be more restricted in the negative direction.
- Offset: An imbalance in supply voltages can introduce an offset voltage at the output, even when the inputs are balanced. This is because the internal circuitry of the op-amp may not be perfectly symmetrical.
- Common-mode range: The input common-mode range will shift towards the larger supply voltage. This means the range of input voltages that the op-amp can handle without distortion will be asymmetrical.
- Power consumption: The op-amp may consume more power from one supply than the other, which could be an issue in some designs.
- Stability: In some cases, significantly unbalanced supply voltages might affect the op-amp's stability, potentially leading to oscillations or other undesired behaviors.

It is important to consider these effects when designing circuits with op-amps and ensure that the supply voltages are properly balanced to achieve the desired performance.

(b) Is it possible to use an op-amp with the supply voltages 0 and $+V_s$? Explain.

Yes, it is indeed possible to use an operational amplifier (op-amp) with the supply voltages 0 and $+V_s$. This configuration is known as single-supply operation. In this context, the op-amp is powered by a single supply voltage, which is typically positive. The ground reference is connected to the inverting input, while the non-inverting input is biased to a mid-supply voltage (around $+\frac{V_s}{2}$) to create a virtual ground. It's important to note following points about single-supply op-amp operation:

- Many modern op-amps are designed to work with a single supply voltage. In this case, the inverting input (or leg) is connected to ground ($0V$), and the non-inverting input is connected to the signal source within the range of 0 to $+V_s$.
- The input common-mode range and output swing will be limited compared to a dual-supply configuration. The output can swing from near 0 to near $+V_s$, but it cannot go below 0 or above $+V_s$.
- To utilize the full range of the op-amp, input signals often need to be biased to a mid-supply voltage (around $+\frac{V_s}{2}$). This creates a "virtual ground" that allows the op-amp to handle both positive and negative variations of the input signal around this mid-point.
- It is important to note that the op-amp cannot produce negative output voltages in this configuration. Care must be taken to ensure the input doesn't go below ground, which could cause the op-amp to behave unpredictably or even damage the device.

Single-supply op-amps are common in battery-powered devices and systems where generating a negative supply would be inconvenient or inefficient. However, they require careful design and signal conditioning to ensure proper operation.

Experiment 8

Return your work report by filling the LaTeXtemplate of the manual. Include useful and high-quality images to make the report more readable and understandable.