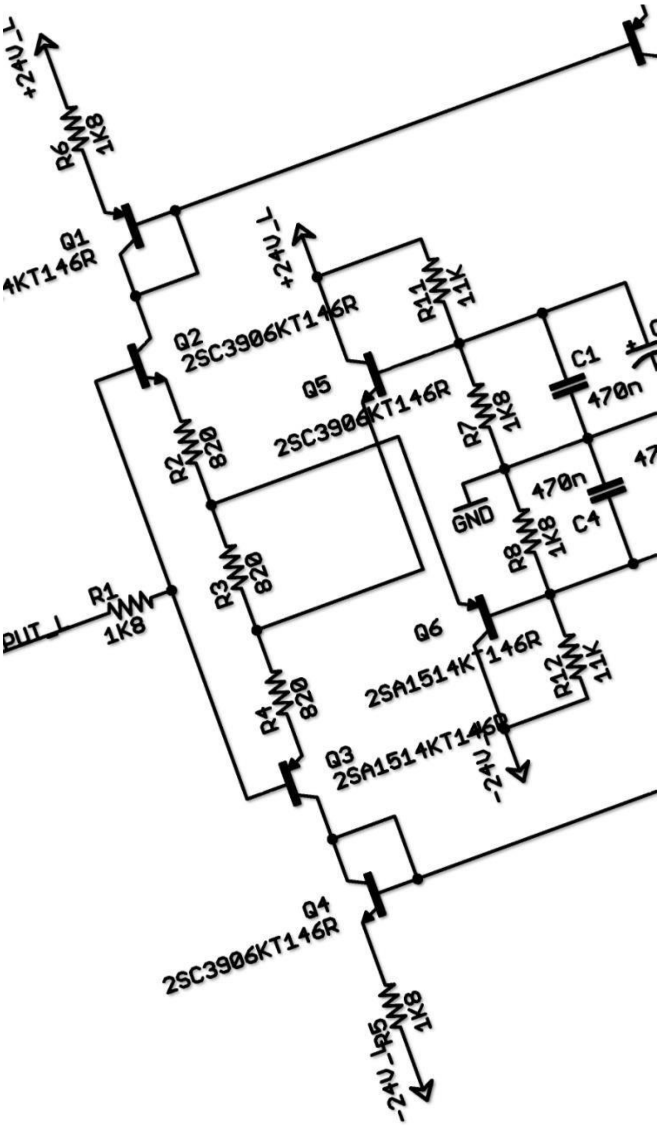
MONASH University
Engineering

ECE2131

Electrical Circuits

Laboratory Notes



2022 Edition

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2022

7 Introduction to Operational Amplifiers

Operational Amplifiers (op-amps) are a common type of flexible high gain differential input amplifiers. When combined with a couple of discrete components, they can be configured as signal buffers, filters, amplifiers, integrators, differentiators, adders, and more. In the following two labs, we will explore some of these applications. However, this lab aims to introduce op-amps, demonstrate some simple amplifier configurations, and gain some hands on experience in working with these devices. This will bedone by:

1. Investigating the basic operating characteristics of an operational amplifier,
2. Verifying the principle of virtual earth analysis and negative feedback,
3. Investigating the behaviour of an inverting operational amplifier circuit,
4. Investigating the behaviour of a non-inverting operational amplifier circuit, and
5. Investigating the operating limits of the TL074 opamp.

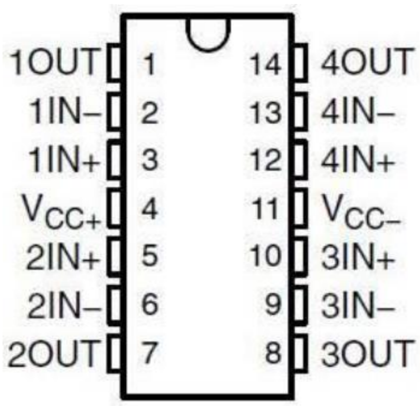
By the end of this lab you should:

- Build and characterise simple inverting and non-inverting amplifiers based on op-amps.
- See what the ‘virtual short’ concept in negative feedback means in real circuits
- Understand the effect of supply rails and gain-bandwidth product in limiting op-amp outputs

7.2 Equipment and Components

- Breadboard.
- Opamp TL074.
- Resistors: 10 kOhm, 100 kOhm.
- Capacitors: 100 nF, 100 pF.

TL074 Connection Diagram



7.3 EXPERIMENTAL PROCEDURE FOR LABS 7-9

The circuits are constructed on a prototype board using fixed value discrete components. Power your operational amplifier circuits using a fixed ±15V DC supply source. However, if you are using Adalm and Scopy, the DC power supply is limited to ±5V DC. Remember this!!!

When constructing your operational amplifier circuit, take care to make sure you connect the supply voltages with the correct polarity – reversing the supply voltage connections across the operational amplifier will most likely cause device failure. It is good practice (and helps semiconductor devices not to fail), if you only make circuit changes, plug in components, etc, when the circuit is de-energized. Get into the habit of turning the power supplies OFF before making any circuit changes.

The easiest way to construct your circuit is to do so in stages. Before you plug in your op-amp, measure the voltages supplied to the TL074 pins 4 and 11. Then turn off the power supplies, insert the op amp, and quickly check basic circuit operation after you turn on the power supply again to try and find any fundamental problems before damaging the device.

When constructing your circuits, make sure the input pins of the unused TL074 amplifier sections are connected to ground. Circuits are to be excited by the signal generator, set to produce a SINE wave. Circuit responses should be measured using the oscilloscope channels.

Where a particular voltage or frequency performance is specified in these notes, do not waste time adjusting your circuit to achieve exactly this result. The reason is simple - the circuit relationships you are exploring hold for any response that is reasonably close to the specified requirements.

7.4 EXPERIMENTAL WORK

7.4.1 PART A – INVERTING OPERATIONAL AMPLIFIER

Construct the following inverting amplifier circuit on the prototype board.

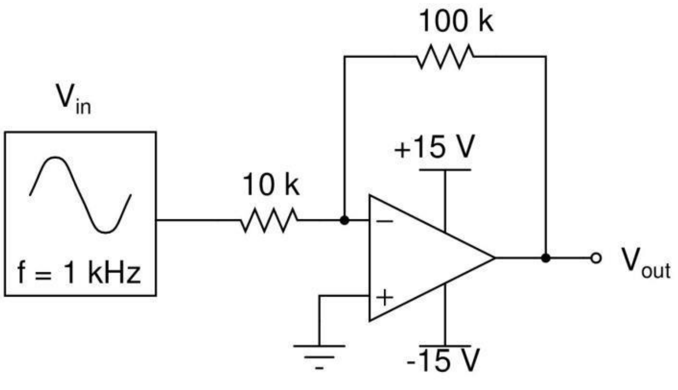


Fig. 1: Inverting amplifier

7.4.1.1 Set the signal generator DC offset to 0V, and adjust the signal generator to produce a $600mV_{p\text{-}p}$ ($\pm 300mV_{peak}$) sine wave at frequency of 1kHz. How does the measured gain of the circuit <u>compare</u> with the theoretical value you calculated in the preliminary quiz?

Theoretical Gain

Due to negative feedback, I- = 0A, V- = V+ = 0V
KCL @ V-

KCL at V-
$I_{input} = I_1$
$(V_- - V_{in}) / R_{in} = -(V_- - V_0)/R_f$

$$\frac{-\mathrm{Vin}}{R_{in}} = \frac{V_0}{R_f}$$

$$\frac{V_0}{V_{in}} = -\frac{R_f}{R_{in}}$$

We will get our theoretical gain to be $-\frac{R_f}{R_{in}}$ which equates to a value of -10.

Measured Gain

Based on the visual observation of the graph above, our measured gain would be

$$Measured\ Gain = \frac{V_{out}}{V_{in}}$$

$$\frac{5.947\ V}{-631.229\ mV}$$

The measured gain we will obtain equates to -9.42.

7.4.1.2 Is there a phase shift between the signal generator and the output of the opamp? If there is a phase shift, what is this phase shift equal to? Attach a screenshot to clearly show your measurement of the phase shift.

Yes, there is a phase shift between the signal generator and the output of the opamp. The phase shift can be calculated with the equation of **Δt x f x 360** = 491.468 μs x 1000 x 360° = 176.93°

The phase shift is approximately close to 180°
The phase shift holds true as this is meant to be an inverting amplifier.

7.4.1.3 Measure the opamp output voltage (OUT) with one oscilloscope channel. Connect another oscilloscope channel to the opamp inverting input terminal (IN-).

How do the magnitudes and phase compare?

How does the negative input voltage (IN-) correlate with the "virtual short" concept?

HINT for desktop oscilloscope: You will have to set the CRO probe to X1 gain to measure the opamp negative input voltage, since it is very small. Make sure you reset the probe to X10 and readjust the CRO channel setup accordingly after this test.

The magnitude of the output voltage remains the same which is 5.947 V. The negative input voltage is 38.543 mV. We can see that the op-amp negative input voltage is close to being zero but is not. The phase angle obtained would be 245.734μs x 1000 x 360° = 88.46°.
Since the op-amp output voltage graph comes before the op-amp negative input voltage, the op-amp output voltage leads the op-amp negative input voltage by 90 degrees. The negative input voltage correlates to the “virtual short” concept as according to the rule V+ = V-.
Since the positive input voltage is 0V as it is connected to ground, the negative input voltage of the op-amp would also be 0V.
The reason for it having oscillations is that the op-amp will constantly switch between drawing voltage from the positive Vss and negative Vss due to the constantly changing value of Vout.
This will ensure the negative input voltage of the op-amp is not fully 0V, but it oscillates between such small values that the graph of the negative input voltage of the op-amp will seem to be
0V.
Since the voltage is approximately 0V, the negative input of the op-amp will basically act as a short circuit which correlates to the “virtual short” concept.

7.4.1.4 Increase the input signal magnitude to 10Vp-p (±5Vpeak). Measure the V_{in} and opamp output voltages and explain your observations.

When we increase the voltage of the input signal, the output voltage will be increased. There is a catch. The output voltage can only be increased only up to its gain (maximum allowable value) as given in the supply voltage. This would cause the op-amp to be in a saturated state. The voltage output will be forced to resemble a square wave.

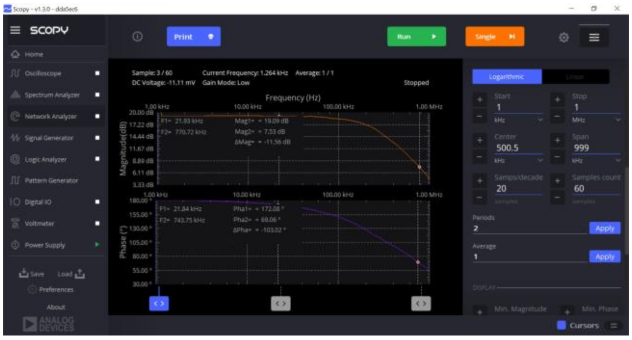
7.4.1.5 Adjust the input signal magnitude and identify the opamp input signal voltage levels at which the opamp output voltage starts to "clip" at its maximum values, both for positive and negative voltage inputs. Are these maximum output values equal to the supply voltage rails? How do they compare with the maximum output voltage swing as specified in the TL074 data sheet?

The maximum output value is not equal to the supply voltage rails. This is due to the internal configurations and components inside the opamp which will consume some of this voltage, making the output voltage to never reach the supply voltage value.

The maximum output voltage swing as specified in the TL074 data sheet is between -13.5 to 13.5 V.

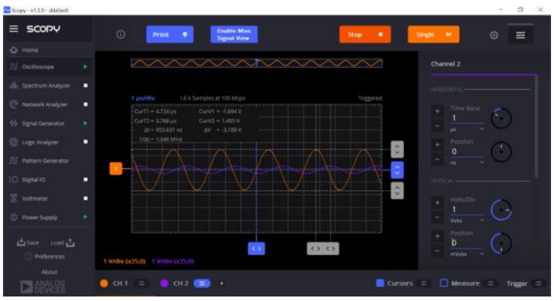
7.4.1.6 Reset the signal generator output to 600mVp-p (±300mVpeak). Increase the signal generator frequency in stages up to 1MHz using the network analyzer and using the input signal as the reference, observe the opamp output voltage response against frequency. Find the frequency at which the output magnitude reduces to $1/\sqrt{2}$ of the output magnitude at low frequency response (1kHz).

The output magnitude to be found is $\frac{3}{\sqrt{2}} = 2.12$ V



The frequency in which the output magnitude reduces to $1/\sqrt{2}$ of its low frequency response is 329kHz ($\frac{3}{\sqrt{2}}$).

7.4.1.7 Determine the phase shift between the source and opamp output voltages at this frequency. NOTE: In theory, this frequency should be the "gain-bandwidth" frequency as per the data sheet, divided by the gain of this circuit, and the opamp output should be shifted by 45 degrees. Is this the case in your experiment?



The phase angle will have a value of 955.631ns x 350kHz x 360 = 120.4°.

From the data sheet, the frequency is calculated to be $\frac{3M}{10}$ which equates to 300kHz and the op-amp lags by 45°. Comparing with the values that I have obtained, it is quite different from each other. The reason for this difference is due to the internal components or configurations of the op-amp absorbing some of the voltage thus skewing results.

☐ CHECKPOINT: Get a demonstrator to check your answers, and initial here

7.4.2 PART B – NON-INVERTING AMPLIFIER

7.4.2.1 Construct the following non-inverting amplifier circuit on the prototype breadboard.

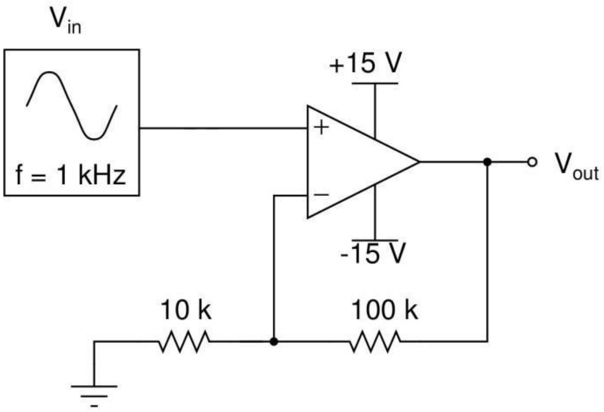


Fig. 3: Non-inverting amplifier with low pass filter function.

7.4.2.2 Set the signal generator DC offset to 0V, and adjust the signal generator to produce a $200mV_{p-p}$ ($100mV_{peak}$) signal at a frequency of 1 kHz. Observe the output and verify the basic operation of the circuit. What is the theoretical gain of this circuit? Show your circuit analysis of how you obtain this theoretical gain. How does the measured gain of the circuit compare to the theoretical calculations?

Theoretical Gain

Due to negative feedback, I- = 0A, V- = V+ = 0V
KCL @ V-

KCL at V-

$$I_{input} = -I_1$$

$$(V_- - 0) / R_{in} = -(V_- - V_0)/R_f$$

$$\frac{\text{Vin}}{R_{in}} + \frac{\text{Vin}}{R_f} = \frac{V_0}{R_f}$$

$$(\frac{Rf + Rin}{Rin}) = \frac{V_0}{V_{in}}$$

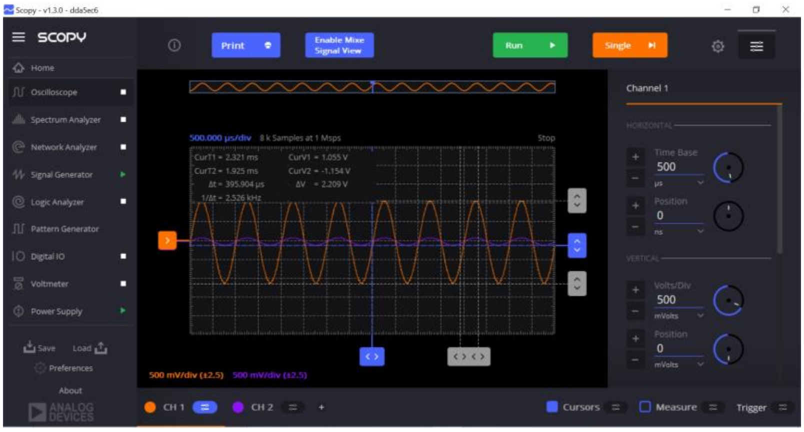
$$(\frac{Rf}{Rin} + 1) = \frac{V_0}{V_{in}}$$

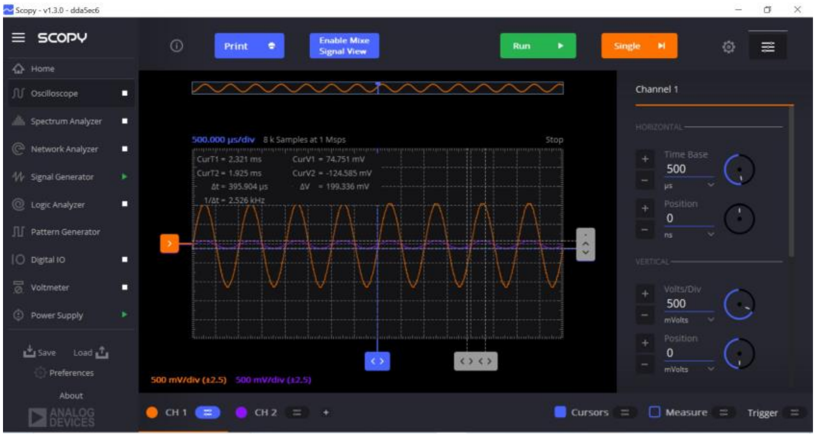
We will get our theoretical gain to be $\frac{R_f}{R_{in}} + 1$ which equates to a value of 11.

Measured Gain

Based on the visual observation of the graph above, our measured gain would be

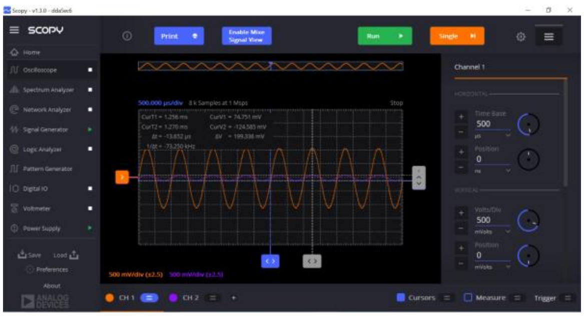
$$Measured\ Gain = \frac{V_{out}}{V_{in}}$$





The measured gain we will obtain equates to $\frac{2.209\ V}{199.336\ mV} = 11.08$

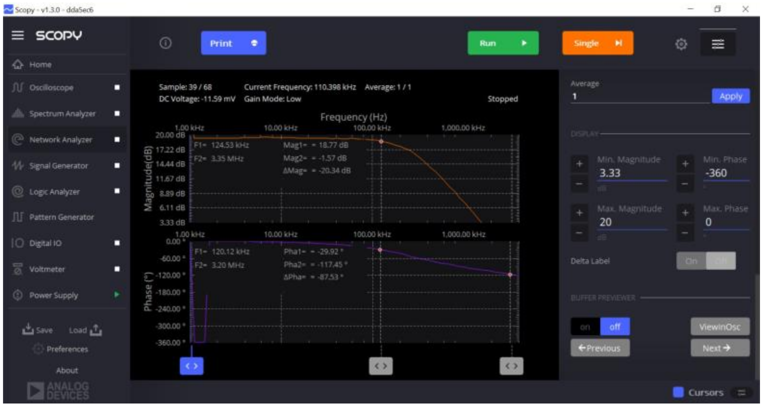
7.4.2.3 Is there a phase shift between the signal generator input and the opamp output? If there is phase shift, how much is the phase shift? If there is no phase shift, explain why.



There is no phase shift between the two waves. This is because the current configuration of the circuit is a non-inverting amplifier, so there will be no phase shift between the two waves.

☐ CHECKPOINT: Get a demonstrator to check your answers, and initial here

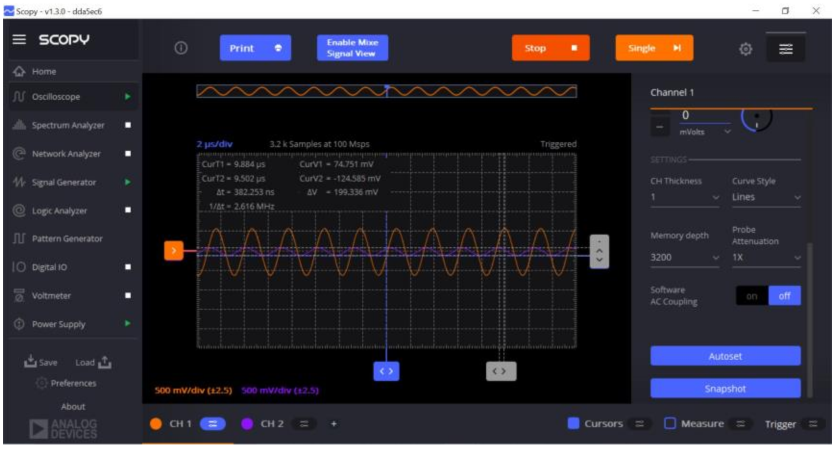
7.4.2.4 Gradually increase the signal generator frequency in stages up to 4 MHz using the network analyzer, and explore the opampoutput voltage response as the frequency increases. Find the frequency at which the output magnitude reduces to $1/\sqrt{2}$ of the output magnitude at low frequency response (1kHz).



Output magnitude to be found = $\frac{1}{\sqrt{2}}$ x 1.1 = 0.778V

The frequency at the output magnitude would be $\frac{1.1}{\sqrt{2}}$ = 329 kHz.

7.4.2.5 Determine the phase shift between the signal generator output and opamp output voltages at this frequency.

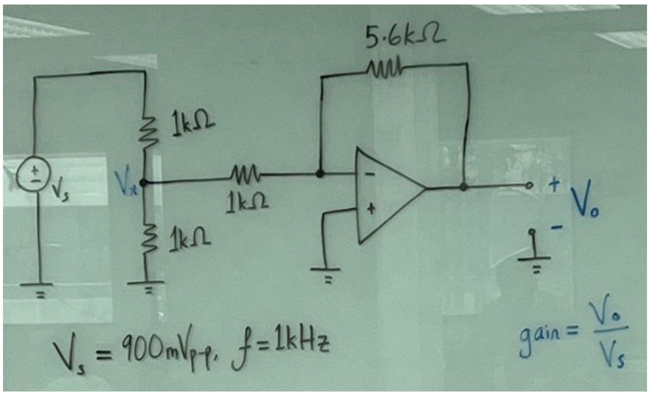


The phase angle obtained would be -382.253ns x 329kHz x 360° which equates to -45.27°.

☐ CHECKPOINT: Get a demonstrator to check your answers, and initial here

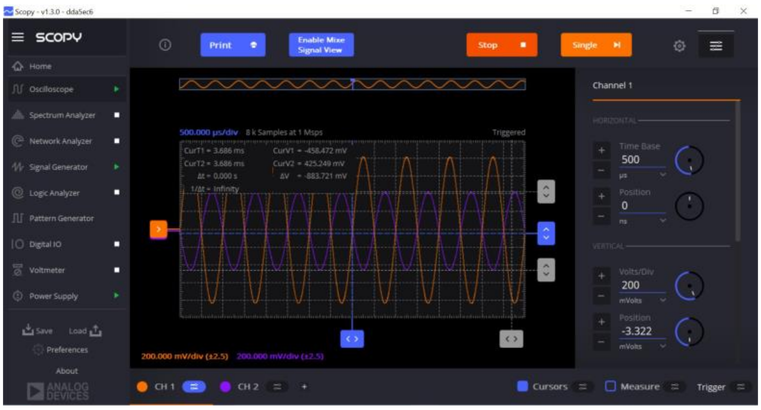
LAB ASSESSMENT

Given Circuit



3. The gain of the circuit

The theoretical value for the gain of the circuit is



The measured value for the gain of the circuit can be calculated as follows

$$Gain = \frac{1.668\ V}{-883.721\ mV}$$

$$= -1.887$$

The theoretical value for the gain of the circuit can be found using KCL

$$\frac{Vs-Vx}{1000} - \frac{Vx}{1000} - \frac{Vx}{1000} = 0$$

$$Vs - Vx - Vx - Vx = 0$$

$$Vs = 3Vx$$

$$900mV = 3Vx$$

$$Vx = 300mV$$

Since we have found the value of Vx, we can find the value of Vo.

$$\frac{Vx}{1000} + \frac{Vo}{5600} = 0$$

$$\frac{Vx}{1000} = -\frac{Vo}{5600}$$

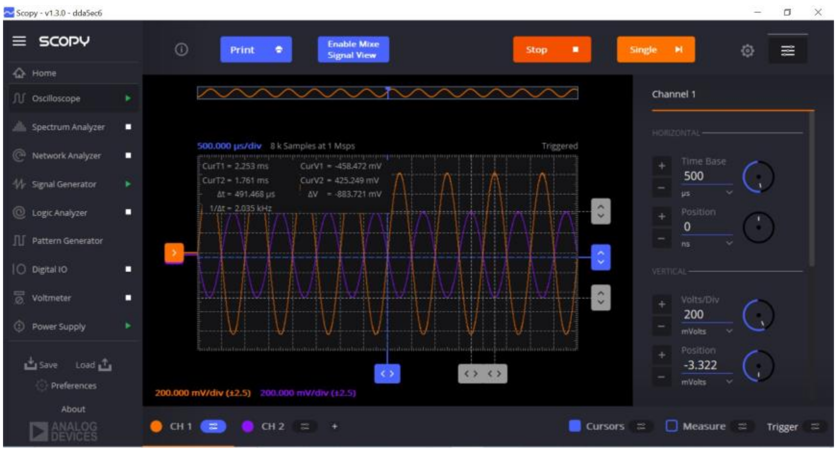
$$Vo = -1.68\ V$$

The gain can be calculated using the formula

$$\frac{Vout}{Vs} = \frac{1.68\ V}{-900\ mV}$$

We will get our answer (the value of gain) to be -1.867

4. Phase Angle



The measured phase angle can be calculated with the equation of **Δt x f x 360** = 491.468 µs x 1000 x 360 = 176.93°.

The theoretical value of the phase angle can be found by converting the value of the magnitude of the voltage from cartesian form into polar form. We will get the value of 180°.

ASSESSMENT

Student Statement:

I have read the university's statement on cheating and plagiarism, as described in the *Student Resource Guide*. This work is original and has not previously been submitted as part of another unit/subject/course. I have taken proper care safeguarding this work and made all reasonable effort to make sure it could not be copied. I understand the consequences for engaging in plagiarism as described in *Statue 4.1 Part III – Academic Misconduct*. **I certify that I have not plagiarized the work of others or engaged in collusion when preparing this submission.**

Student signature: Tan Jin Chun Date: 28/4/ 2022

TOTAL: ________(/7)

ASSESSOR: ________