Inverting_Amplifier --

Inverting Amplifier

Objectives:

After performing this lab exercise, learner will be able to:

- Understand and comprehend working of opamp
- Design & build inverting amplifier of desired voltage gain using opamp
- Establish relationship between input and output signal
- Practice working with measuring equipment and laboratory tools like digital oscilloscope, signal generator, multimeter and power supply
- Use digital oscilloscope to debug/analyze the circuit

Equipment:

To perform this lab experiment, learner will need:

- Digital Storage Oscilloscope (TBS1000B-Edu from Tektronix or any equivalent)
- Power Supply (2231A-30-3 Power Supply from Keithley or any equivalent power supply capable of supplying +/- 10V DC)
- Signal generator (AFG1000 from Tektronix or equivalent) for providing AC input to circuit
- Multimeter
- Electronic Components
  - Opamp 741 / TL082 or equivalent - as single IC or as part of any analog circuit kit (like ASLK board from TI)
  - Resistor (1K, 2.2K, 4.7K and 10K ohms)
- BNC cables
- Breadboard and connecting wires

Theory / Key Concepts:

Before performing this lab experiment, it is important to learn following concepts:

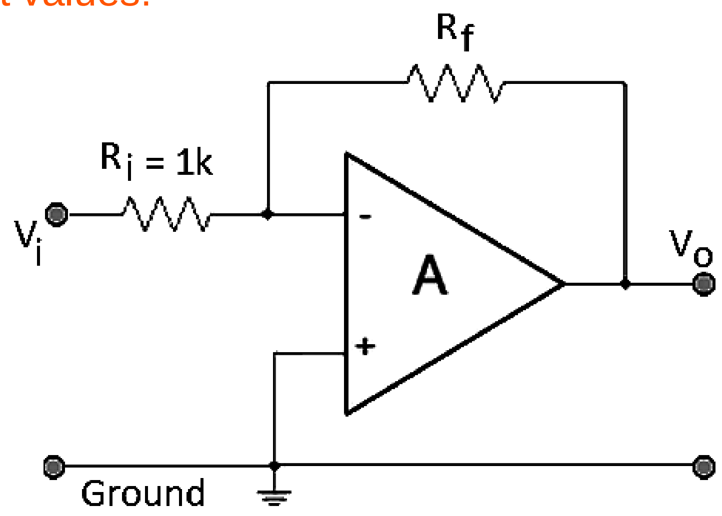
- An opamp is a high-gain differential amplifier with very high input impedance. Very high open-loop gain allow for creating amplifiers with stable gain using feedback.
- In an inverting amplifier, the input signal is applied to inverting pin of the opamp and there is a phase inversion (180 degree phase difference between output and input).
- The amplification factor or gain can be controlled by external components - Resistor in feedback path R_f and input path R_i.
- Voltage gain of the non-inverting amplifier is given by:

$$Gain = -\frac{R_f}{R_i}$$

- While designing opamp circuits, one has to be careful about output saturation - if the gain or input signal is high enough to drive output beyond the supply voltages (V_{cc} and V_{ee}), the amplifier goes into saturation and output is limited to supply voltages.

Circuit Design:

Learner can use the theoretical design rules to calculate the circuit component values:



- For inverting amplifier, the gain depends on R_f and R_i. .
- followign table shows the estimated (and expected) voltage gain for different combinations of R_f and R_i :

Rf (kΩ)	Ri (kΩ)	Voltage Gain
		Estimated
1.0	1.0	-1.00
2.2	1.0	-2.20
4.7	1.0	-4.70
10.0	1.0	-10.00

*- sign on the gain indicates phase inversion (output is 180 degree out of phase with respect to input)

Inverting_Amplifier -- Procedures

Step 1

Check Your Understanding:

Before performing this lab experiment, learners can check their understanding of key concepts by answering these?

- For an inverting amplifier circuit, if $R_f < R_i$, the phase shift between output and input will be:
  - 0 Degree
  - less than 90 Degree
  - 180 Degree
  - more than 90 Degree

- For an inverting amplifier circuit, is it possible to reduce the voltage to less than 1?

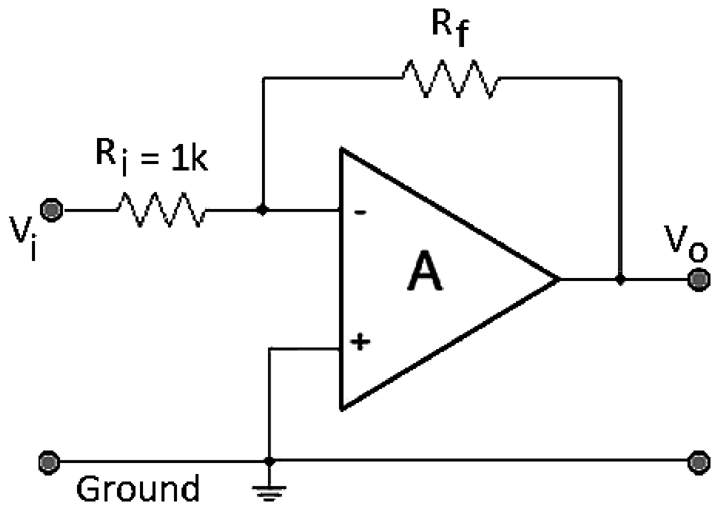
- Yes, by choosing R_f less than R_i
- Yes, by choosing $R_f = R_i$
- No. Not possible.
- Yes, by choosing R_i = 0 ohms

- In an inverting amplifier circuit the ratio of R_f to R_i is 10. What will be the effect on its voltage gain if positions of R_f and R_i are interchanged?
    - Gain will be 10 times of its previous gain
    - Gain will remain unchanged
    - Gain will reduce to 1/10th of its previos value
    - Gain will reduce to 1/100th of its previos value

Step 2

Circuit diagram / Connection Details

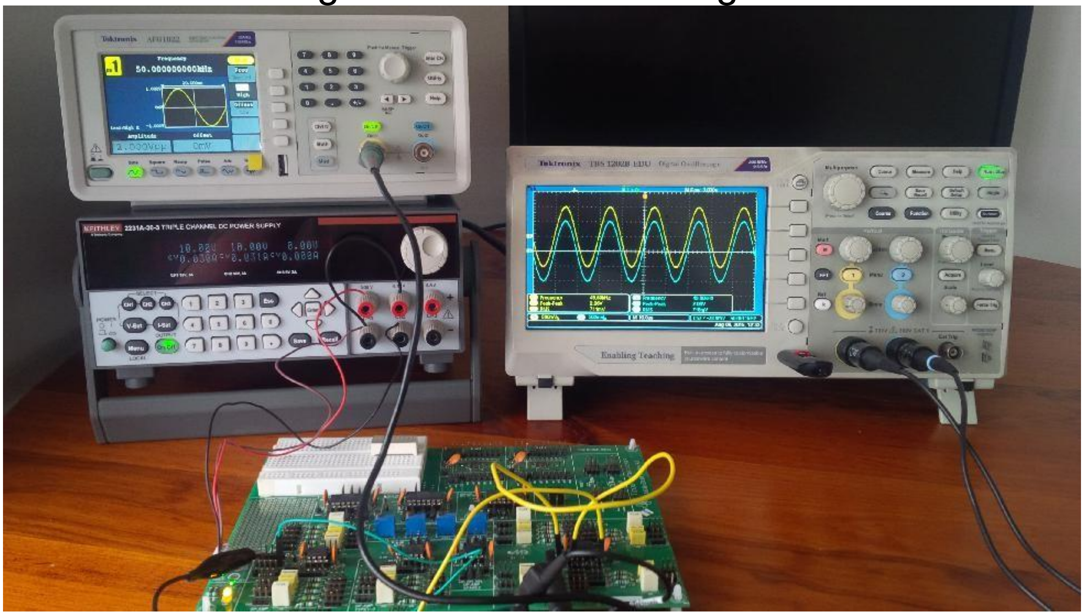
- Using the jumper / connecting wires prepare the circuit as shown below - Choose $R_f = R_i$ = 1k ohm:



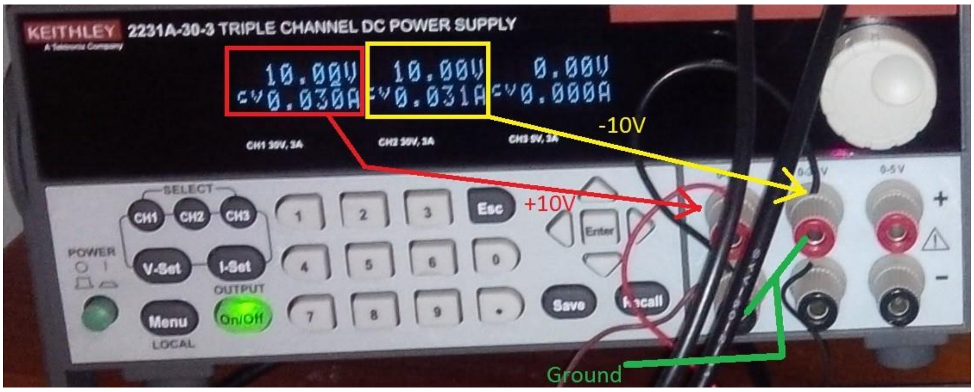
Step 3

Experiment Setup

- Make the arrangement as shown in figure below -



- Turn on the DC power supply, ensure that +/- 10V is applied to ASLK /Opamp circuit
  - You can use '2 channels' of 2231A DC power supply in independent mode and combine negative one channel with positive of other to be treated as common or ground point



- Use signal from AFG/signal generator to feed to opamp input
- Probe at input and output pins of the amplifier to view the signal on oscilloscope - View input on channel 1 and output on channel 2

Step 4

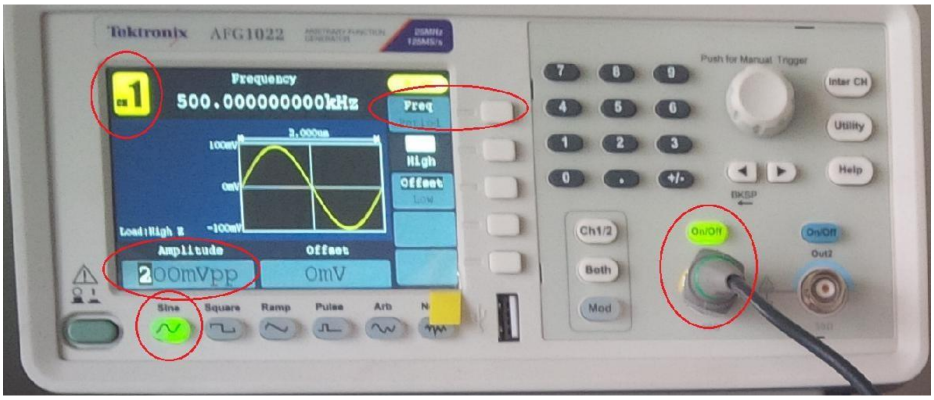
Make the Circuit Work

- Use signal from AFG/signal generator to feed to opamp input
- Set sinusoidal signal from channel 1 of the AFG
  - amplitude = 200 mV_{pp}
  - frequency = 50 kHz
- Autoset the oscilloscope to see both input and output waveforms

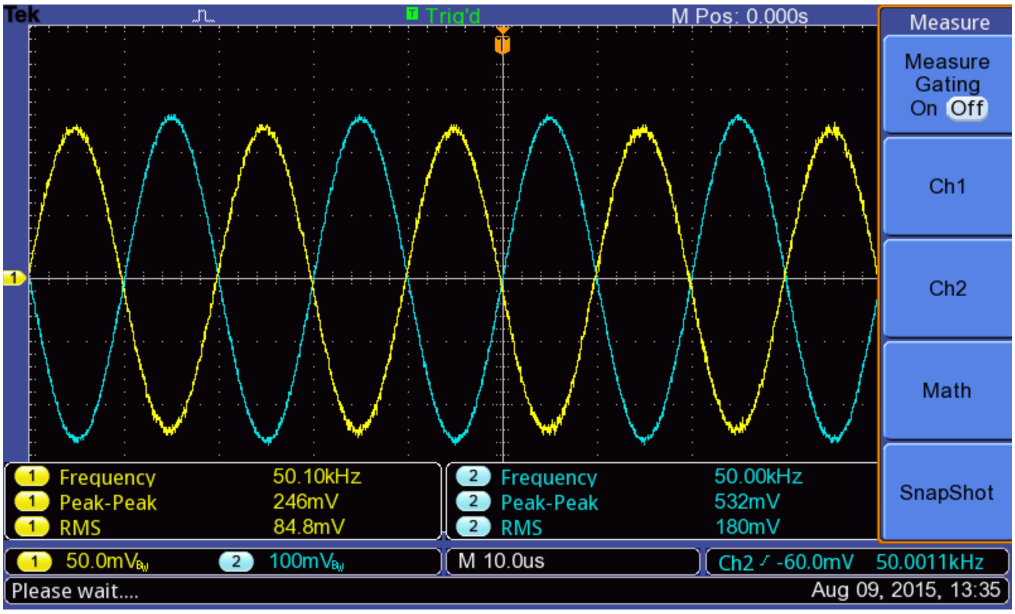
Step 5

Taking the Measurements

- Set input
  - Sinusoidal, 200 mV peak-to-peak amplitude
  - 50kHz frequency
  - Continous mode (on AFG)
  - enable the channel 1 output on AFG



- Autoset the oscilloscope to optimally see both input and output signal
- Set up following measurements:
  - On Ch1 - V_{pp}, V_{rms}, Frequency
  - On Ch2 - V_{pp}, V_{rms}
- Read the measurements in a tabular format, for different input amplitude (200mV / 300mV and 400mV peak-to-peak) for different values of R_f (1K / 2.2K / 4.7K and 10K ohms). You can also capture screenshot for each measurement set.



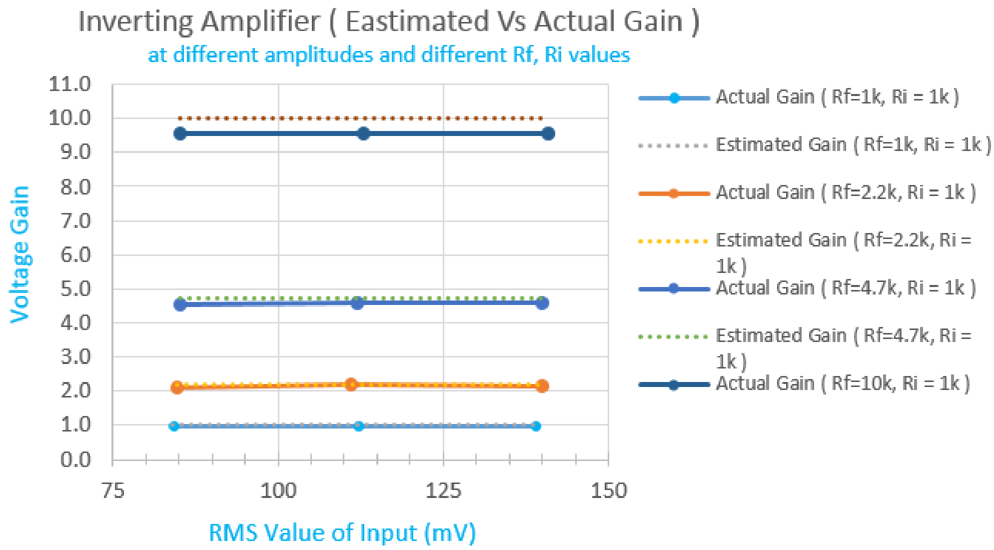
Step 6

Analyzing the Result

- The observation table would look like as shown below. Calculate actual voltage (observed from measurements) and its deviation from estimated (based on resistance values).

#	Rf (kΩ)	Ri (kΩ)	Peak-to-Peak (mV)		Voltage Gain		%	RMS (mV)		Voltage Gain		%
			INPUT	OUTPUT	Estimated	Actual	Deviation	INPUT	OUTPUT	Estimated	Actual	Deviation
1	1.0	1.0	246.0	244.0	1.00	0.99	-0.8%	84.1	82.9	1.00	0.99	-1.4%
2	1.0	1.0	336.0	324.0	1.00	0.96	-3.6%	112.0	110.0	1.00	0.98	-1.8%
3	1.0	1.0	408.0	404.0	1.00	0.99	-1.0%	139.0	138.0	1.00	0.99	-0.7%
4	2.2	1.0	246.0	532.0	2.20	2.16	-1.7%	84.8	180.0	2.20	2.12	-3.5%
5	2.2	1.0	344.0	712.0	2.20	2.07	-5.9%	111.0	242.0	2.20	2.18	-0.9%
6	2.2	1.0	424.0	880.0	2.20	2.08	-5.7%	140.0	302.0	2.20	2.16	-1.9%
7	4.7	1.0	250.0	1120.0	4.70	4.48	-4.7%	85.1	387.0	4.70	4.55	-3.2%
8	4.7	1.0	328.0	1500.0	4.70	4.57	-2.7%	112.0	514.0	4.70	4.59	-2.4%
9	4.7	1.0	412.0	1880.0	4.70	4.56	-2.9%	140.0	642.0	4.70	4.59	-2.4%
10	10.0	1.0	256.0	2340.0	10.00	9.14	-8.6%	85.1	813.0	10.00	9.55	-4.5%
11	10.0	1.0	340.0	3100.0	10.00	9.12	-8.8%	113.0	1080.0	10.00	9.56	-4.4%
12	10.0	1.0	416.0	3920.0	10.00	9.42	-5.8%	141.0	1350.0	10.00	9.57	-4.3%

- Voltage gain (estimated and actual) can be plotted, for different values of input voltage and resistor combinations, to highlight the difference between actual and estimated gain.



- Brainstorm the reasons for such difference between actual and estimated voltage gain

Step 7

Conclusion

The analysis of the observation confirms that (As expected):

- The observed voltage gain follows the estimated value (calculated from resistor values)
- The voltage gain remains constant for given input voltage range
- The phase of output is inverted w.r.t. input - there is a phase inversion as it is inverting amplifier
- The deviation in observed voltage gain from estimated value is more for higher gain (higher R_f to R_i ratio) which could be because of varation in resistance values. Choosing a precise (low tolerance) resistors would reduce this deviation.

Non_Inverting_Amplifier -- Overview

Non-Inverting Amplifier

Objectives:

After performing this lab exercise, learner will be able to:

- Understand and comprehend working of opamp
- Design & build non-inverting amplifier of desired voltage gain using opamp
- Establish relationship between input and output signal
- Practice working with measuring equipment and laboratory tools like digital oscilloscope, signal generator, multimeter and power supply
- Use digital oscilloscope to debug/analyze the circuit

Equipment:

To perform this lab experiment, learner will need:

- Digital Storage Oscilloscope (TBS1000B-Edu from Tektronix or any equivalent)
- Power Supply (2231A-30-3 Power Supply from Keithley or any equivalent power supply capable of supplying +/- 10V DC)
- Signal generator (AFG1000 from Tektronix or equivalent) for providing AC input to circuit
- Multimeter
- Electronic Components
  - Opamp 741 / TL082 or equivalent - as single IC or as part of any analog circuit kit (like ASLK board from TI)
  - Resistor (1K, 2.2K, 4.7K and 10K ohms)
- BNC cables
- Breadboard and connecting wires

Theory / Key Concepts:

Before performing this lab experiment, it is important to learn following concepts:

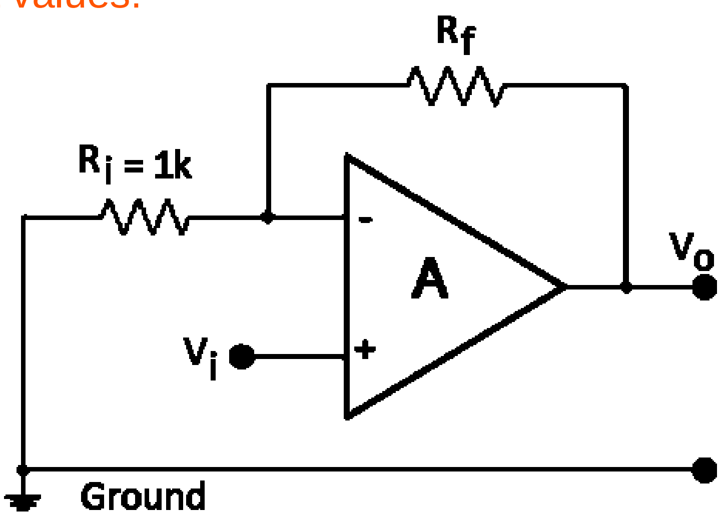
- An opamp is a high-gain differential amplifier with very high input impedance. Very high open-loop gain allow for creating amplifiers with stable gain using feedback.
- In a non-inverting amplifier, the input signal is applied to non-inverting pin of the opamp and there is no phase inversion between output and input.
- The amplification factor or gain can be controlled by external components - Resistor in feedback path R_f and input path R_i.
- Voltage gain of the non-inverting amplifier is given by:

$$Gain = 1 + \frac{R_f}{R_i}$$

- While designing opamp circuits, one has to be careful about output saturation - if the gain or input signal is high enough to drive output beyond the supply voltages (V_{cc} and V_{ee}), the amplifier goes into saturation and output is limited to supply voltages.

Circuit Design:

Learner can use the theoretical design rules to calculate the circuit component values:



- For non-inverting amplifier, the gain depends on R_f and R_i. .
- followign table shows the estimated (and expected) voltage gain for different combinations of R_f and R_i :

Rf (kΩ)	Ri (kΩ)	Voltage Gain Estimated
1.0	1.0	2.00
2.2	1.0	3.20
4.7	1.0	5.70
10.0	1.0	11.00

Non_Inverting_Amplifier -- Procedures

Step 1

Check Your Understanding:

Before performing this lab experiment, learners can check their understanding of key concepts by answering these?

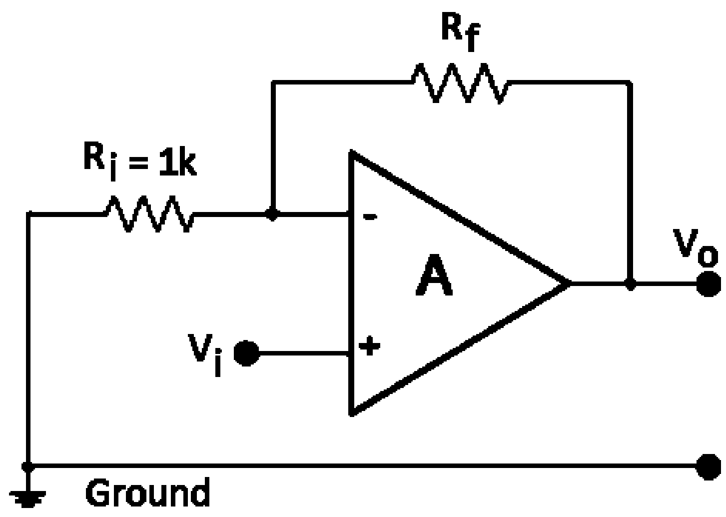
- For a non-inverting amplifier circuit, if $R_f < R_i$, the phase shift between output and input will be:
  - 0 Degree
  - less than 90 Degree
  - 180 Degree
  - more than 90 Degree
- For a non-inverting amplifier circuit, is it possible to reduce the voltage to less than 1?
  - Yes, by choosing R_f less than R_i
  - Yes, by choosing $R_f = R_i$
  - No. Not possible.
  - Yes, by choosing $R_f = 0$ ohms

- In a non-inverting amplifier circuit the ratio of R_f to R_i is 10. What will be the effect on its voltage gain if positions of R_f and R_i are interchanged?
  - Gain will be 10 times of its previous gain
  - Gain will remain unchanged
  - Gain will reduce to 1/10th of its previos value
  - Gain will increase by 10

Step 2

Circuit diagram / Connection Details

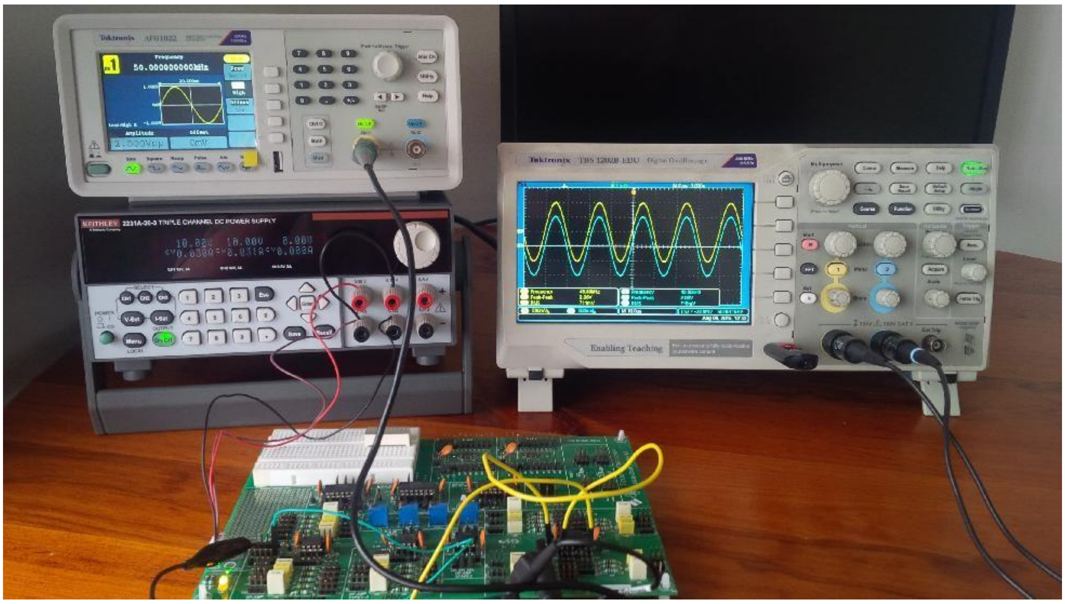
- Using the jumper / connecting wires prepare the circuit as shown below - Choose $R_f = R_i = 1k$ ohm:



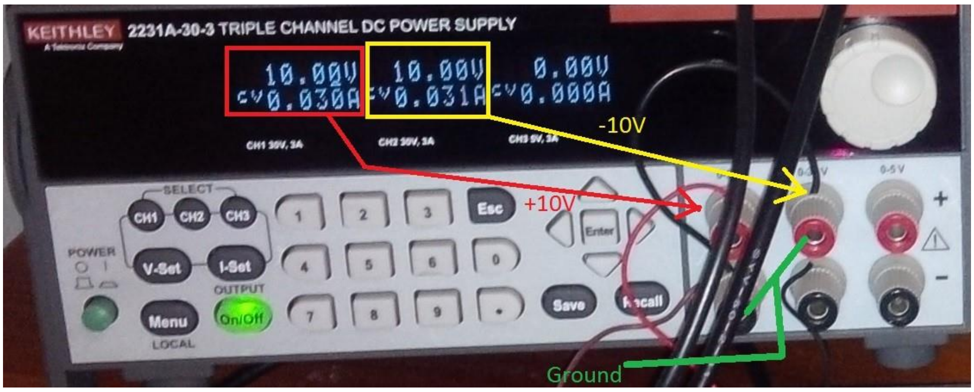
Step 3

Experiment Setup

- Make the arrangement as shown in figure below -



- Turn on the DC power supply, ensure that +/- 10V is applied to ASLK /Opamp circuit
  - You can use '2 channels' of 2231A DC power supply in independent mode and combine negative one channel with positive of other to be treated as common or ground point



- Use signal from AFG/signal generator to feed to opamp input
- Probe at input and output pins of the amplifier to view the signal on oscilloscope - View input on channel 1 and output on channel 2

Step 4

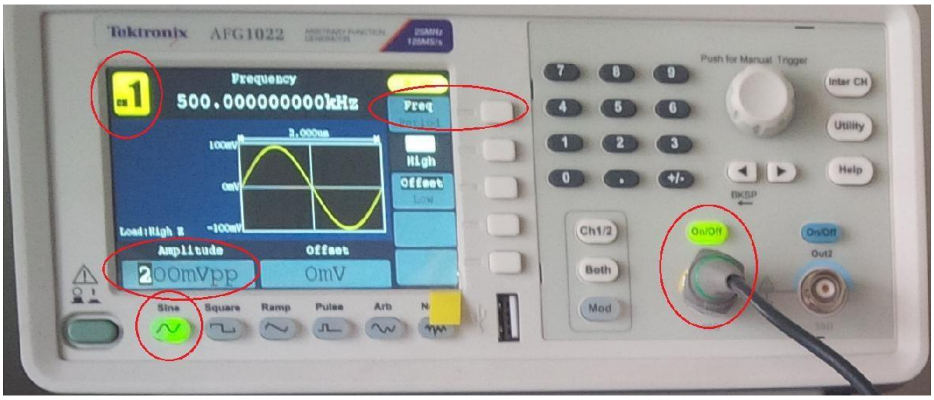
Make the Circuit Work

- Use signal from AFG/signal generator to feed to opamp input
- Set sinusoidal signal from channel 1 of the AFG
  - amplitude = 0.5 V_{pp}
  - frequency = 50 kHz
- Autoset the oscilloscope to see both input and output waveforms

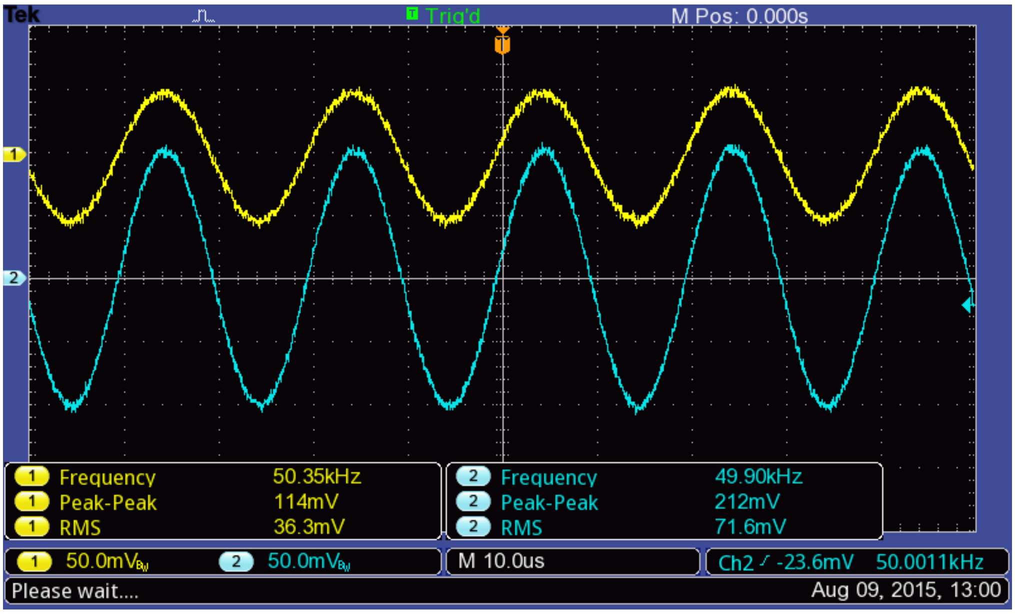
Step 5

Taking the Measurements

- Set input
  - Sinusoidal, 100 mV peak-to-peak amplitude
  - 50kHz frequency
  - Continous mode (on AFG)
  - enable the channel 1 output on AFG



- Autoset the oscilloscope to optimally see both input and output signal
- Set up following measurements:
  - On Ch1 - V_{pp}, V_{rms}, Frequency
  - On Ch2 - V_{pp}, V_{rms}
- Read the measurements in a tabular format, for different input amplitude (100mV / 200mV and 500mV peak-to-peak) for different values of R_f (1K / 2.2K / 4.7K and 10K ohms). You can also capture screenshot for each measurement set.



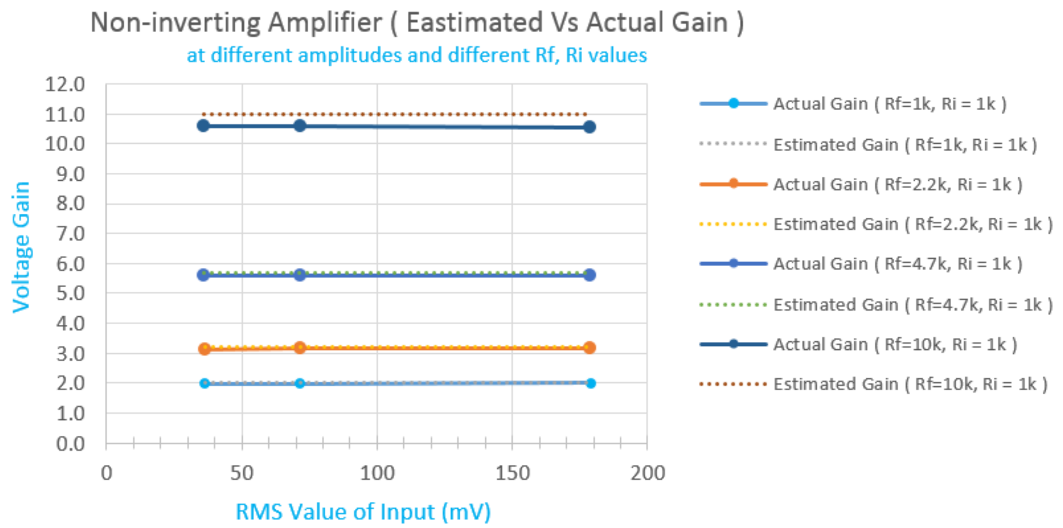
Step 6

Analyzing the Result

- The observation table would look like as shown below. Calculate actual voltage (observed from measurements) and its deviation from estimated (based on resistance values).

#	Rf (kΩ)	Ri (kΩ)	INPUT Vpp (mV)	OUTPUT Vpp (mV)	Voltage Gain Estimated	Voltage Gain Actual	% Deviation
1	1.0	1.0	114.0	212.0	2.00	1.86	-7.0%
2	1.0	1.0	216.0	416.0	2.00	1.93	-3.7%
3	1.0	1.0	536.0	1030.0	2.00	1.92	-3.9%
4	2.2	1.0	108.0	336.0	3.20	3.11	-2.8%
5	2.2	1.0	232.0	680.0	3.20	2.93	-8.4%
6	2.2	1.0	528.0	1640.0	3.20	3.11	-2.9%
7	4.7	1.0	112.0	592.0	5.70	5.29	-7.3%
8	4.7	1.0	216.0	1150.0	5.70	5.32	-6.6%
9	4.7	1.0	528.0	2880.0	5.70	5.45	-4.3%
10	10.0	1.0	102.0	1100.0	11.00	10.78	-2.0%
11	10.0	1.0	212.0	2200.0	11.00	10.38	-5.7%
12	10.0	1.0	536.0	5480.0	11.00	10.22	-7.1%

- Voltage gain (estimated and actual) can be plotted, for different values of input voltage and resistor combinations, to highlight the difference between actual and estimated gain.



- Brainstorm the reasons for such difference between actual and estimated voltage gain

Step 7

Conclusion

The analysis of the observation confirms that (As expected):

- The observed voltage gain follows the estimated value (calculated from resistor values)
- The voltage gain remains constant for given input voltage range
- The phase of input and output remains same - there is no phase inversion as it is non-inverting amplifier
- The deviation in observed voltage gain from estimated value is more for higher gain (higher R_f to R_i ratio) which could be because of varation in resistance values. Choosing a precise (low tolerance) resistors would reduce this deviation.

Non_Inverting_Voltage_Follower -- Overview

Non-Inverting, Unity-Gain Amplifier

Objectives:

After performing this lab exercise, learner will be able to:

- Understand and comprehend working of opamp
- Design & build non-inverting amplifier of unity gain using opamp
- Establish relationship between input and output signal
- Practice working with measuring equipment and laboratory tools like digital oscilloscope, signal generator, multimeter and power supply
- Use digital oscilloscope to debug/analyze the circuit

Equipment:

To perform this lab experiment, learner will need:

- Digital Storage Oscilloscope (TBS1000B-Edu from Tektronix or any equivalent)
- Power Supply (2231A-30-3 Power Supply from Keithley or any equivalent power supply capable of supplying +/- 10V DC)
- Signal generator (AFG1000 from Tektronix or equivalent) for providing AC input to circuit
- Multimeter
- Electronic Components
    - Opamp 741 / TL082 or equivalent - as single IC or as part of any analog circuit kit (like ASLK board from TI)
    - Resistor (10K ohms)
- BNC cables
- Breadboard and connecting wires

Theory / Key Concepts:

Before performing this lab experiment, it is important to learn following concepts:

- An opamp is a high-gain differential amplifier with very high input impedance. Very high open-loop gain allow for creating amplifiers with stable gain using feedback.
- In a non-inverting amplifier, the input signal is applied to non-inverting pin of the opamp and there is no phase inversion between output and input.
- The amplification factor or gain can be controlled by external components - Resistor in feedback path R_f and input path R_i.
- Voltage gain of the non-inverting amplifier is given by:

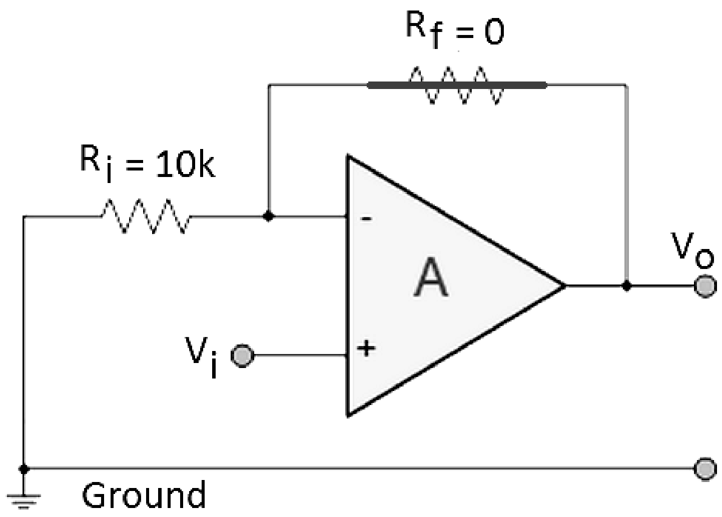
$$Gain = 1 + \frac{R_f}{R_i}$$

- While designing opamp circuits, one has to be careful about output saturation - if the gain or input signal is high enough to drive output beyond the supply voltages (V_{cc} and V_{ee}), the amplifier goes into saturation and output is limited to supply voltages.

Circuit Design:

Learner can use the theoretical design rules to calculate the circuit component values:

- For non-inverting amplifier, the gain depends on R_f and R_i. If R_f = 0 ohms, then gain becomes 1.
- So we will choose R_f = 0 ohms and R_i = 10k ohms as shown in the circuit below:



Non_Inverting_Voltage_Follower -- Procedures

Step 1

Check Your Understanding:

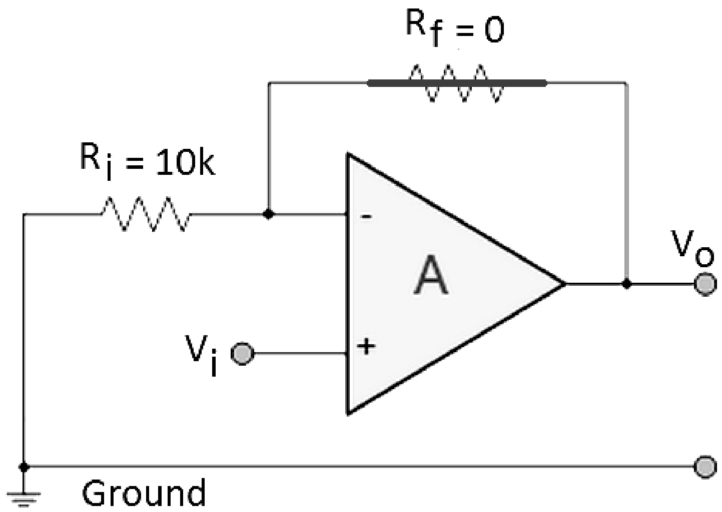
Before performing this lab experiment, learners can check their understanding of key concepts by answering these?

- For a non-inverting amplifier circuit, if R_f = 10K and R_i = 100K ohms, the phase shift between output and input will be:
  - 0 Degree
  - 90 Degree
  - 180 Degree
  - -90 Degree
- For a non-inverting amplifier circuit, if R_f = 10K and R_i = 100K ohms, what will be relation between amplitude of input and output signals?
  - input amplitude will be greater than output
  - both will have same input
  - output amplitude will be greater than input
  - it will depend on the opamp IC chosen
- What will be the effect on gain of a non-inverting voltage follower circuit, if R_i is doubled of its previous value?
  - Gain will be doubled
  - Gain will remain the same (no change)
  - Gain will be halved
  - Gain will be ¼ of previous gain

Step 2

Circuit diagram / Connection Details

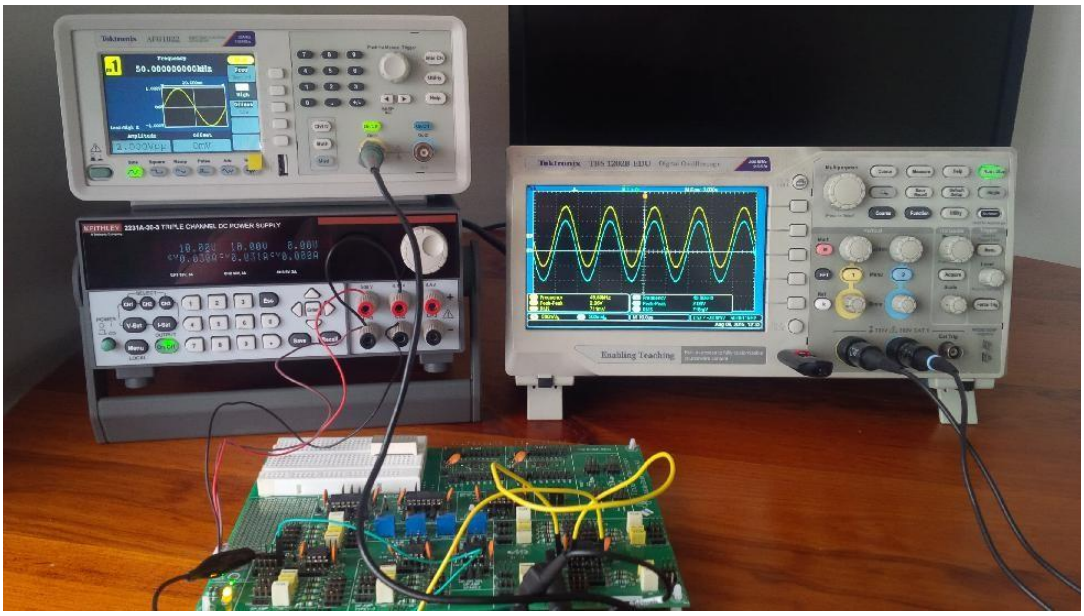
- Using the jumper / connecting wires prepare the circuit as shown below:



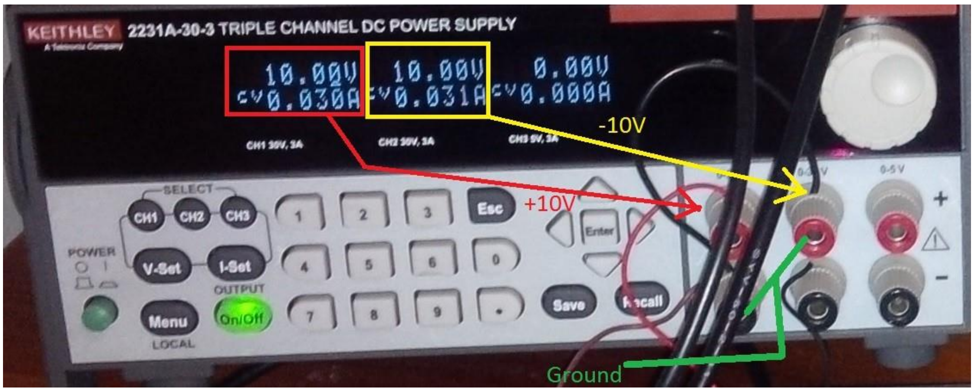
Step 3

Experiment Setup

- Make the arrangement as shown in figure below -



- Turn on the DC power supply, ensure that +/- 10V is applied to ASLK /Opamp circuit
  - You can use '2 channels' of 2231A DC power supply in independent mode and combine negative one channel with positive of other to be treated as common or ground point



- Use signal from AFG/signal generator to feed to opamp input
- Probe at input and output pins of the amplifier to view the signal on oscilloscope - View input on channel 1 and output on channel 2

Step 4

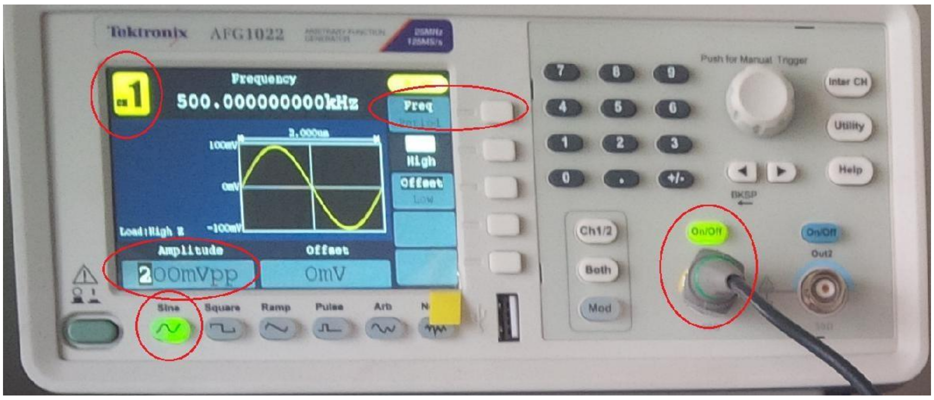
Make the Circuit Work

- Use signal from AFG/signal generator to feed to opamp input
- Set sinusoidal signal from channel 1 of the AFG
  - amplitude = 1 V_{pp}
  - frequency = 500 kHz
- Autoset the oscilloscope to see both input and output waveforms

Step 5

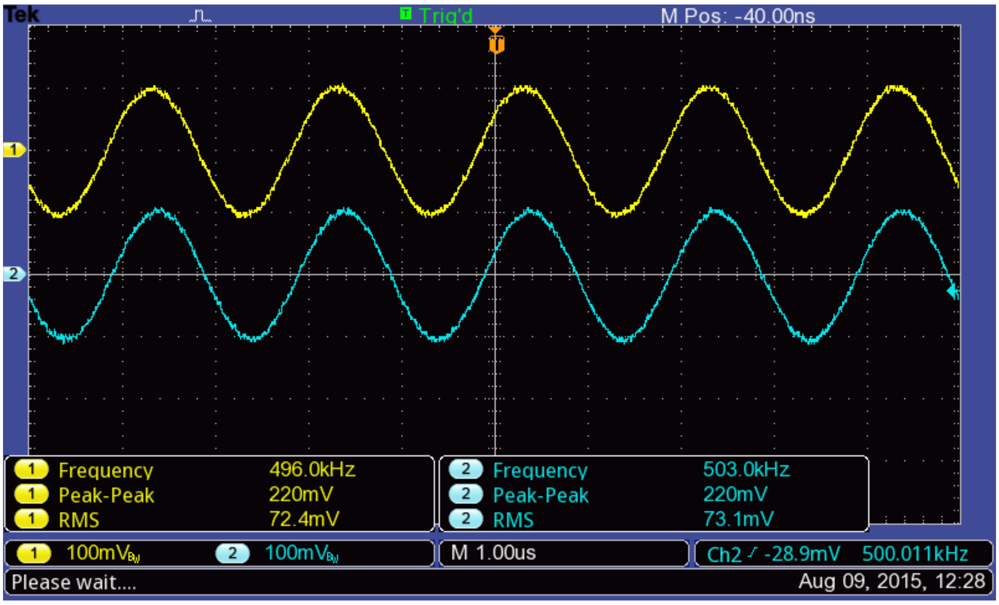
Taking the Measurements

- Set input
  - Sinusoidal, 1V peak-to-peak amplitude
  - 500kHz frequency
  - Continous mode (on AFG)
  - enable the channel 1 output on AFG



- Autoset the oscilloscope to optimally see both input and output signal
- Set up following measurements:
  - On Ch1 - V_{pp}, V_{rms}, Frequency

- On Ch2 - V_{pp}, V_{rms}
- Read the measurements in tabular format, for different input amplitude and (optionally) for another frequency. You can also capture screenshot for each measurement set.



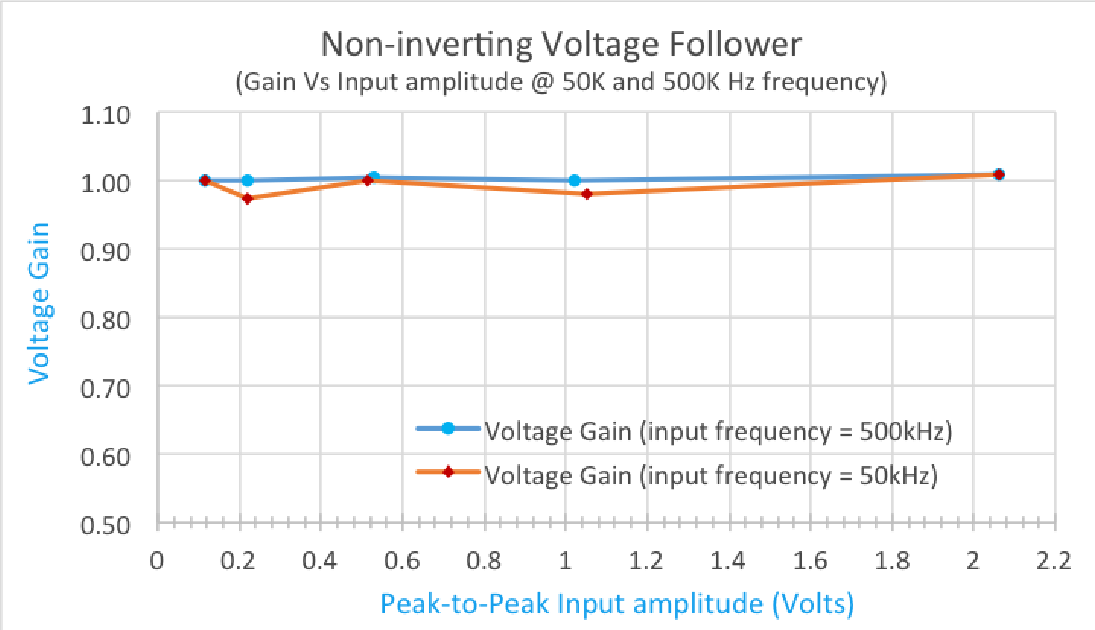
Step 6

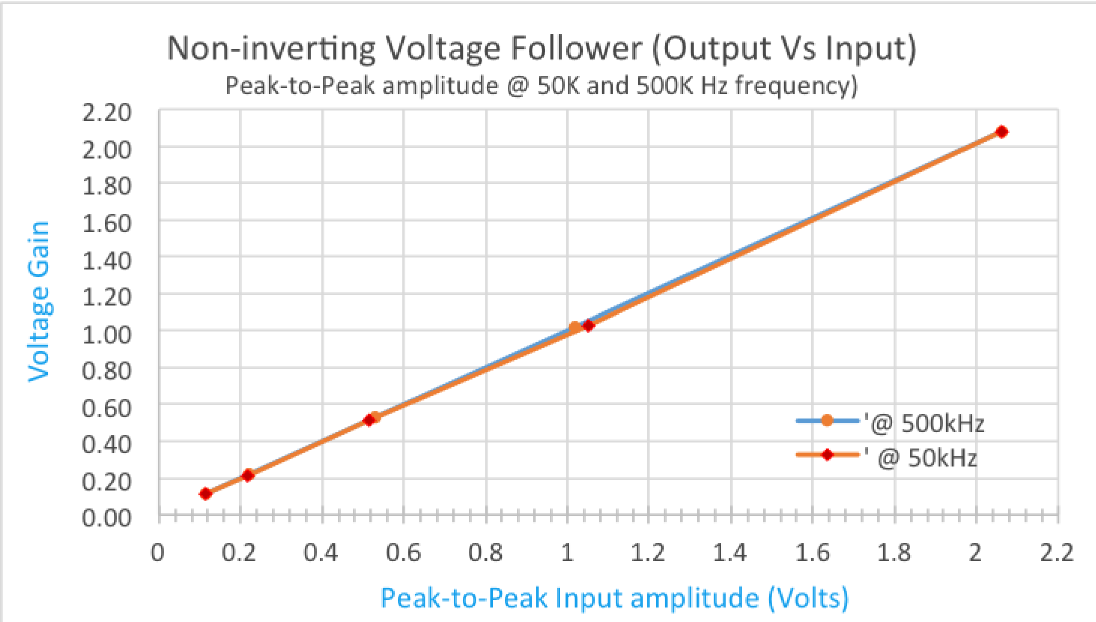
Analyzing the Result

- The observation table would look like this:

#	Frequency (Hz)	INPUT		OUTPUT		Voltage Gain	Voltage Gain (dB)
		Vpp (V)	Vrms (mV)	Vpp (V)	Vrms (mV)		
1	5,00,000	0.114	36.7	0.114	36.9	1.00	0.00
2	5,00,000	0.220	72.4	0.220	73.0	1.00	0.00
3	5,00,000	0.528	181	0.530	182.0	1.00	0.03
4	5,00,000	1.020	349	1.020	349.0	1.00	0.00
5	5,00,000	2.060	709	2.080	710.0	1.01	0.08
6	50,000	0.114	36.7	0.114	36.3	1.00	0.00
7	50,000	0.218	72.3	0.212	71.4	0.97	-0.24
8	50,000	0.516	179	0.516	178.0	1.00	0.00
9	50,000	1.050	360	1.030	359.0	0.98	-0.17
10	50,000	2.060	711	2.080	715.0	1.01	0.08

- The relationship between input and output can be summarized using graphs





Step 7

Conclusion

The analysis of the observation confirms that (As expected):

- The voltage gain is ~ 1 (as expected)
- The voltage gain remains constant for given voltage and frequency range
- The phase of input and output remains same - no phase inversion

Low_Pass_Filter_1st_Order --Overview

1st Order Low Pass Filter

Objectives:

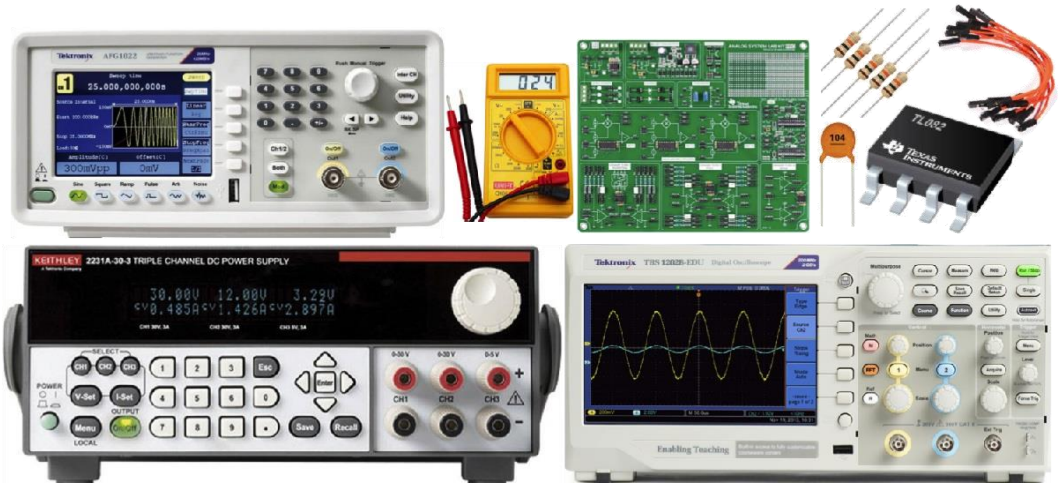
After performing this lab exercise, learner will be able to:

- Understand and comprehend working of opamp
- Comprehend basics of filtering circuits using resistor & capacitor
- Design & build a 1st order low pass filter using opamp
- Establish relationship between input and output signal - prepare a Bode plot for the filter circuit
- Practice working with measuring equipment and laboratory tools like digital oscilloscope, signal generator, multimeter and power supply
- Use digital oscilloscope to debug/analyze the circuit

Equipment:

To perform this lab experiment, learner will need:

- Digital Storage Oscilloscope (TBS1000B-Edu from Tektronix or any equivalent)
- Power Supply (2231A-30-3 Power Supply from Keithley or any equivalent power supply capable of supplying +/- 10V DC)
- Signal generator (AFG1000 from Tektronix or equivalent) for providing AC input to circuit
- Multimeter
- Electronic Components
  - Opamp 741 / TL082 or equivalent - as single IC or as part of any analog circuit kit (like ASLK board from TI)
  - Resistor (1K ohms)
  - Capacitor (0.1uF)
- BNC cables
- Breadboard and connecting wires



Theory / Key Concepts:

Before performing this lab experiment, it is important to learn following concepts:

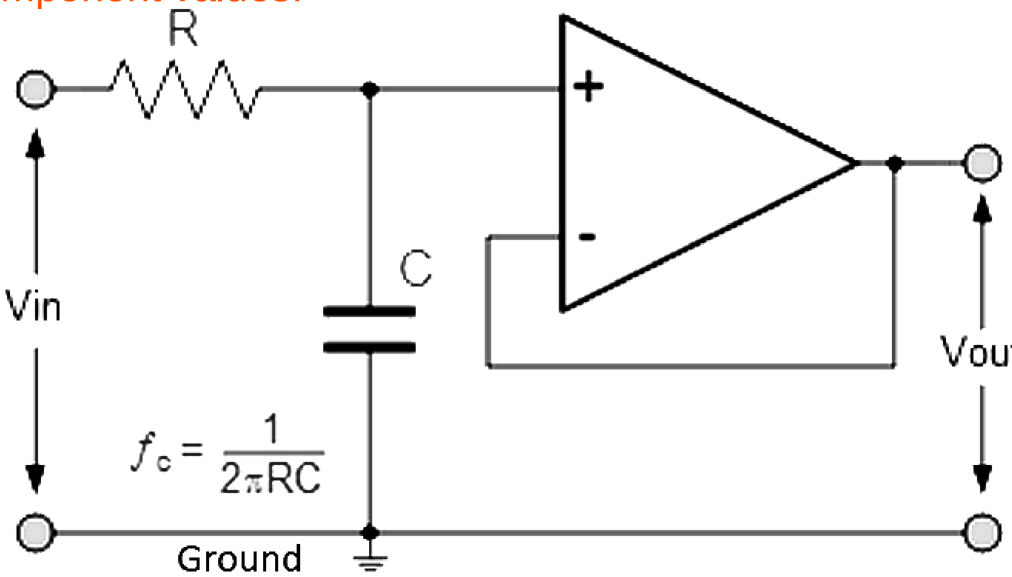
- An opamp is a high-gain differential amplifier with very high input impedance. Very high open-loop gain allow for creating amplifiers with stable gain using feedback.
- A low pass filter is an electronic circuit that passes signals with a frequency lower than a certain value and attenuates signals of higher frequencies.
  - The 'certain' frequency after which the atteneuation starts is called as 'cut-off frequency' of the filter.
  - Range of frequencies below cut-off frequency is called pass-band and higher frequency ranges are called stop band.
- At cut-off frequency, the signal amplitude is 0.707 times of its value in the passband i.e., the signal level is 3dB below the passband value.
- A simple R, C filter makes a 1st order filter of cut-off frequency:

$$f_c = \frac{1}{2.\Pi.R.C}$$

- Filter characteristics is usually shown by a Bode plot which is a graph of the frequency response of the system. A Bode plot show magnitude and phase variation w.r.t. input signal frequency.
- Low pass filter is used for eliminating high-frequency noise from the system.

Circuit Design:

Learner can use the theoretical design rules to calculate the circuit component values:



- Choosing R = 1k Ohms and C = 0.1uF, cut-off frequency will be 1592 Hz

Low_Pass_Filter_1st_Order -- Procedures

Step 1

Check Your Understanding:

Before performing this lab experiment, learners can check their understanding of key concepts by answering these?

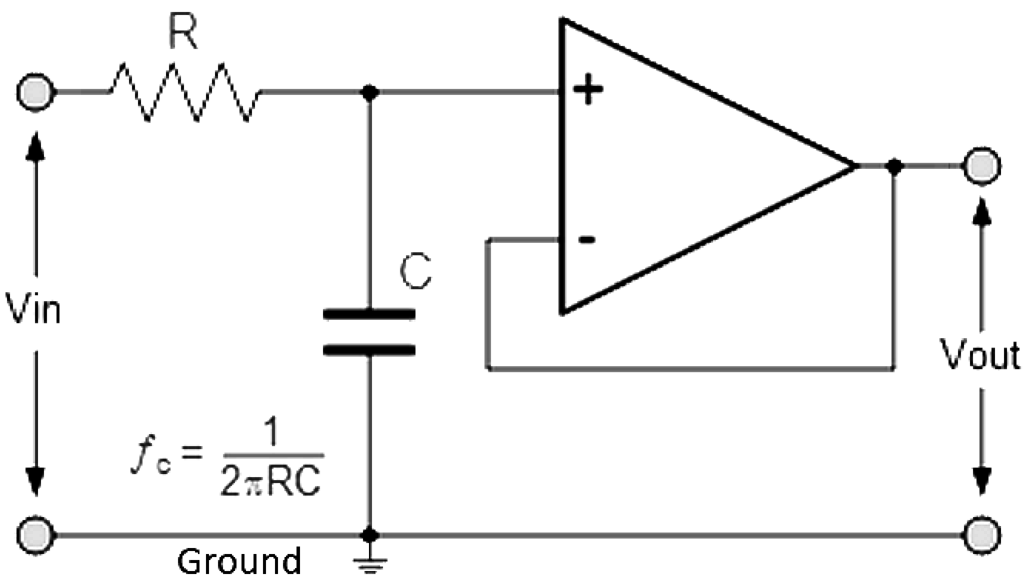
- What will be the effect of a low-pass filter with cut-off frequency of 10kHz, on a sinusoid of 35kHz?
  - Signal will be amplified
  - Signal will be attenuated
  - Signal amplitude will remain same
  - Signal will be rectified
- If 1V peak-to-peak, 10kHz sinusoid is applied to a low-pass filter of cut-off frequency 10kHz, the amplitude of the filter output will be?
  - 1.707 V_{pp}
  - 1.414 V_{pp}
  - 1.000 V_{pp}
  - 0.707 V_{pp}
- A low-pass filter also behaves as:
  - A differentiator circuit
  - An integrator circuit
  - A rectifier circuit

- A logrithmic amplifier circuit

Step 2

Circuit diagram / Connection Details

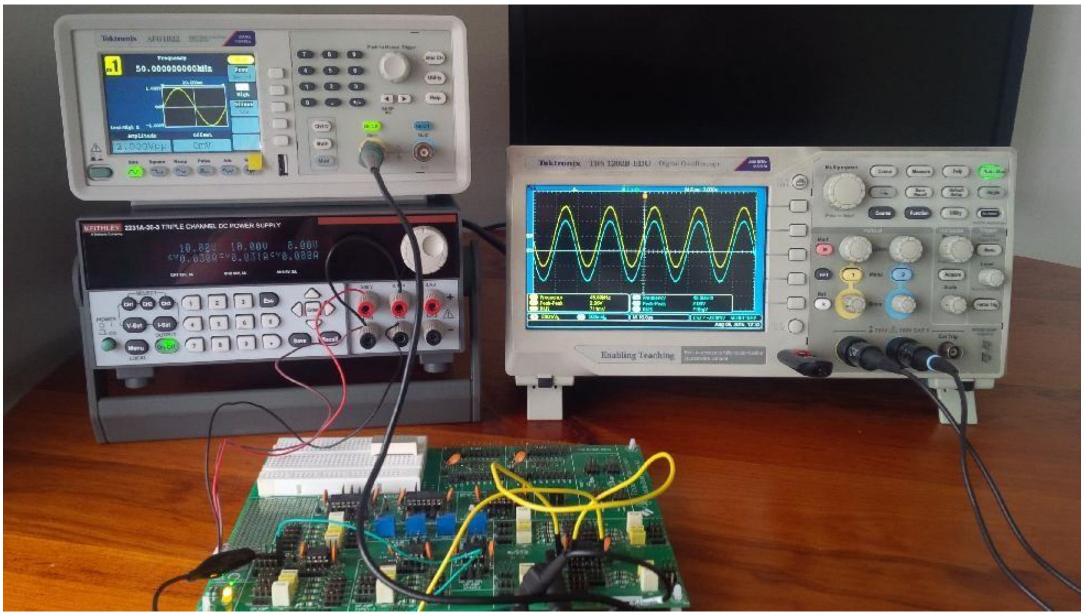
- Using the jumper / connecting wires prepare the circuit as shown below - Choose C = 0.1uF & R = 1k ohm:



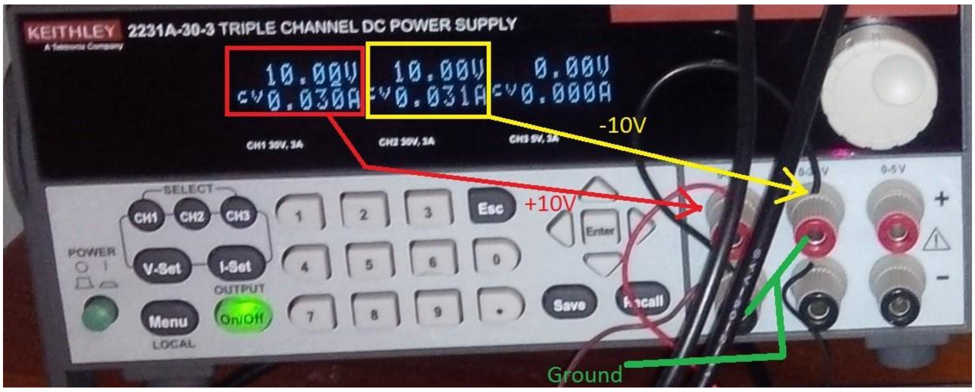
Step 3

Experiment Setup

- Make the arrangement as shown in figure below -



- Turn on the DC power supply, ensure that +/- 10V is applied to ASLK /Opamp circuit
    - You can use '2 channels' of 2231A DC power supply in independent mode and combine negative one channel with positive of other to be treated as common or ground point



- Use signal from AFG/signal generator to feed to opamp input
- Probe at input and output pins of the filter to view the signal on oscilloscope - View input on channel 1 and output on channel 2

Step 4

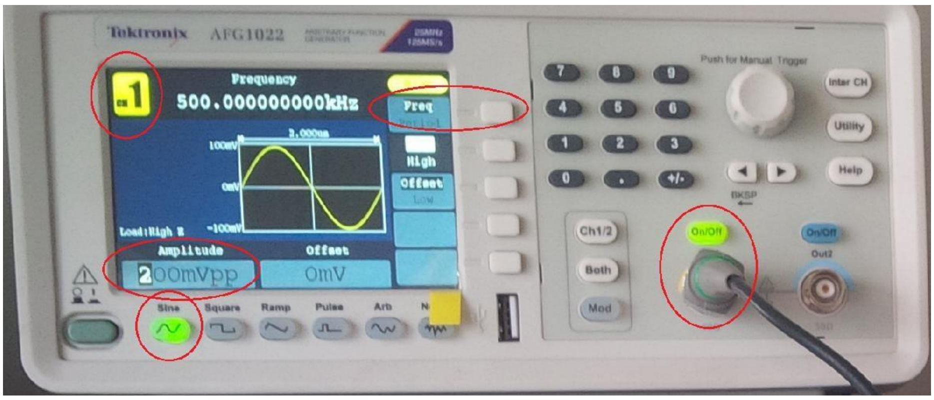
Make the Circuit Work

- Use signal from AFG/signal generator to feed to opamp input
- Set sinusoidal signal from channel 1 of the AFG
  - amplitude = 1 V_{pp}
  - frequency = 50 Hz
- Autoset the oscilloscope to see both input and output waveforms

Step 5

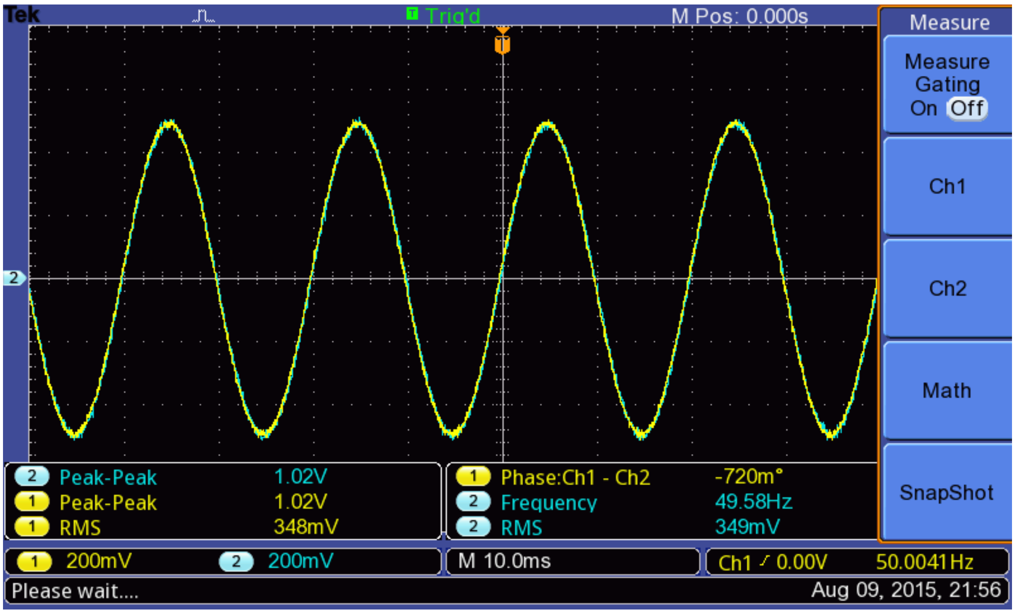
Taking the Measurements

- Set input
  - Sinusoidal, 1V peak-to-peak amplitude
  - 50 Hz frequency
  - Continous mode (on AFG)
  - enable the channel 1 output on AFG



- Autoset the oscilloscope to optimally see both input and output signal
- Set up following measurements:
  - On Ch1 - V_{pp}, V_{rms}, Frequency
  - On Ch2 - V_{pp}, V_{rms}, and Phase (between Ch1 and Ch2)

- Keeping the amplitude of the sinusoid input fixed at 1V peak-to-peak, vary its frequency from 50Hz to 50kHz. You may take more readings near cut-off frequency.
- Tabulate the measurements. You can also capture screenshot for each measurement set.



Step 6

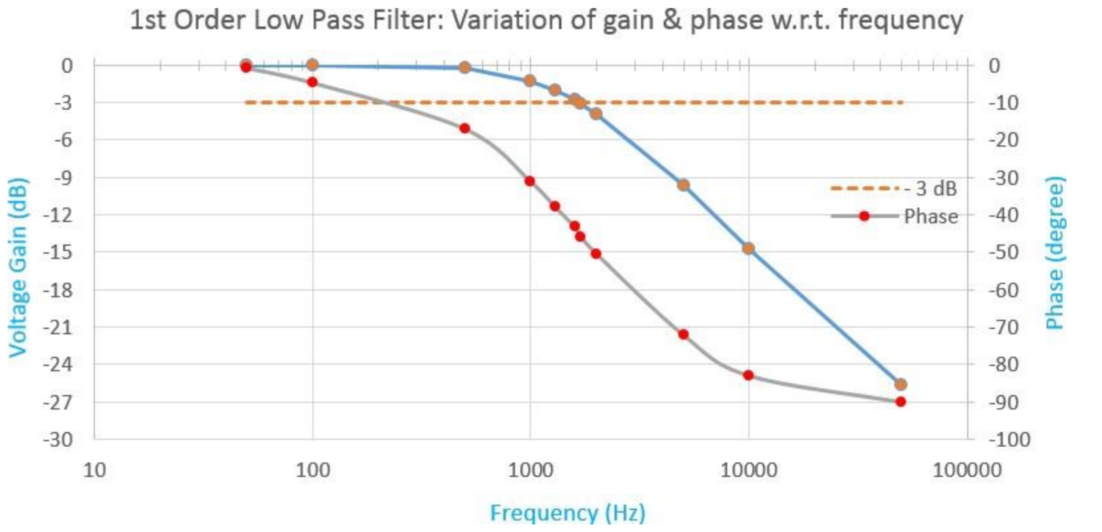
Analyzing the Result

- The observation table would look like as shown below. Calculate voltage gain (observed from measurements) and its decible equivalent.

#	Frequency (Hz)	INPUT		OUTPUT		Phase Difference (Degrees)	Voltage Gain	Voltage Gain (dB)
		Vpp (V)	Vrms (mV)	Vpp (V)	Vrms (mV)			
1	50	1.020	348	1.020	349.0	-0.72	1.00	0.00
2	100	1.020	348	1.020	349.0	-4.68	1.00	0.00
3	500	1.020	351	0.992	336.0	-17.00	0.97	-0.24
4	1,000	1.010	348	0.872	297.0	-31.10	0.86	-1.28
5	1,302	1.010	354	0.800	277.0	-38.00	0.79	-2.02
6	1,601	1.000	348	0.728	249.0	-43.30	0.73	-2.76
7	1,702	1.000	343	0.704	242.0	-45.90	0.70	-3.05
8	2,004	1.010	351	0.640	222.0	-50.40	0.63	-3.96
9	5,000	1.000	347	0.328	110.0	-72.00	0.33	-9.68
10	10,000	1.000	349	0.184	58.0	-82.90	0.18	-14.70
11	50,000	1.000	351	0.052	12.8	-90.00	0.05	-25.68

** MINUS sign in the phase signifies that output lags input

- Prepare Bode plot - plot voltage gain and phase against frequency.



- Find out the cut-off frequency from the plot (where the gain drops to -3dB from its passband value)

Step 7

Conclusion

The analysis of the observed results confirm that (As expected):

- The voltage gain of the filter circuit reduces as input frequency is increased
- The cut-off frequency (where gain is -3dB or 3dB down from its passband value) is 1700Hz. Which is quite close to estimated (calculated from R and C values) value of 1592 Hz.
- The phase at cut-off frequency is -45 degrees. (minus sign in the phase signifies, output lags input)

High_Pass_Filter_1st_Order -- Overview

1^{st} Order High Pass Filter

Objectives:

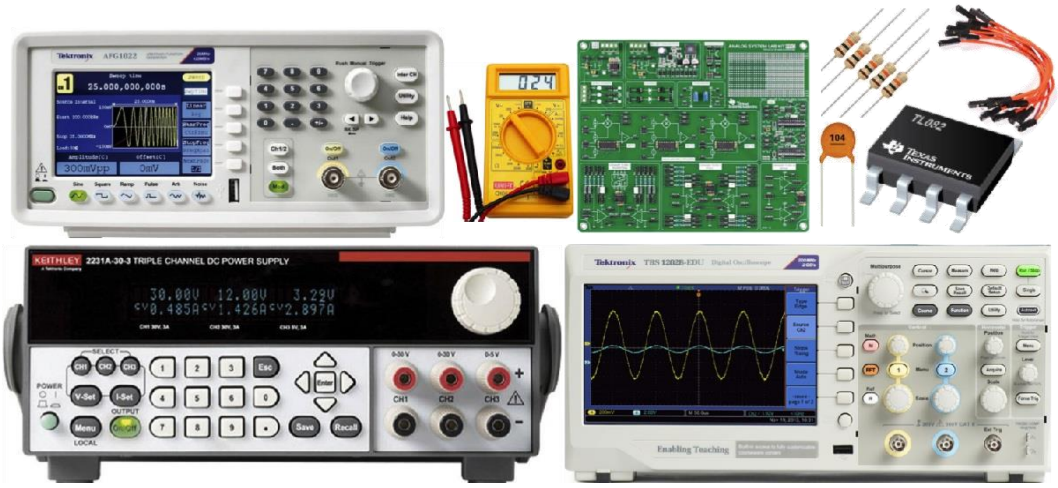
After performing this lab exercise, learner will be able to:

- Understand and comprehend working of opamp
- Comprehend basics of filtering circuits using resistor & capacitor
- Design & build a 1^{st} order high pass filter using opamp
- Establish relationship between input and output signal - prepare a Bode plot for the filter circuit
- Practice working with measuring equipment and laboratory tools like digital oscilloscope, signal generator, multimeter and power supply
- Use digital oscilloscope to debug/analyze the circuit

Equipment:

To perform this lab experiment, learner will need:

- Digital Storage Oscilloscope (TBS1000B-Edu from Tektronix or any equivalent)
- Power Supply (2231A-30-3 Power Supply from Keithley or any equivalent power supply capable of supplying +/- 10V DC)
- Signal generator (AFG1000 from Tektronix or equivalent) for providing AC input to circuit
- Multimeter
- Electronic Components
  - Opamp 741 / TL082 or equivalent - as single IC or as part of any analog circuit kit (like ASLK board from TI)
  - Resistor (1K ohms)
  - Capacitor (0.1uF)
- BNC cables
- Breadboard and connecting wires



Theory / Key Concepts:

Before performing this lab experiment, it is important to learn following concepts:

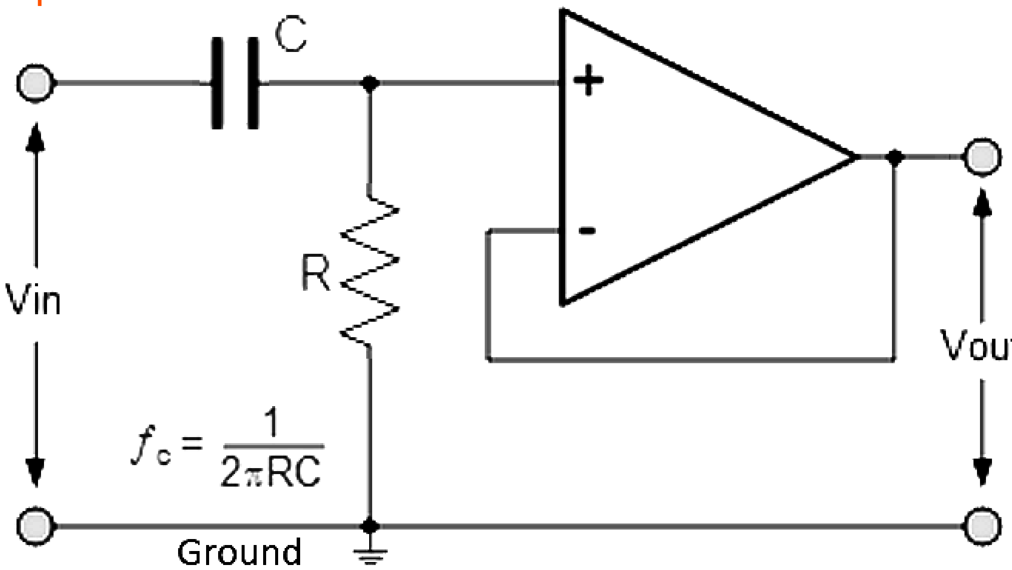
- An opamp is a high-gain differential amplifier with very high input impedance. Very high open-loop gain allow for creating amplifiers with stable gain using feedback.
- A high-pass filter is an electronic circuit that attenuates signals with a frequency lower than a certain value and passes signals of higher frequencies.
  - The 'certain' frequency after which the atteneuation ends is called as 'cut-off frequency' of the filter.
  - Range of frequencies below cut-off frequency is called stop band and higher frequency ranges are called pass band.
- At cut-off frequency, the signal amplitude is 0.707 times of its value in the passband i.e., the signal level is 3dB below the passband value.
- A simple R, C filter makes a 1st order filter of cut-off frequency:

$$f_c = \frac{1}{2.\Pi.R.C}$$

- Filter characteristics is usually shown by a Bode plot which is a graph of the frequency response of the system. A Bode plot show magnitude and phase variation w.r.t. input signal frequency.
- High-pass filter is used for eliminating low-frequency motion artefacts / noise from the medical signal like ECG.

Circuit Design:

Learner can use the theoretical design rules to calculate the circuit component values:



- Choosing R = 1k Ohms and C = 0.1uF, cut-off frequency will be 1592 Hz

High_Pass_Filter_1st_Order -- Procedures

Step 1

Check Your Understanding:

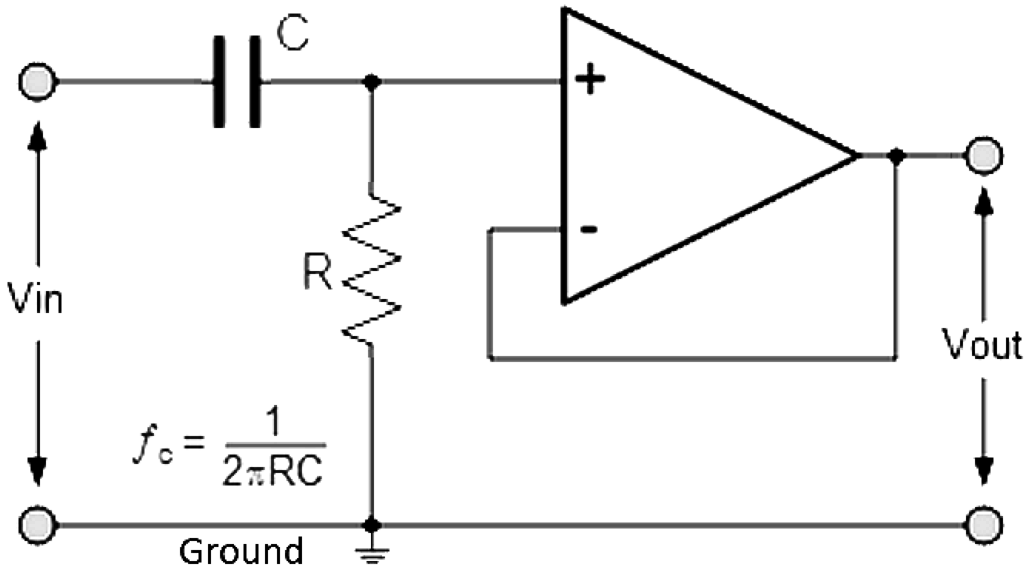
Before performing this lab experiment, learners can check their understanding of key concepts by answering these?

- What will be the effect of a high-pass filter with cut-off frequency of 1kHz, on a sinusoid of 35kHz?
  - Signal will be amplified
  - Signal will be attenuated
  - Signal amplitude will remain same
  - Signal will be rectified
- If 1V peak-to-peak, 10kHz sinusoid is applied to a high-pass filter of cut-off frequency 10kHz, the amplitude of the filter output will be?
  - 1.707 V_{pp}
  - 1.414 V_{pp}
  - 1.000 V_{pp}
  - 0.707 V_{pp}
- A high-pass filter also behaves as:
  - A differentiator circuit
  - An integrator circuit
  - A rectifier circuit
  - A logrithmic amplifier circuit

Step 2

Circuit diagram / Connection Details

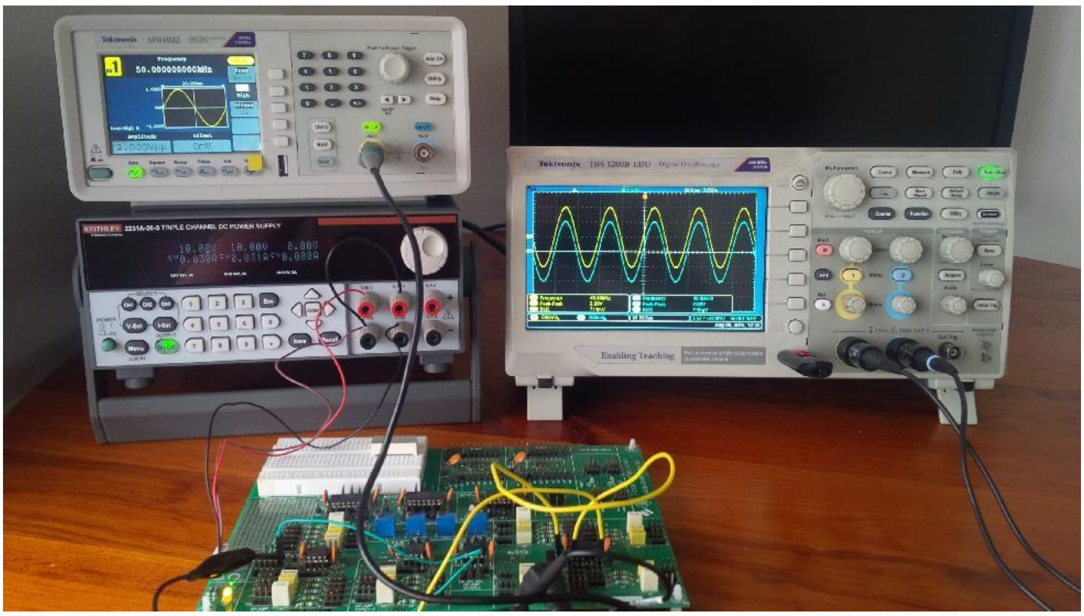
- Using the jumper / connecting wires prepare the circuit as shown below - Choose C = 0.1uF & R = 1k ohm:



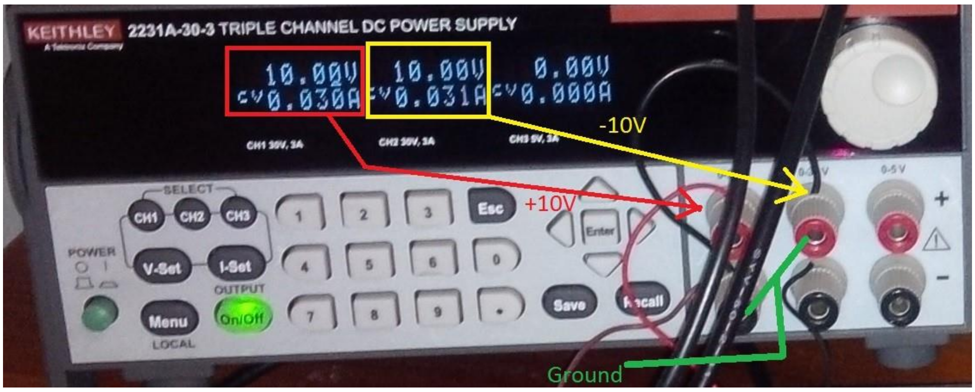
Step 3

Experiment Setup

- Make the arrangement as shown in figure below -



- Turn on the DC power supply, ensure that +/- 10V is applied to ASLK /Opamp circuit
    - You can use '2 channels' of 2231A DC power supply in independent mode and combine negative one channel with positive of other to be treated as common or ground point



- Use signal from AFG/signal generator to feed to opamp input
- Probe at input and output pins of the filter to view the signal on oscilloscope - View input on channel 1 and output on channel 2

Step 4

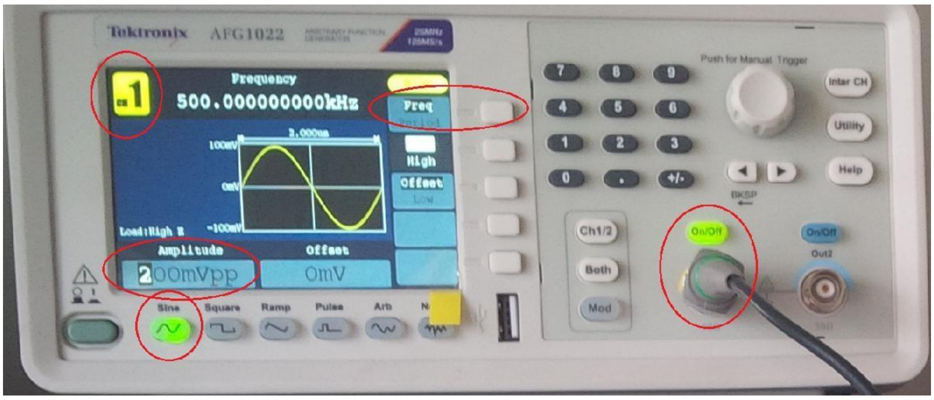
Make the Circuit Work

- Use signal from AFG/signal generator to feed to opamp input
- Set sinusoidal signal from channel 1 of the AFG
  - amplitude = 1 V_{pp}
  - frequency = 50 kHz
- Autoset the oscilloscope to see both input and output waveforms

Step 5

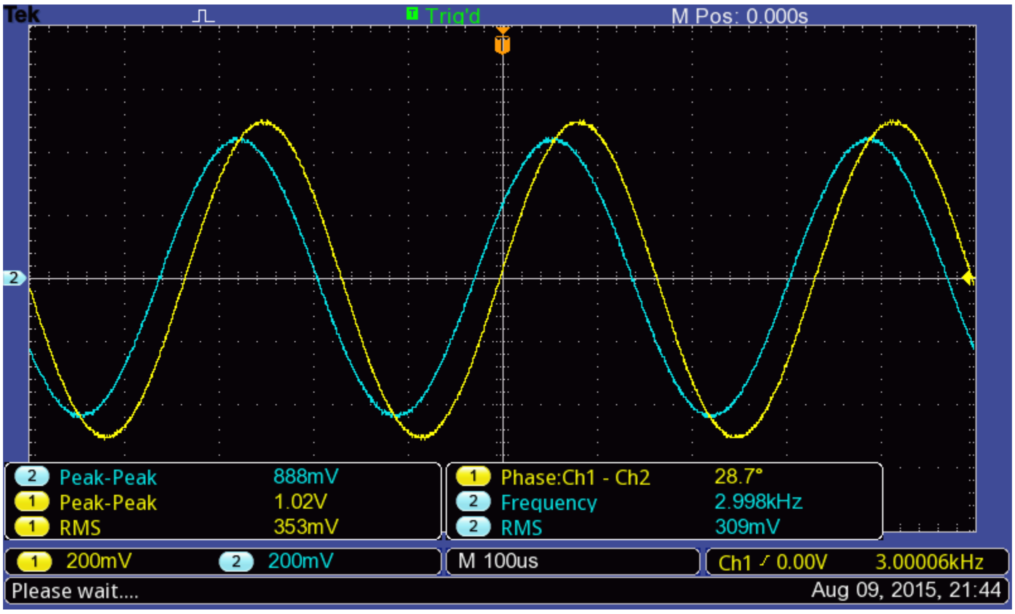
Taking the Measurements

- Set input
  - Sinusoidal, 1V peak-to-peak amplitude
  - 50 kHz frequency
  - Continous mode (on AFG)
  - enable the channel 1 output on AFG



- Autoset the oscilloscope to optimally see both input and output signal
- Set up following measurements:
  - On Ch1 - V_{pp}, V_{rms}, Frequency
  - On Ch2 - V_{pp}, V_{rms}, and Phase (between Ch1 and Ch2)

- Keeping the amplitude of the sinusoid input fixed at 1V peak-to-peak, vary its frequency from 50Hz to 50kHz. You may take more readings near cut-off frequency.
- Tabulate the measurements. You can also capture screenshot for each measurement set.



Step 6

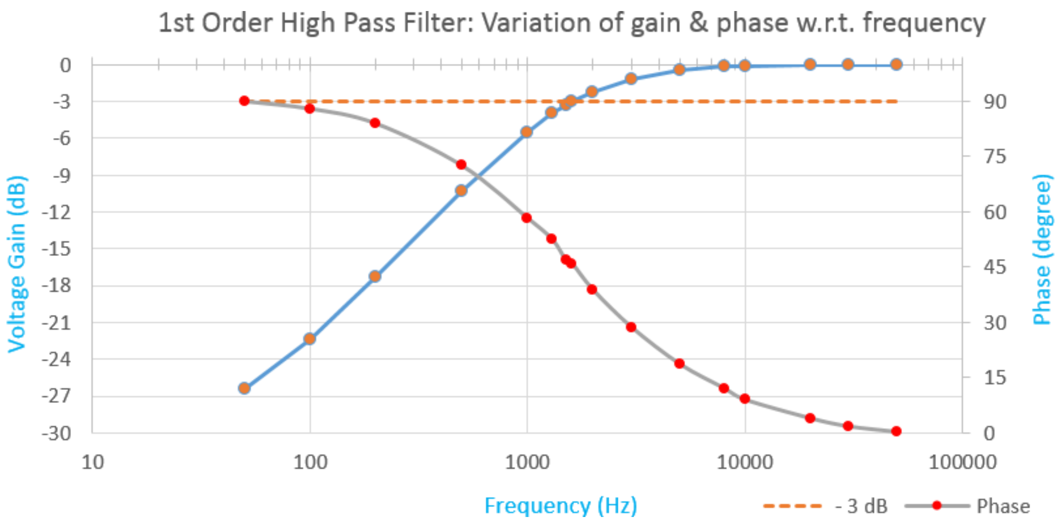
Analyzing the Result

- The observation table would look like as shown below. Calculate voltage gain (observed from measurements) and its decible equivalent.

#	Frequency (Hz)	INPUT		OUTPUT		Phase Difference (Degrees)	Voltage Gain	Voltage Gain (dB)
		Vpp (V)	Vrms (mV)	Vpp (V)	Vrms (mV)			
1	50	1.000	349	0.048	10.9	90.00	0.05	-26.375
2	100	1.000	349	0.076	21.7	88.00	0.08	-22.384
3	200	1.000	349	0.136	42.8	84.00	0.14	-17.329
4	500	1.000	348	0.304	102.0	72.50	0.30	-10.343
5	1,000	1.020	355	0.536	185.0	58.30	0.53	-5.589
6	1,300	1.000	349	0.632	217.0	52.50	0.63	-3.986
7	1,500	1.000	347	0.680	235.0	46.80	0.68	-3.350
8	1,600	1.010	352	0.712	246.0	46.00	0.70	-3.037
9	2,000	1.010	351	0.776	272.0	38.80	0.77	-2.289
10	3,000	1.020	353	0.888	309.0	28.70	0.87	-1.204
11	5,000	1.000	349	0.952	331.0	18.70	0.95	-0.427
12	8,000	1.000	351	0.984	343.0	12.10	0.98	-0.140
13	10,000	1.000	342	0.984	336.0	9.00	0.98	-0.140
14	20,000	1.000	342	1.000	321.0	3.93	1.00	0.000
15	30,000	1.000	343	1.000	342.0	1.72	1.00	0.000
16	50,000	1.010	347	1.000	342.0	0.24	0.99	-0.086

** POSITIVE phase signifies that output leads input

- Prepare Bode plot - plot voltage gain and phase against frequency.



- Find out the cut-off frequency from the plot (where the gain drops to -3dB from its passband value)

Step 7

Conclusion

The analysis of the observed results confirm that (As expected):

- The voltage gain of the filter circuit increases towards '1' as input frequency is increased
- The cut-off frequency (where gain is -3dB or 3dB down from its passband value) is 1600Hz. Which is quite close to estimated (calculated from R and C values) value of 1592 Hz.
- The phase at cut-off frequency is 45 degrees.

Sallen-Key_Low_Pass_Filter -- Overview

Sallen-Key LowPass Filter

Objectives:

After performing this lab exercise, learner will be able to:

- Understand & analyze working of Sallen-Key topology of active filters
- Design & build a Sallen-Key low pass filter using opamp
- Establish relationship between input and output signal - prepare a Bode plot for the filter circuit
- Practice working with measuring equipment and laboratory tools like digital oscilloscope, signal generator, multimeter and power supply
- Use digital oscilloscope to debug/analyze the circuit

Equipment:

To perform this lab experiment, learner will need:

- Digital Storage Oscilloscope (TBS1000B-Edu from Tektronix or any equivalent)
- Power Supply (2231A-30-3 Power Supply from Keithley or any equivalent power supply capable of supplying +/- 10V DC)
- Signal generator (AFG1000 from Tektronix or equivalent) for providing AC input to circuit
- Multimeter
- Electronic Components
  - Opamp 741 / TL082 or equivalent - as single IC or as part of any analog circuit kit (like ASLK board from TI)
  - Resistor (2 x 1K ohms)
  - Capacitor (2 x 0.1 uF)
- BNC cables
- Breadboard and connecting wires

Theory / Key Concepts:

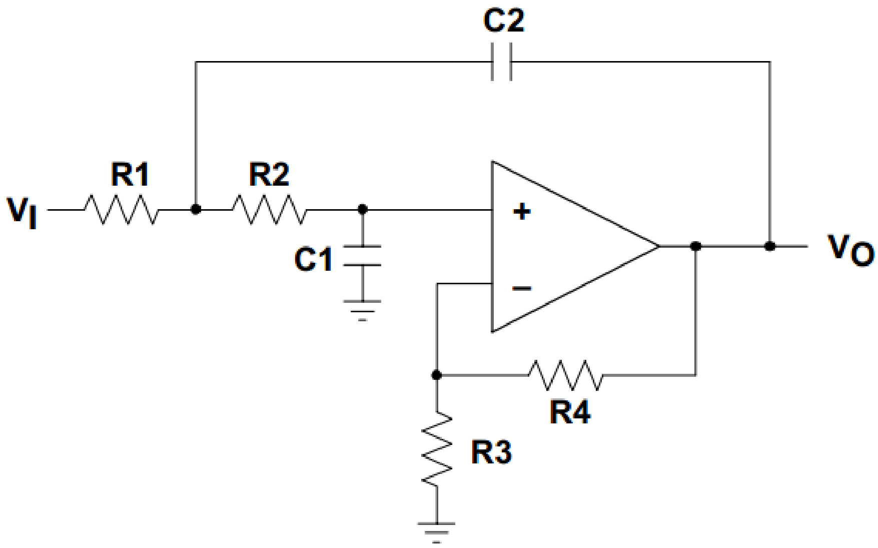
Before performing this lab experiment, it is important to learn following concepts:

- An opamp is a high-gain differential amplifier with very high input impedance. Very high open-loop gain allow for creating amplifiers with stable gain using feedback.
- A low pass filter is an electronic circuit that passes signals with a frequency lower than a certain value and attenuates signals of higher frequencies.
  - The 'certain' frequency after which the atteneuation starts is called as 'cut-off frequency' of the filter.
  - Range of frequencies below cut-off frequency is called pass-band and higher frequency ranges are called stop band.
- At cut-off frequency, the signal amplitude is 0.707 times of its value in the passband i.e., the signal level is 3dB below the passband value.
- Professors R.P. Sallen and E.L. Key described a new filter topology in 1955, which was named after them, the Sallen-Key filters.
- An active Sallen-Key filter can be cascaded easily to make higher order filters. The opamp provides the buffering buffering between cascaded stages.
- Sallen-Key filter gives the flexibility of modifying the filter characteristics (cut-off frequency and Q) using R, C values and amplifier gain. This makes filter design easy.
- Low pass filter is used for eliminating high-frequency noise from the system.

Circuit Design:

Learner can use the theoretical design rules to calculate the circuit component values:

- A generic Sallen-Key low pass filter circuit is shown below with filter parameters:



Where:

- K = amplifier gain = 1 + (R4 / R3)
- Transfer function = V_0/V_i

$$= \frac{K}{s^2(R1R2C1C2) + s(R1C1 + R2C1 + R1C2(1 - K)) + 1}$$

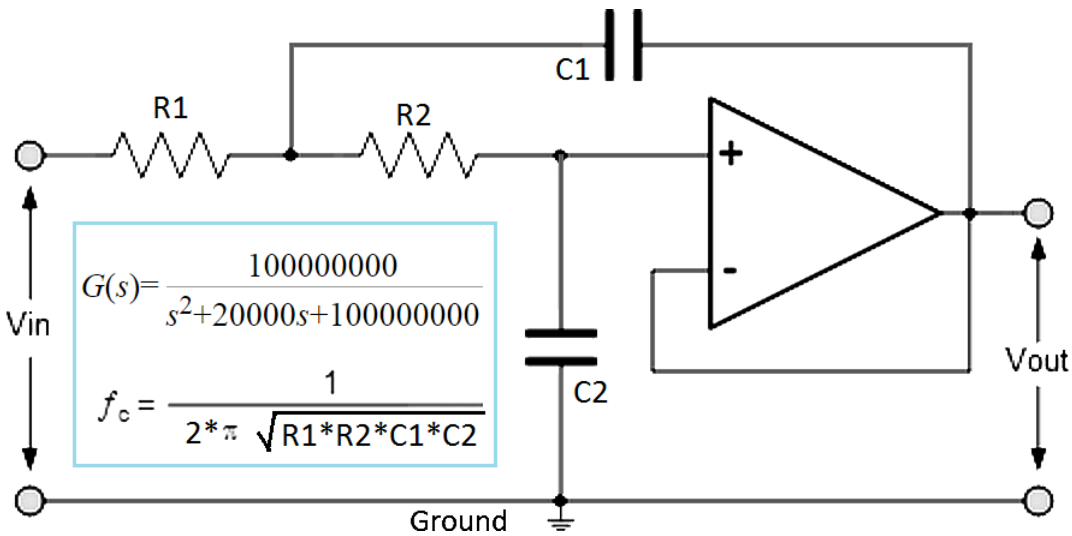
- Cut-off frequency =

$$fc = \frac{1}{2\pi\sqrt{R1R2C1C2}}$$

and

$$Q = \frac{\sqrt{R1R2C1C2}}{R1C1 + R2C1 + R1C2(1 - K)}$$

- We can simplify the filter design by choosing R1 = R2 = R = 1k Ohms and C1 = C2 = C = 0.1uF. The opamp gain is kept unity (R4 = 0 and R3 = infinty).



- This makes
  - Amplifier gain K =1
  -

- With the given R and C values, the cut-off frequency will be 1592 Hz, Q = 1/2 and K (opamp amplifier gain) = 1

Sallen-Key_Low_Pass_Filter -- Procedures

Step 1

Check Your Understanding:

Before performing this lab experiment, learners can check their understanding of key concepts by answering these?

- What will be the slope of magnitude response in the stop band of a Sallen-Key low-pass filter?
    - -20dB / decade
    - 0 dB / decade
    - -40dB / decade
    - +20dB / decade

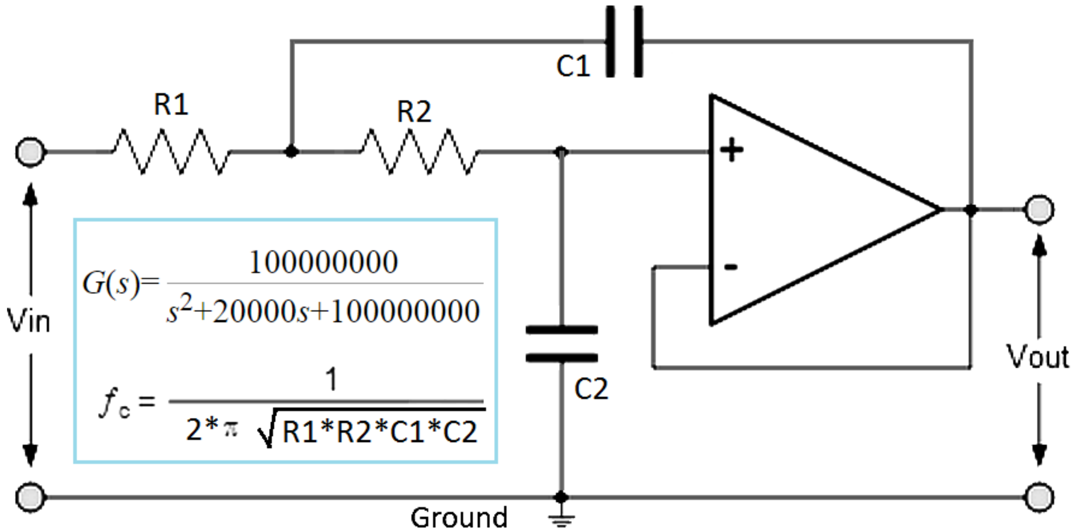
- How will the phase respones for Sallen-Key low pass filter vary with frequency of input signal?
    - Phase will vary from 0 to 90 degrees as frequency goes low to high
    - Phase will vary from 0 to -90 degrees as frequency goes low to high
    - Phase will vary from 0 to -180 degrees as frequency goes low to high
    - Phase will vary from 180 to 0 degrees as frequency goes low to high

- The response of the filter circuit will not produce any overshoot or oscillation for:
    - Q = 1
    - Q=0.5
    - Q<0.5
    - Q = infinity

Step 2

Circuit diagram / Connection Details

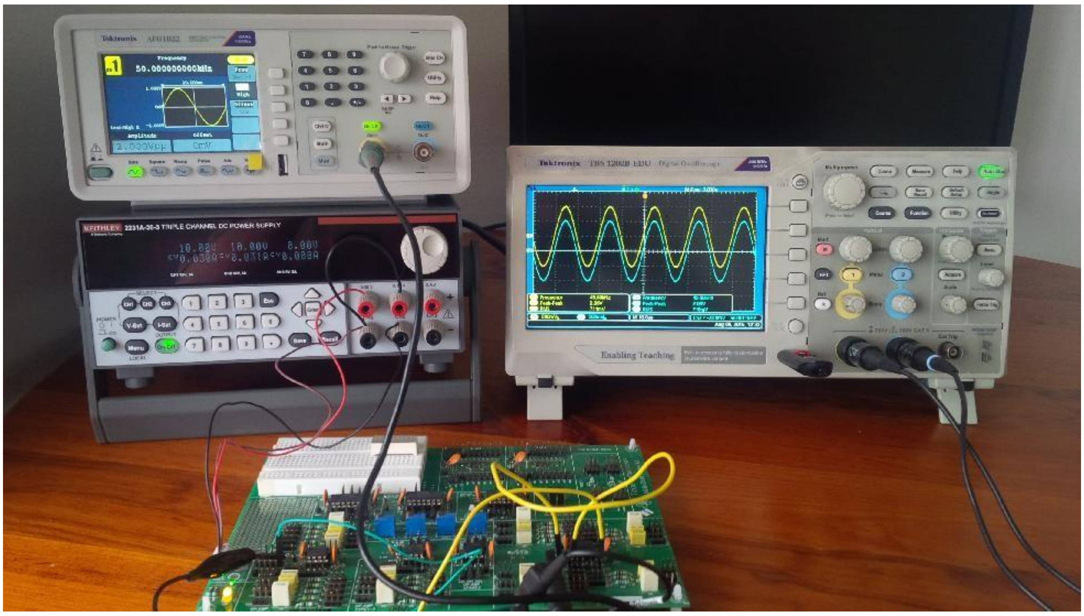
- Using the jumper / connecting wires prepare the circuit as shown below - Choose C1 = C2 = 0.1uF & R1 = R2 = 1k ohm.
- When using the ASLK board, you will have to use additional R and C (not available on board) on the small breadboard provided



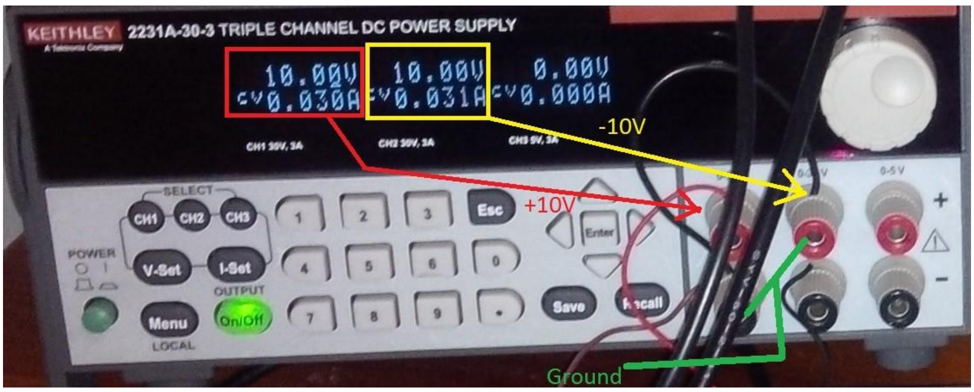
Step 3

Experiment Setup

- Make the arrangement as shown in figure below -



- Turn on the DC power supply, ensure that +/- 10V is applied to ASLK /Opamp circuit
    - You can use '2 channels' of 2231A DC power supply in independent mode and combine negative one channel with positive of other to be treated as common or ground point



- Use signal from AFG/signal generator to feed to opamp input
- Probe at input and output pins of the filter to view the signal on oscilloscope - View input on channel 1 and output on channel 2

Step 4

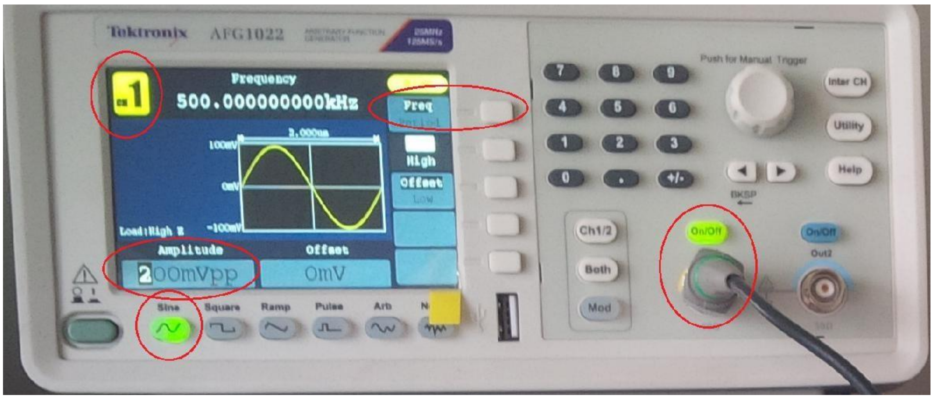
Make the Circuit Work

- Use signal from AFG/signal generator to feed to opamp input
- Set sinusoidal signal from channel 1 of the AFG
  - amplitude = 1 V_{pp}
  - frequency = 50 Hz
- Autoset the oscilloscope to see both input and output waveforms

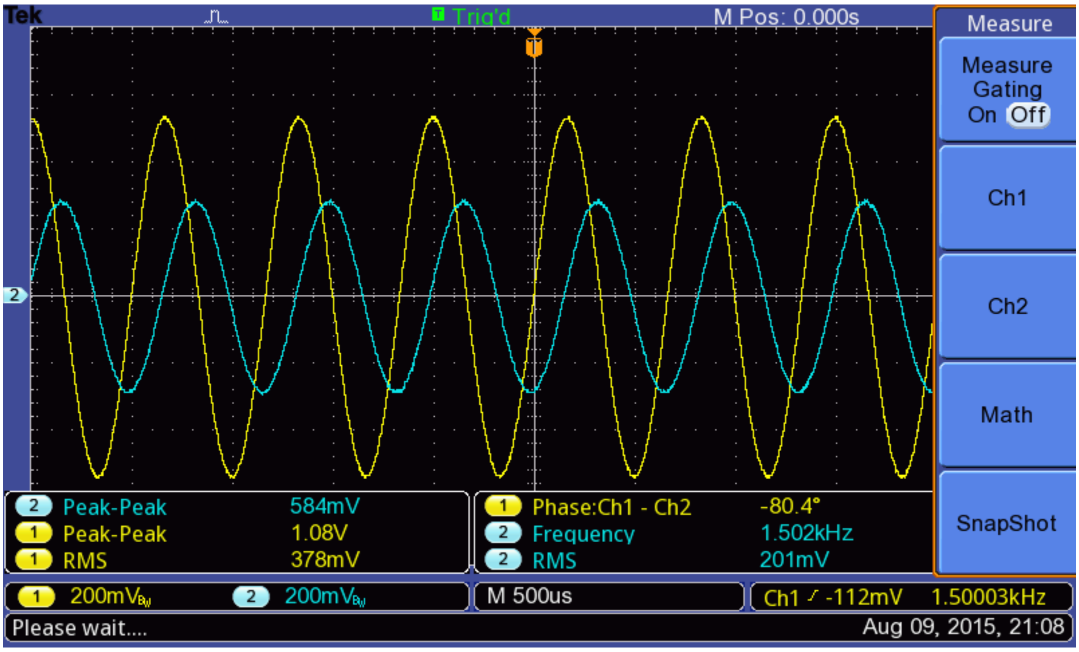
Step 5

Taking the Measurements

- Set input
  - Sinusoidal, 1V peak-to-peak amplitude
  - 1 Hz frequency
  - Continous mode (on AFG)
  - enable the channel 1 output on AFG



- Autoset the oscilloscope to optimally see both input and output signal
- Set up following measurements:
  - On Ch1 - V_{pp}, V_{rms}, Frequency
  - On Ch2 - V_{pp}, V_{rms}, and Phase (between Ch1 and Ch2)
- Keeping the amplitude of the sinusoid input fixed at 1V peak-to-peak, vary its frequency from 1Hz to 50kHz. You may take more readings near cut-off frequency.
- Tabulate the measurements. You can also capture screenshot for each measurement set.



Step 6

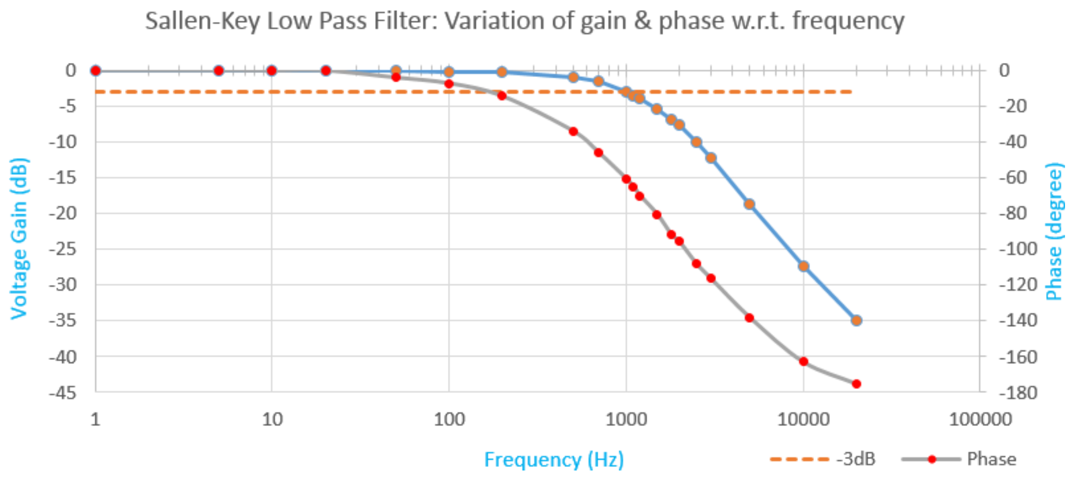
Analyzing the Result

- The observation table would look like as shown below. Calculate voltage gain (observed from measurements) and its decible equivalent.

#	Frequency (Hz)	INPUT		OUTPUT		Phase Difference (Degrees)	Voltage Gain	Voltage Gain (dB)
		Vpp (V)	Vrms (mV)	Vpp (V)	Vrms (mV)			
1	1	1.030	358	1.03	357.0	0.00	1.00	0.00
2	5	1.030	358	1.02	356.0	0.00	0.99	-0.08
3	10	1.030	358	1.02	356.0	-0.07	0.99	-0.08
4	20	1.030	358	1.02	356.0	-0.08	0.99	-0.08
5	50	1.030	358	1.020	356.0	-3.97	0.99	-0.08
6	100	1.030	358	1.010	354.0	-7.20	0.98	-0.17
7	200	1.030	358	1.000	350.0	-14.40	0.97	-0.26
8	500	1.030	358	0.920	324.0	-33.80	0.89	-0.98
9	700	1.030	358	0.872	301.0	-45.90	0.85	-1.45
10	1,000	1.050	368	0.752	261.0	-60.40	0.72	-2.90
11	1,100	1.060	370	0.712	248.0	-64.80	0.67	-3.46
12	1,200	1.060	372	0.680	235.0	-69.90	0.64	-3.86
13	1,500	1.080	378	0.584	201.0	-80.40	0.54	-5.34
14	1,800	1.100	384	0.496	172.0	-91.60	0.45	-6.92
15	2,000	1.100	388	0.456	156.0	-95.70	0.41	-7.65
16	2,500	1.130	396	0.360	121.0	-108.00	0.32	-9.94
17	3,000	1.150	402	0.280	96.7	-116.00	0.24	-12.27
18	5,000	1.190	413	0.138	44.0	-138.00	0.12	-18.71
19	10,000	1.210	420	0.052	13.1	-162.70	0.04	-27.34
20	20,000	1.220	422	0.022	4.4	-175.00	0.02	-34.88

** MINUS sign in the phase signifies that output lags input

- Prepare Bode plot - plot voltage gain and phase against frequency.



- Find out the cut-off frequency from the plot (where the gain drops to -3dB from its passband value)

Step 7

Conclusion

The analysis of the observed results confirm that (As expected):

- The voltage gain of the filter circuit reduces as input frequency is increased
- The roll-off is -40dB/decade as it is a 2nd order filter
- The cut-off frequency (where gain is -3dB or 3dB down from its passband value) is 1000Hz.
- At the estimated (calculated from R and C values) cut-off frequency of 1592 Hz, the gain is down by ~ 6dB and phase is -90 degrees. (minus sign in the phase signifies, output lags input)

Sallen-Key_High_Pass_Filter -- Overview

Sallen-Key High Pass Filter

Objectives:

After performing this lab exercise, learner will be able to:

- Understand & analyze working of Sallen-Key topology of active filters
- Design & build a Sallen-Key high pass filter using opamp
- Establish relationship between input and output signal - prepare a Bode plot for the filter circuit
- Practice working with measuring equipment and laboratory tools like digital oscilloscope, signal generator, multimeter and power supply
- Use digital oscilloscope to debug/analyze the circuit

Equipment:

To perform this lab experiment, learner will need:

- Digital Storage Oscilloscope (TBS1000B-Edu from Tektronix or any equivalent)
- Power Supply (2231A-30-3 Power Supply from Keithley or any equivalent power supply capable of supplying +/- 10V DC)
- Signal generator (AFG1000 from Tektronix or equivalent) for providing AC input to circuit
- Multimeter
- Electronic Components
    - Opamp 741 / TL082 or equivalent - as single IC or as part of any analog circuit kit (like ASLK board from TI)
    - Resistor (2 x 1K ohms)
    - Capacitor (2 x 0.1 uF)
- BNC cables
- Breadboard and connecting wires

Theory / Key Concepts:

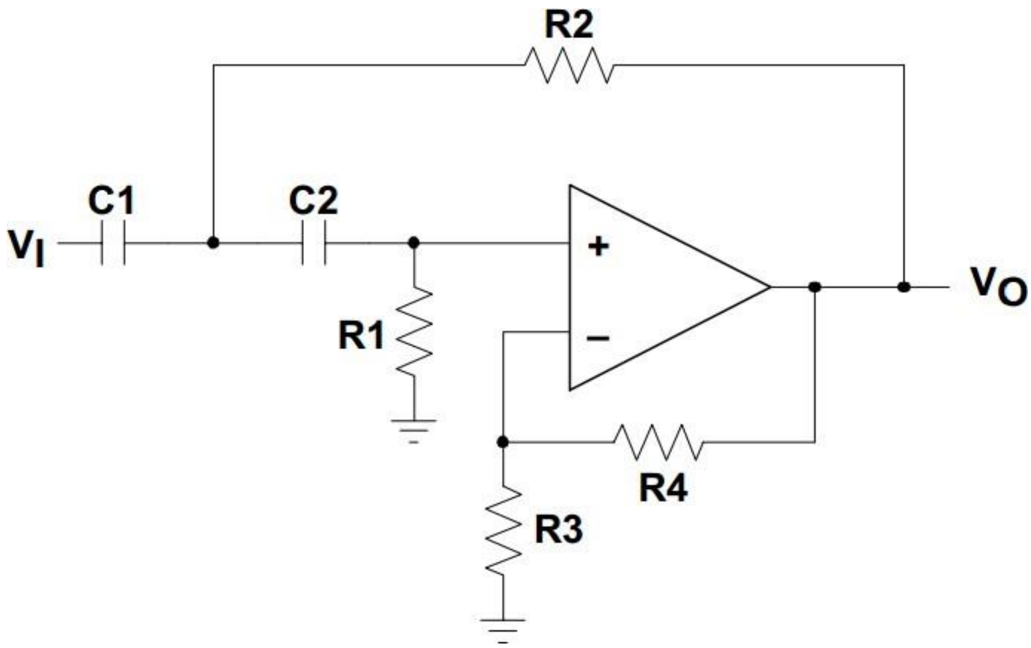
Before performing this lab experiment, it is important to learn following concepts:

- An opamp is a high-gain differential amplifier with very high input impedance. Very high open-loop gain allow for creating amplifiers with stable gain using feedback.
-
- A high-pass filter is an electronic circuit that attenuates signals with a frequency lower than a certain value and passes signals of higher frequencies.
    - The 'certain' frequency after which the atteneuation ends is called as 'cut-off frequency' of the filter.
    - Range of frequencies below cut-off frequency is called stop band and higher frequency ranges are called pass band.
- At cut-off frequency, the signal amplitude is 0.707 times of its value in the passband i.e., the signal level is 3dB below the passband value.
- Professors R.P. Sallen and E.L. Key described a new filter topology in 1955, which was named after them, the Sallen-Key filters.
- An active Sallen-Key filter can be cascaded easily to make higher order filters. The opamp provides the buffering buffering between cascaded stages.
- Sallen-Key filter gives the flexibility of modifying the filter characteristics (cut-off frequency and Q) using R, C values and amplifier gain. This makes filter design easy.

Circuit Design:

Learner can use the theoretical design rules to calculate the circuit component values:

- A generic Sallen-Key high pass filter circuit is shown below with filter parameters:



Where:

- K = amplifier gain = 1 + (R4 / R3)
- Transfer function = V_0/V_i

$$= \frac{K(s^2(R1R2C1C2))}{s^2(R1R2C1C2) + s(R2C2 + R2C1 + R1C2(1 - K)) + 1}$$

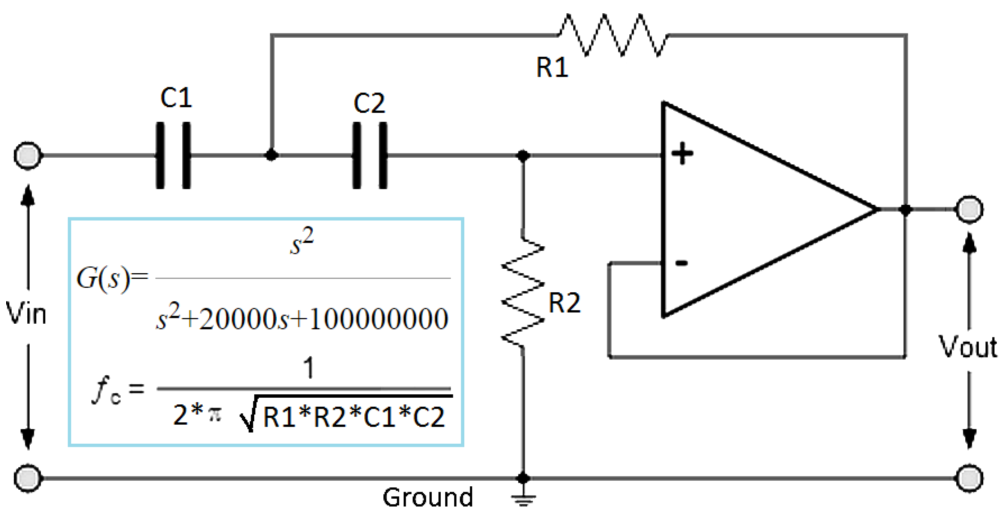
- Cut-off frequency =

$$fc = \frac{1}{2\pi\sqrt{R1R2C1C2}}$$

and

$$Q = \frac{\sqrt{R1R2C1C2}}{R2C2 + R2C1 + R1C2(1 - K)}$$

- We can simplify the filter design by choosing R1 = R2 = R = 1k Ohms and C1 = C2 = C = 0.1uF. The opamp gain is kept unity (R4 = 0 and R3 = infinty).



- This makes
  - Amplifier gain K =1

◦

- With the given R and C values, the cut-off frequency will be 1592 Hz, Q = 1/2 and K (opamp amplifier gain) = 1

Sallen-Key_High_Pass_Filter -- Procedures

Step 1

Check Your Understanding:

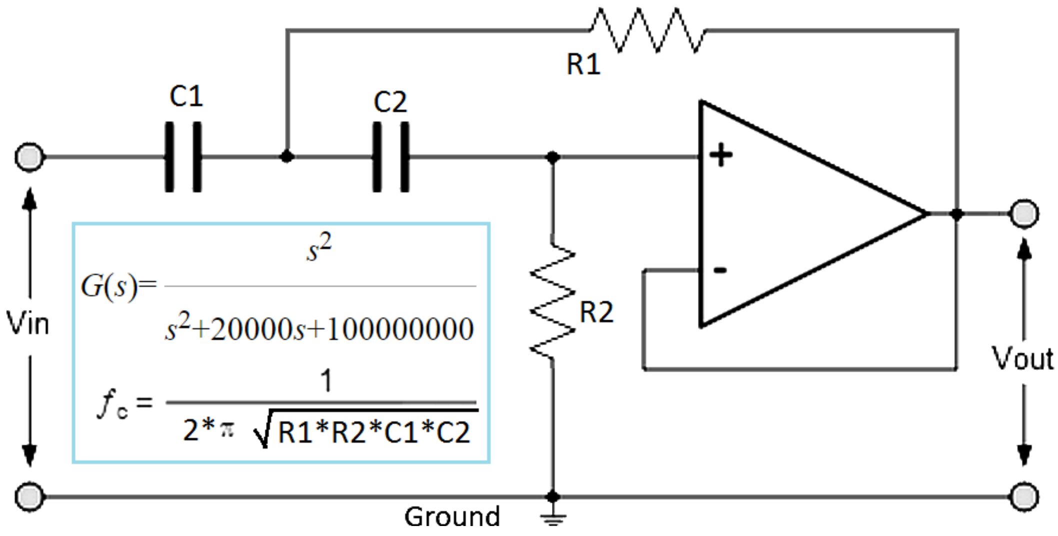
Before performing this lab experiment, learners can check their understanding of key concepts by answering these?

- What will be the slope of magnitude response in the stop band of a Sallen-Key high-pass filter?
  - -20dB / decade
  - 0 dB / decade
  - -40dB / decade
  - +20dB / decade
- How will the phase respones for Sallen-Key high pass filter vary with frequency of input signal?
  - Phase will vary from 0 to 90 degrees as frequency goes low to high
  - Phase will vary from 0 to -90 degrees as frequency goes low to high
  - Phase will vary from 0 to -180 degrees as frequency goes low to high
  - Phase will vary from 180 to 0 degrees as frequency goes low to high
- The response of the filter circuit will produce any overshoot or oscillation for:
  - Q > 0.5
  - Q = 0.5
  - Q < 0.5
  - Q = infinity

Step 2

Circuit diagram / Connection Details

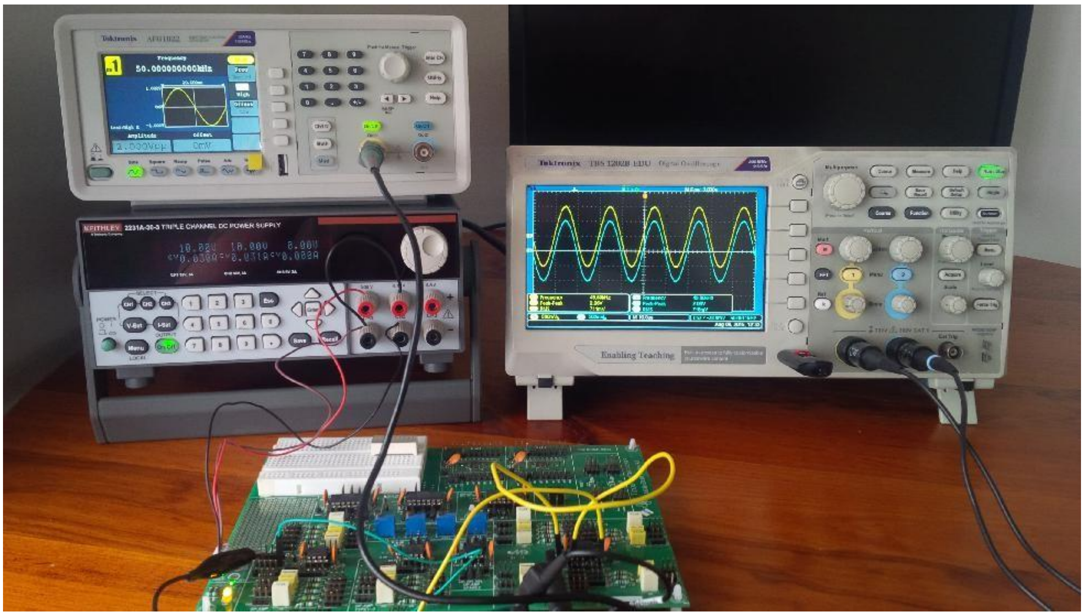
- Using the jumper / connecting wires prepare the circuit as shown below - Choose C1 = C2 = 0.1uF & R1 = R2 = 1k ohm.
- When using the ASLK board, you will have to use additional R and C (not available on board) on the small breadboard provided



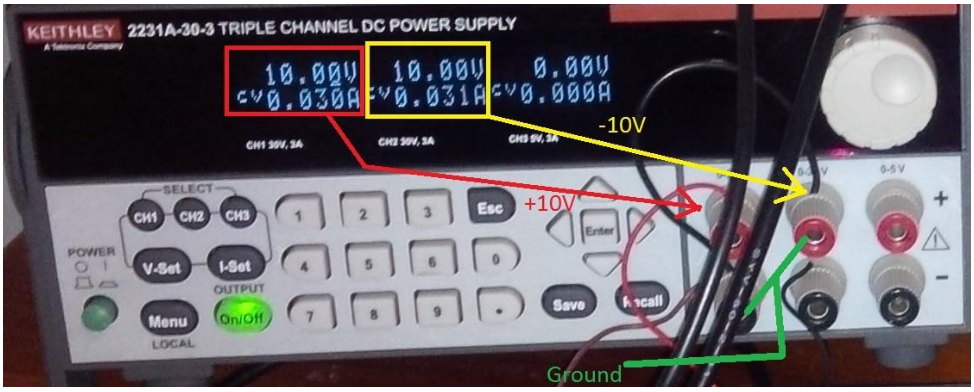
Step 3

Experiment Setup

- Make the arrangement as shown in figure below -



- Turn on the DC power supply, ensure that +/- 10V is applied to ASLK /Opamp circuit
  - You can use '2 channels' of 2231A DC power supply in independent mode and combine negative one channel with positive of other to be treated as common or ground point



- Use signal from AFG/signal generator to feed to opamp input
- Probe at input and output pins of the filter to view the signal on oscilloscope - View input on channel 1 and output on channel 2

Step 4

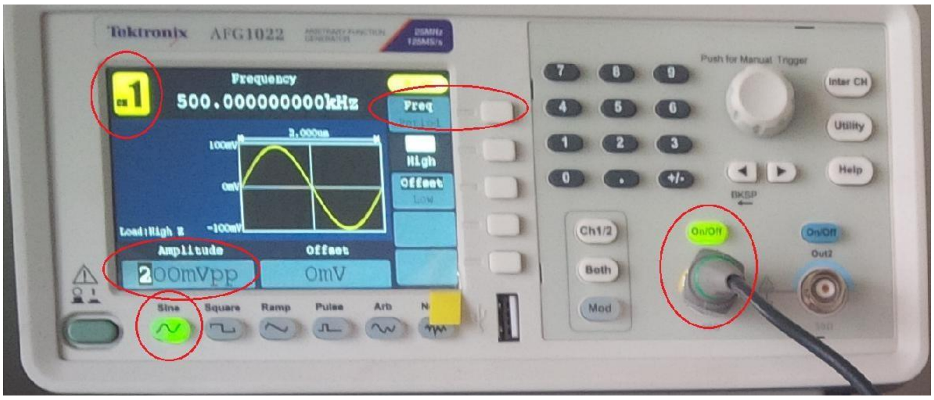
Make the Circuit Work

- Use signal from AFG/signal generator to feed to opamp input
- Set sinusoidal signal from channel 1 of the AFG
    - amplitude = 1 V_{pp}
    - frequency = 10K Hz
- Autoset the oscilloscope to see both input and output waveforms

Step 5

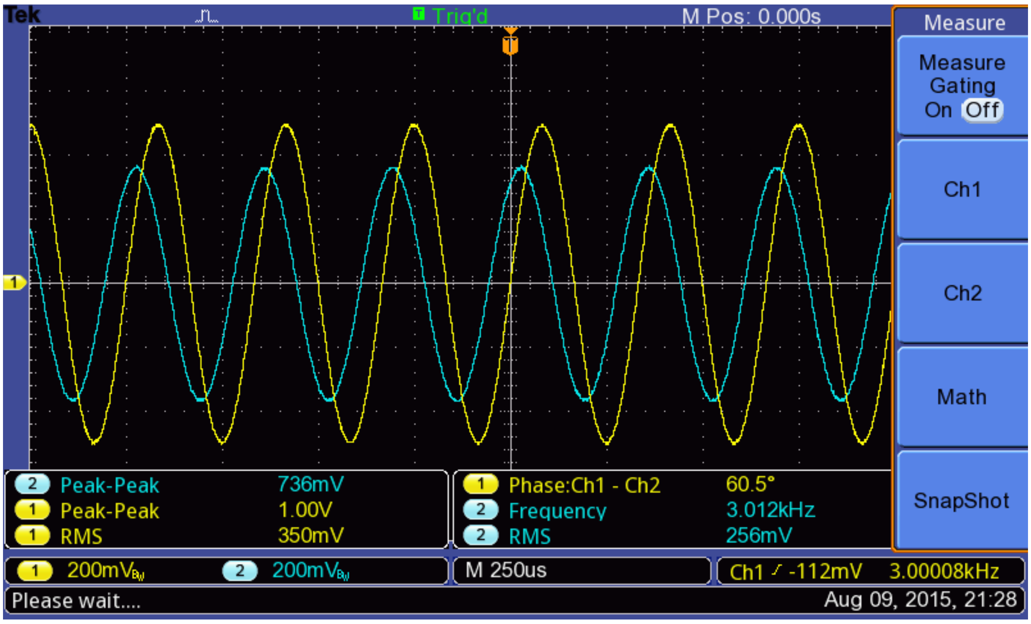
Taking the Measurements

- Set input
    - Sinusoidal, 1V peak-to-peak amplitude
    - 100 Hz frequency
    - Continous mode (on AFG)
    - enable the channel 1 output on AFG



- Autoset the oscilloscope to optimally see both input and output signal
- Set up following measurements:
    - On Ch1 - V_{pp}, V_{rms}, Frequency
    - On Ch2 - V_{pp}, V_{rms}, and Phase (between Ch1 and Ch2)

- Keeping the amplitude of the sinusoid input fixed at 1V peak-to-peak, vary its frequency from 100Hz to 100kHz. You may take more readings near cut-off frequency.
- Tabulate the measurements. You can also capture screenshot for each measurement set.



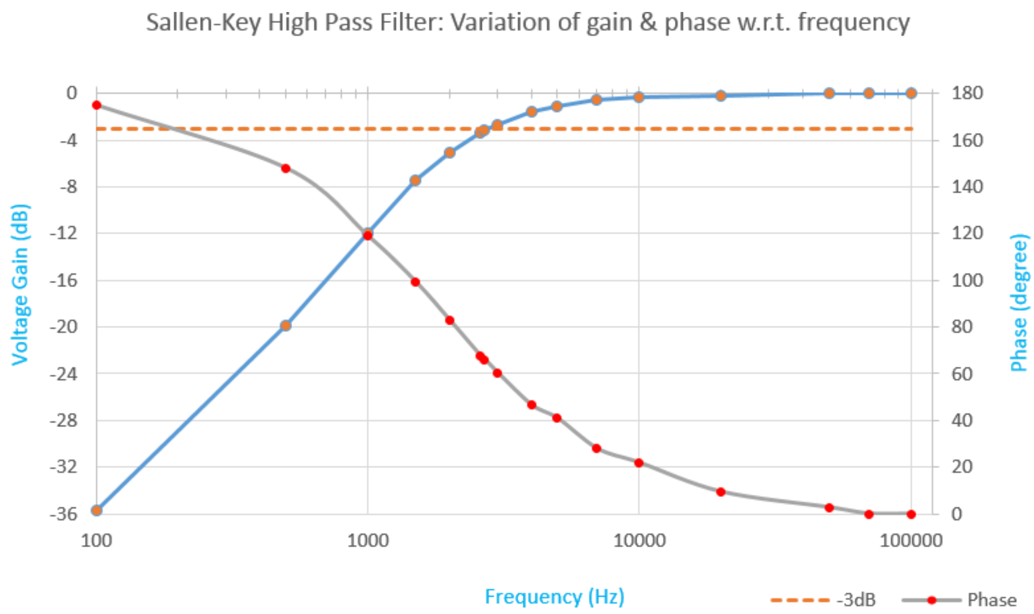
Step 6

Analyzing the Result

- The observation table would look like as shown below. Calculate voltage gain (observed from measurements) and its decible equivalent.

#	Frequency (Hz)	INPUT		OUTPUT		Phase Difference (Degrees)	Voltage Gain	Voltage Gain (dB)
		Vpp (V)	Vrms (mV)	Vpp (V)	Vrms (mV)			
1	100	0.976	342	0.016	2.55	175.00	0.02	-35.71
2	500	0.992	345	0.1	26.5	148.00	0.10	-19.93
3	1,000	1.020	353	0.256	85.9	119.00	0.25	-12.01
4	1,500	1.000	355	0.424	143	99.30	0.42	-7.45
5	2,000	0.984	345	0.552	192	82.90	0.56	-5.02
6	2,600	1.020	354	0.696	238	67.60	0.68	-3.32
7	2,700	1.020	354	0.712	243	66.00	0.70	-3.12
8	3,000	1.000	351	0.736	256	60.50	0.74	-2.66
9	4,000	0.968	334	0.808	276	46.60	0.83	-1.57
10	5,000	0.984	338	0.864	297	40.80	0.88	-1.13
11	7,000	0.992	342	0.928	318	27.80	0.94	-0.58
12	10,000	1.000	342	0.960	332	21.80	0.96	-0.35
13	20,000	1.020	347	0.992	341	9.36	0.97	-0.24
14	50,000	1.000	345	1.000	345	2.69	1.00	0.00
15	70,000	1.000	345	1.000	345	0.00	1.00	0.00
16	100000	1.000	345	1.000	345	0.00	1.00	0.00

- Prepare Bode plot - plot voltage gain and phase against frequency.



- Find out the cut-off frequency from the plot (where the gain drops to -3dB from its passband value)

Step 7

Conclusion

The analysis of the observed results confirm that (As expected):

- The voltage gain of the filter circuit increses to 1 (0 dB) as input frequency is increased
- The attenuation roll-off is -40dB/decade as it is a 2nd order filter
- The cut-off frequency (where gain is -3dB or 3dB down from its passband value) is 2800Hz.
- At the estimated (calculated from R and C values) cut-off frequency of 1592 Hz, the gain is down by ~ 6dB and phase is -90 degrees. (Positive sign in the phase signifies, output leads input)