MS101 Makerspace
2024-25/II Spring
Expt 2: Op amp Circuits (ver_Jan14)

Objectives

- To familiarize with the Keithley 2231A Triple Channel DC Power Supply (so as to adjust and obtain +Vcc and −Vcc for the LM741 op amp).
- To observe the input and output waveforms of an op amp inverting amplifier.
- To obtain the V-I characteristics of a resistor, a rectifier diode, a Zener diode, an LED, and a photodiode using an op-amp based current-to-voltage converter.

List of components

LM741 op amp, rectifier diode, Zener diode, LED, photodiode, resistors

Part A – Keithley 2231A Triple Channel DC Power Supply

The Model 2231A-30-3 Triple Channel Programmable DC Power Supply is a flexible DC source designed to power a wide range of applications. It has three independent and isolated power channels and can be used to power circuits with different references or polarities. Each output has voltage and current settings. If the load current is less than the current setting, it serves as a voltage source with the output voltage equal to the set voltage. As the load current reaches the set current, it serves as a current source.

For details of the basic operations of the power supply, refer to the user manual '**Keithley-2231A-30-3-User-Manual**'.

Part A Experiment

1. Familiarize yourself with the front panel of the Keithley Model 2231A-30-3 Triple Channel Programmable DC Power Supply (see Fig.1).

2. **Setting the DC output voltage and current limit for a channel (CH1, CH2, or CH3)**
   a. We will be using this power supply to obtain the +Vcc and −Vcc voltages for the op amp LM741.
   b. Switch ON the Keithley Power Supply. Initially, ensure that the DC output voltages are not enabled. DC output voltages are enabled by pressing the '**Output On/Off**' button. When the output voltages are enabled. the button gives a green color, as shown in Fig. 1.
   c. Press the **V-Set** button and then press CH1. A cursor will appear on the output voltage display section of CH1. Now type '12' through the numeric keypad. (You may also use the knob located at the rightmost-top side to set 12 V). After entering '12', press the **Enter** button. Now CHI output will be set for 12 V.
   Note: If the '**Output On/Off**' button is in the OFF state, then the 12 V set in step (c) will be flashing for a few seconds, and then '0.00' will be displayed to indicate that this voltage is set, but not available at the terminals now. However, if the '**Output On/Off**' button is in the ON state (i.e. the '**Output On/Off**' button is green), then the 12 V set in step (c) will stay as it is on the display, to indicate that this voltage is appearing at the output terminals.
   d. <u>Current limit setting</u>: In this experiment, the maximum current to be supplied by the CH1 and CH2 channels is within 100 mA. Hence both CH1 and CH2 should have the maximum current limit setting as 100 mA. Use the following steps to set the maximum current setting for CH1 and CH2.
   - Press **I-Set** button and then press CH1. The present current setting will be displayed on the panel. Set it to 0.1A. Repeat the same for CH2.

   e. Using your DMM verify that 12 V is appearing at the output terminals of CH1. You can do this by first pressing the '**Output On/Off**' button to make the button green, and then using your DMM to measure the voltage at the CH1 terminals (right-side). Red terminal is +ve and Black is '−' of the DC output.
   f. Similarly, set 12 V on CH2.
   g. You need not set the CH3 output. This channel can be set only up to around 5 V.

h. In this experiment, you will be using only CH1 and CH2 of the Keithley Power Supply. Remember that these two outputs are equivalent to two independent battery outputs with two terminals for each output.

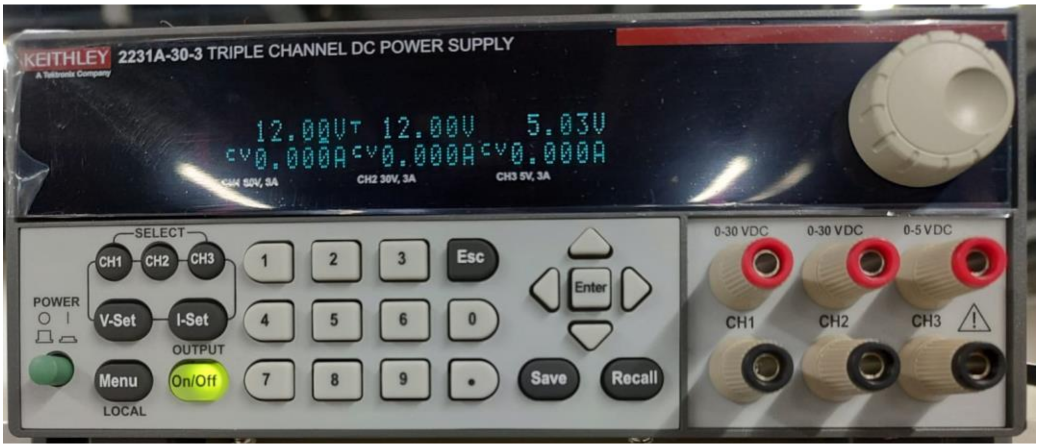
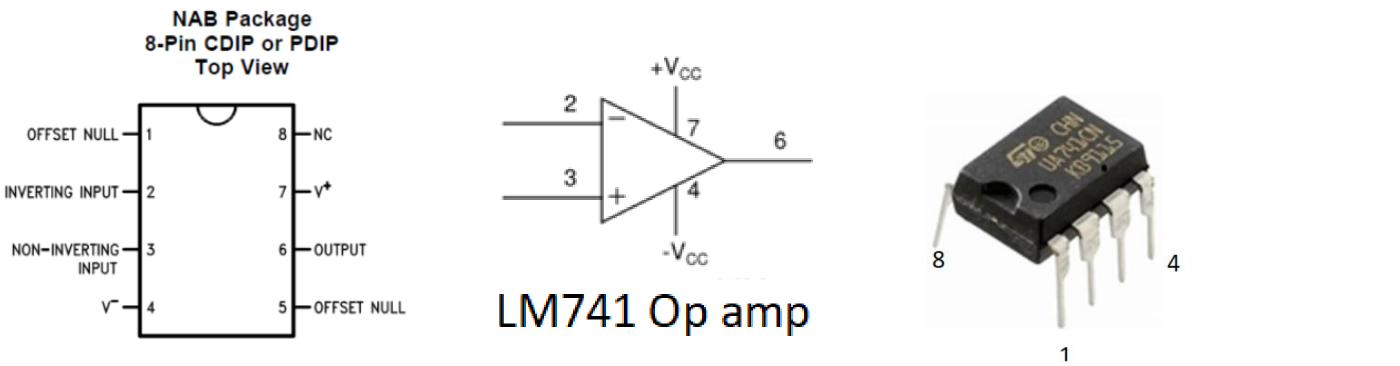


Fig. 1 Keithley Model 2231A-30-3 Triple Channel Programmable DC Power Supply (Front panel image)

Part B – LM741 Operational Amplifier



Note: NC: no connection.

(a) Pinout details (b) Op amp symbol with pin numbers (c) LM741 Op amp image

Fig**. 2** Pinout, symbol, and image of the LM741 op amp

LM741 is a commonly used op amp IC. Its pinout is shown in Fig. 2. Its basic parameters (nominal values) are given below:

DC Open-loop gain (A_d): 2×10^5 V/V (typ)	Open-loop cut-off frequency: 5 Hz (typ)
Open-loop input resistance: 2 MΩ (typ)	Open-loop output resistance: 75 Ω (typ)
Slew rate: 0.5 V/μs (typ)	CMRR (= 20 log A_d/A_{cm}) > 90 dB (typ)

For making circuit connections, it is important to identify the LM741 IC pins correctly. In order to do this, a circular mark is put close to pin 1. The image of LM741 shown in Fig. 2(c) has a semi-circular depression between pins 1 and 8, and also a small circle just above pin 1. Yet another way to identify pin 1 is to check for the way the IC number is printed on the top surface. From Fig. 2(c), you will notice that when the IC is inserted with the correct orientation (i.e., with pin 1 at the extreme left side and pin 4 on the extreme right side), the IC number "UA741CN" can be read easily from left to right.

Part C – Op Amp Inverting Amplifier

Circuit values: +Vcc = +12 V, −Vcc = −12 V; R_1 = 10 kΩ, R_F = 470 kΩ

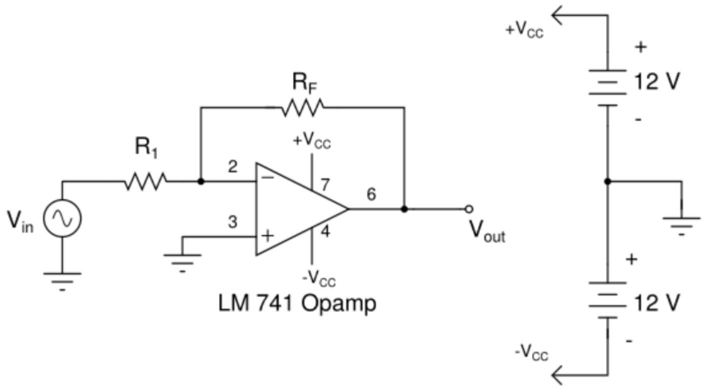


Fig. 3 Op amp inverting amplifier circuit (with +Vcc and −Vcc power supply connections)

Part C.1 Experiment

i) Circuit wiring

Wire the op amp inverting voltage amplifier carefully. While connections are being made, the Power Supply should be in the OFF mode (i.e. no green light in the 'Output ON/OFF' button). You should put the power supply output in the ON mode only after the circuit is verified by your TA.

a. Ensure that the pins are connected correctly, as shown in Fig. 1. Take extra care in ensuring the IC orientation; otherwise, the IC will be damaged at power ON.
b. There will be a marks penalty for careless wiring (incorrect IC orientation and V_{cc} connections).

ii) Keithley Power Supply parameters for +V_{cc} and −V_{cc}

a. Verify that Keithley Power Supply CH1 and CH2 are set to 12 V. Ensure that the power supply outputs are disabled (or OFF). In the OFF mode, the green LED of the '**Output On/Off**' button will not glow.
b. Connect CH1 '+' output as the +V_{cc} supply voltage and CH2 '−' output as the −V_{cc} supply voltage. This is done by connecting the ' – ' terminal of the CH1 output (Black terminal) to the '+' terminal of CH2 (Red terminal). This common terminal should then be connected to your circuit GND on your bread board. Note that with connections done as above, the '+' terminal (Red) of CH1 will be your +V_{cc} and the '− ' terminal (Black) of CH2 will be your negative supply, i.e. −V_{cc}.
c. Power Supply output should be made ON only after your TA checks your circuit.

iii) AFG1022 parameters for V_{in}

a. Verify that the output load of the channel used is set at Hi Z (Utility > Output Setup).
b. Set the test signal (V_{in}) to be 0.1 sin ωt V (i.e. +ve peak +100 mV, and −ve peak −100 mV, with a peak-to-peak output of 200 mV). Keep the test signal frequency as 1 kHz.
c. Connect V_{in} to the circuit as shown in Fig. 3 and connect it also to DSO CH1.
d. Connect the inverting amplifier output (V_{out}) to DSO CH2. Ensure that the AFG output is in the Off mode till the op amp power supply is ON.

Observation and Measurement

After your circuit has been verified by your TA, put the Keithley Power Supply Output in the ON mode by pressing the '**Output On/Off**' button. (In the ON mode, the LED will glow).

a) Enable the AFG output by pressing the '**Out On/Off**' button.
b) Now you should be able to see both V_{in} and V_{out} waveforms on the DSO. Measure the peak-to-peak output voltages. (The peak-to-peak voltage of V_{in} should be 200 mV, while that of V_{out} should be around 9.4 V. If your V_{in} and V_{out} waveforms are not correct, debug the problem and rectify it by keeping the power supply and the AFG Off).
c) Once the waveforms are correctly displayed, sketch the V_{in} and V_{out} waveforms.

Lab Notebook

a) Draw the circuit diagram of the inverting amplifier with all the values.
b) Sketch the V_{in} and V_{out} waveforms.
c) Note down the calculated gain (based on the nominal resistor values) and the measured gain (obtained from the ratio of the peak-to-peak values of V_{in} and V_{out})

Part C.2 Optional step

After completing the inverting amplifier measurements, increase V_{in} to 0.5 sin ωt V (keep the test signal frequency as 1 kHz). Observe the V_{out} waveform. Explain the V_{out} waveform obtained.

a) Sketch the V_{in} and V_{out} waveforms for this case.
b) Explain the V_{out} waveform obtained

Part D – V-I Characteristics of and Diodes Using Current-to-Voltage Converter

In this section, we will be using the LM741 op amp to build a current-to-voltage converter circuit and use this circuit to display the V-I characteristics of a rectifier diode, a Zener diode, an LED, and a photodiode.

Op Amp Based Current-to-Voltage Converter Circuit

The circuit diagram to be used for plotting the V-I characteristics of diodes is shown in Fig. 4. Following are the major blocks of the circuit.

A) X-Y Plot (V-I Characteristic) using the DSO

In this part, we will be using the DSO in X-Y mode. Normally, the X axis on the oscilloscope represents time. However, in the X-Y mode, input to one channel becomes the X axis while input to the other channel becomes the Y axis. Since, we are going to plot V-I characteristics of various devices, the applied voltage will be on the X axis. We sweep the voltage range using a triangular wave generated by the Tek AFG 1022 Arbitrary Function Generator. To plot the current, we first convert it to a voltage using an op amp current-to-voltage converter.

B) Diode Driver (Excitation) through V_{AFG}

The diode under test is driven by a test signal from the AFG (we will call it V_{AFG}). The amplitude of the test signal should cover the required voltage range. We shall use the maximum available voltage swing of 18 Vpp (i.e. V_{max} = +9 V, and V_{min} = −9 V). Choose the test signal frequency to be in the range 200 to 500 Hz. For displaying the V-I characteristic on the DSO, the shape of the test signal is not critical. Any standard signal other than rectangular/square pulse would be fine. We shall choose a triangular waveform as the test signal.

The test signal causes a current to flow in the device-under-test (DUT). Connect a diode as the DUT. For the shown polarity, the connected diode will be forward-biased during the +ve half cycle of the test signal, and it will be reverse-biased during the −ve half cycle. Because of the negative feedback through resistance R_F, the inverting input of the op amp (i.e. terminal C) will be at virtual ground. The voltage V_{BC} (voltage at terminal B w.r.t. terminal C) is the voltage across the device-under-test (DUT), V_{DUT}.

C) Current-to-Voltage Converter

In Fig. 4, the resistance R_1 is used as a current-limiting resistance. We shall choose $R_1 = 1$ kΩ to limit the maximum current to roughly 8 mA. Almost the entire current (I_{DUT}) will flow from the inverting input terminal through R_F to the V_{out} terminal of the Op amp. Hence, $V_{out} = -I_{DUT}\ R_F$. We shall choose $R_F = 1$ kΩ. Thus, a device current of 1 mA will make $V_{out} = -1$ V.

To plot the V- I characteristic of the diode with the correct current direction, we need to invert V_{out}. This can be done by choosing the 'Invert' channel facility of the DSO (as explained below). We may consider the inverted V_{out} output as I_{DUT}.

D) V_{DUT} and I_{DUT} Waveforms

Before using the X-Y plot feature, it is important to observe the V_{DUT} and I_{DUT} waveforms. During the +ve half cycle of the test signal, the diode is forward-biased. Hence, the diode will start conducting around 0.4 to 0.6 V for the rectifier diode and the Zener diode, but at a much higher voltage (around 1.8 V for an LED). Once the diode starts conducting, the diode current will increase exponentially for small increases in the diode voltage. Before conduction, the diode voltage V_{DUT} will be the same as the input voltage, but after conduction, the voltage across it will be almost constant.

During the −ve half cycle, the rectifier diode and the LED will not conduct. Hence, V_{DUT} will be the same as the input signal, but I_{DUT} will be zero. However, for the Zener diode case, the diode voltage will be the same as the input signal till the V_{Zener} voltage (i.e., $I_{DUT} = 0$ before Zener breakdown), after which the Zener diode current will increase exponentially for small increases in the reverse voltage.

Current-to-Voltage Converter Circuit

Circuit values: + Vcc = + 12 V, −Vcc = −12 V; $R_1 = 1$ kΩ, $R_F = 1$ kΩ, DUT: 2.2 kΩ resistor, IN4007 diode, LED, 5.6 V Zener diode.

Given: +Vcc = +12 V, −Vcc = −12 V. Assume that the op amp is ideal. Also assume that the maximum and minimum v_{out} levels are +Vcc and −Vcc respectively.

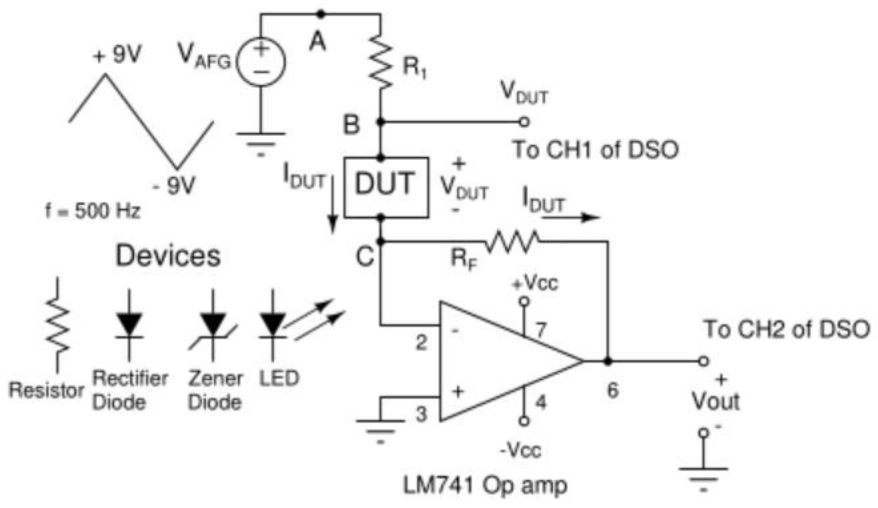


Fig. 4 LM741 Op amp based current-to-voltage converter for obtaining the V-I characteristics of diodes

Case A: **2.2 kΩ Resistor as the DUT (Device)**

We will use a 2.2 kΩ resistor as the first device (DUT) and obtain its V-I characteristic. Connect it between terminals B and C. Let V_{Res} be the voltage across the 2.2 kΩ resistor and I_{Res} the current through it.

Procedure

a) Switch off the AFG output and also the Keithley Power Supply output.
b) Wire the current-to-voltage converter circuit shown in Fig.4. Note that with reference to Fig.4, $I_{DUT} = I_{Res}$; $V_{DUT} = V_{Res}$.
c) Adjust the AFG settings to obtain a 500 Hz triangular test signal with 18 V_{pp} (i.e. Max = + 9 V, Min = −9 V). Ensure that the output load setting of the AFG is Hi-Z.
d) Verify the AFG output on the DSO (but without connecting it to the circuit). Turn the AFG output OFF and then connect the AFG output to point A in the diagram.
e) Connect CH-1 of the DSO to point B. Connect CH-2 of the DSO to the Op amp output. Choose the voltage scale on both CH-1 and CH-2 to 2 V/div.
f) Invert the CH-2 channel display by pressing CH2 Menu > (more page 1/2) > Invert ON.
g) After your circuit has been verified by your TA, put the Keithley Power Supply Output in the ON mode by pressing the '**Output On/Off**' button.
h) Enable the AFG output by pressing the '**Out On/Off**' button.
i) Observe the V_{Res} and I_{Res} waveforms on the DSO.
   $V_{Res} = V_{AFG}$ [2.2 kΩ/(1 kΩ+2.2 kΩ)], and $I_{Res} = V_{Res}$ / 2.2 kΩ. You will notice that both the waveforms have similar shapes, but different peak values.
j) After verifying the above V_{Res} and I_{Res} waveforms, align the GND levels of CH1 and CH2 to be at the centre of the DSO (i.e. the yellow and the blue GND levels indicators of CH1 and CH2).
k) Choose the scales of both CH1 and CH2 to be 1 V/div.
l) Put the DSO in the X-Y mode by pressing the 'Acquire' button under 'Horizontal' and then choosing XY Display on (i.e. Acquire > (more page 1/2) > XY Display On).
m) Calculate the peak V_{Res} and I_{Res} values for the 2.2 kΩ resistor case. Verify the values and sketch the XY plot in your Lab Notebook.

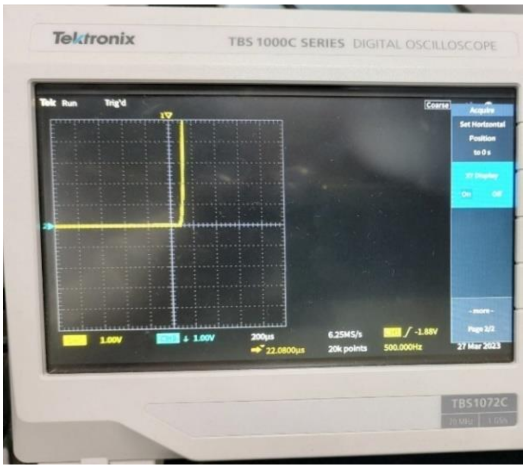
Lab Notebook

i) Draw the circuit diagram of the current-to-voltage converter.
ii) Sketch the V_{Res} and I_{Res} waveforms (as specified in part (i)).
iii) Sketch the XY plot obtained (i.e. the VI characteristic of the 2.2 kΩ resistor).

Case B: IN4007 Rectifier Diode V-I Characteristic

Procedure

a) Switch the AFG output OFF and then turn OFF the Keithley Power Supply outputs.
b) Replace the 2.2 kΩ resistor with the IN4007 rectifier diode (cathode at point C and anode at point B) as the DUT. There will be a black band close to the cathode terminal of the rectifier diode.
c) After connecting the rectifier diode correctly, switch ON first the Keithley Power Supply outputs and then the AFG output.
d) Observe the XY plot of the given IN4007 Rectifier diode. With reference to Fig.4, the voltage across the diode (V_{DUT}) is the X waveform (CH1) and the current through the diode (I_{DUT}) is the Y waveform (CH2).
   a. Choose the scales of both CH1 and CH2 to be 1 V/div.
   b. For the rectifier diode case, the typical waveform you would see in the XY mode is shown below:



   c. Note the Yellow and Blue GND indicators showing the correct alignment in the XY mode. This way the origin will be at the middle of the DSO screen. The diode cut-in voltage can now be measured.

e) Sketch the XY plot in your Lab Notebook.

f) From the displayed XY plot, measure the cut-in voltage of the rectifier diode (in V) and the maximum current (in mA).

Lab Notebook

i) Sketch the V_{DUT} and I_{DUT} waveforms.
ii) Sketch the XY plot obtained (i.e. the VI characteristic of the rectifier diode).
iii) Measure the cut-in voltage of the rectifier diode (in V) and the maximum current (in mA).

Case C: Zener diode V-I Characteristic

Procedure

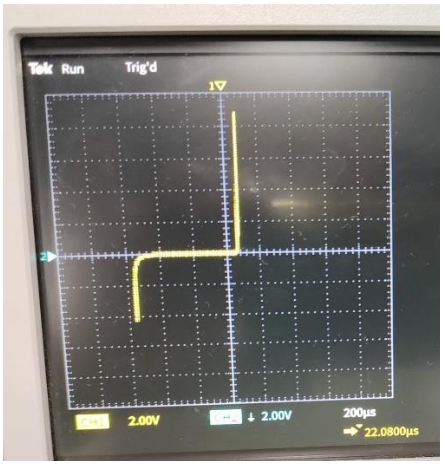
a) Switch the AFG output OFF and then turn OFF the Keithley Power Supply outputs.

b) Replace the rectifier diode with the Zener diode (cathode at point C and anode at point B). Once again there will be a black band close to the cathode terminal of the Zener diode.

c) After connecting the Zener diode correctly, switch ON first the Keithley Power Supply outputs and then the AFG output.

d) Observe the XY plot (X-axis V_{DUT} and Y-axis: I_{DUT}) of the given Zener diode. Choose the scales of both CH1 and CH2 to be 2 V/div.

e) The typical XY plot you will observe for the Zener diode is shown below.



f) Sketch the XY waveform obtained by you in your Lab Notebook.

g) From the displayed XY plot, measure the cut-in voltages (in V) for both forward and Zener regions and the maximum currents in mA.

Lab Notebook

i) Sketch the XY plot obtained (i.e. the VI characteristic of the Zener diode).
ii) Measure the cut-in voltages (in V) for both forward and Zener regions and the maximum currents in mA.

Case D: LED V-I Characteristic

Procedure

a) Switch the AFG output OFF and then turn OFF the Keithley Power Supply outputs.
b) Replace the Zener diode with the Red LED. For the LED, the longer lead is the anode, and the shorter one is the cathode. As in the previous cases, connect the cathode at point C and the anode at point B.
c) After connecting the LED correctly, switch ON first the Keithley Power Supply outputs and then the AFG output.
d) Choose the scales of both CH1 and CH2 to be 1 V/div.
e) Once again observe the XY plot of the given LED.
f) Sketch the XY plot in your Lab Notebook.
g) From the displayed XY plot, measure the cut-in voltage (in V) of the LED and the maximum current in mA.

Lab Notebook

i) Sketch the XY plot obtained (i.e. the VI characteristic of the LED).
ii) Measure the cut-in voltage (in V) of the LED and the maximum current in mA.

Case E: Photodiode V-I Characteristic

Photodiodes

A photodiode is a *pn* junction diode used as optical-to-electrical converter. It is generally reverse-biased and light to be converted falls on its active area. In response to the light, a photocurrent flows through the photodiode, in the same direction is the same as the reverse saturation current. The photocurrent increases with the incident light.

An image of the photodiode is shown below. The photodiode material is silicon. Note the active photodiode area (rectangular), and the anode and cathode terminals (the left side terminal with the active area facing you is the anode, and the right side is the cathode).

Procedure

a) Switch the AFG output OFF and then turn OFF the Keithley Power Supply outputs.
b) Replace the LED with the photodiode. As in the previous cases, connect the cathode at point C and the anode at point B.
c) After connecting the photodiode correctly, switch ON first the Keithley Power Supply outputs and then the AFG output.
d) Once again, observe the XY plot of the given photodiode as it is (i.e. in the room lighting conditions).
e) The X-Y plot will be very similar to what you obtained for the rectifier diode. Since the photocurrents will be in the 20 to 100 μA range, keep the scale of CH1 as 2 V/div, and the scale of CH2 as 100 mV/div. You should be able to see some photocurrent in the reverse region (due to the ambient light).
f) Sketch the XY waveform in your Lab Notebook. (See the X-Y plot image shown below (Fig.E1) for ambient light conditions).
g) Use your mobile flashlight and shine it on the photodiode. Notice the photocurrent increasing with more light falling on the photodiode.
h) Take measurements for two light conditions – medium light and for the maximum light. (See the X-Y plot images shown below (Fig.E2 and Fig.E3) for medium and higher light intensities).
i) From the displayed XY plots, measure the maximum photocurrent you are able to get.

Observation

You will notice that the photodiode gives the same photocurrent for the entire negative half cycle of the triangular wave. Based on this observation how would you model a photodiode – as a voltage source or as a current source?

Lab Notebook

i) Sketch the XY plots obtained for ambient, medium, and higher light intensities.
ii) In each case, measure the photocurrent in µA (as accurately as you can).
iii) Based on your plots how would you model a photodiode – as a voltage source or as a current source? Justify your answer.

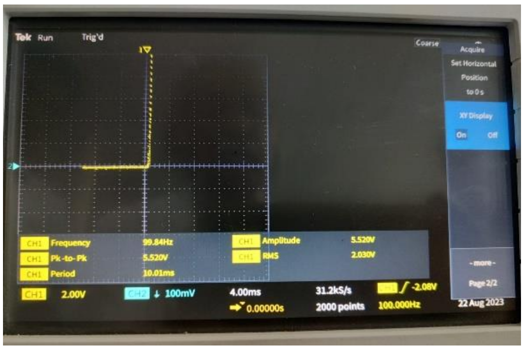


Fig. E1 – XY plot – ambient light conditions

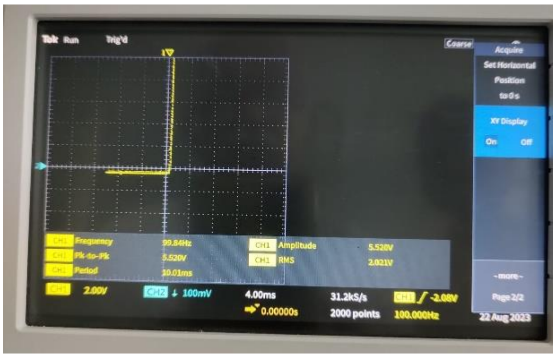


Fig. E2 – XY plot – medium light conditions

Fig. E3 – XY plot – higher light conditions

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Pre-lab Quiz for EE Expt 2 / Sample Set

Duration: 10 min. Marks: 5 × 1 mark = 5 marks. No partial marks for any of the questions. Do your rough work in this paper itself. No extra sheets will be given. No clarifications/explanations will be given.

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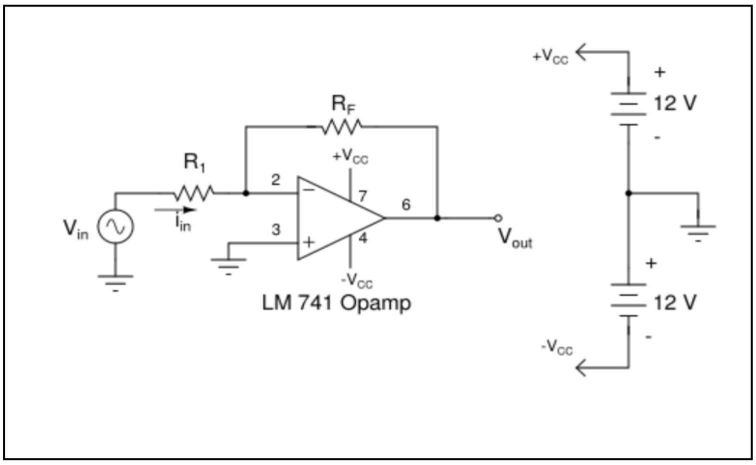
1) The inverting amplifier circuit of Expt 2 is shown in the figure, Given: $v_{in}(t) = 0.5 \sin(\omega t + \theta)$ V of frequency 1 kHz, $R_1 = 4$ kΩ, $R_F = 1$ kΩ . Mark **all the correct options** with regard to this circuit.



A) The voltage gain is –4.

B) The voltage gain is –0.25.

C) V_{in} is a differential signal, and V_{out} is a single-ended signal.

D) V_{in} is a single-ended signal, and V_{out} is also a single-ended signal.

E) The input resistance (V_{in}/I_{in}) is 4 kΩ.

F) The input resistance (V_{in}/I_{in}) is 1 kΩ.

G) The circuit qualifies as an amplifier because it can provide a power gain larger than unity.

H) The circuit qualifies as an amplifier because the output voltage amplitude is larger than the input voltage amplitude.

Answer(s): __________

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2) In the circuit shown above, $R_1 = 2$ kΩ, $R_F = 20$ kΩ . Assume that the v_{out} limits are $+V_{cc}$ and $-V_{cc}$. Mark **all the correct options** with regard to this circuit.

A) The input $v_{in}(t)$ is a triangular wave going from −2 V to + 2V. The output $v_{out}(t)$ will also be a triangular wave.

B) The input $v_{in}(t)$ is a square wave with the maximum and minimum levels of +2 V and −2 V. The output $v_{out}(t)$ will be a square wave with the maximum and minimum levels of +20 V and −20 V.

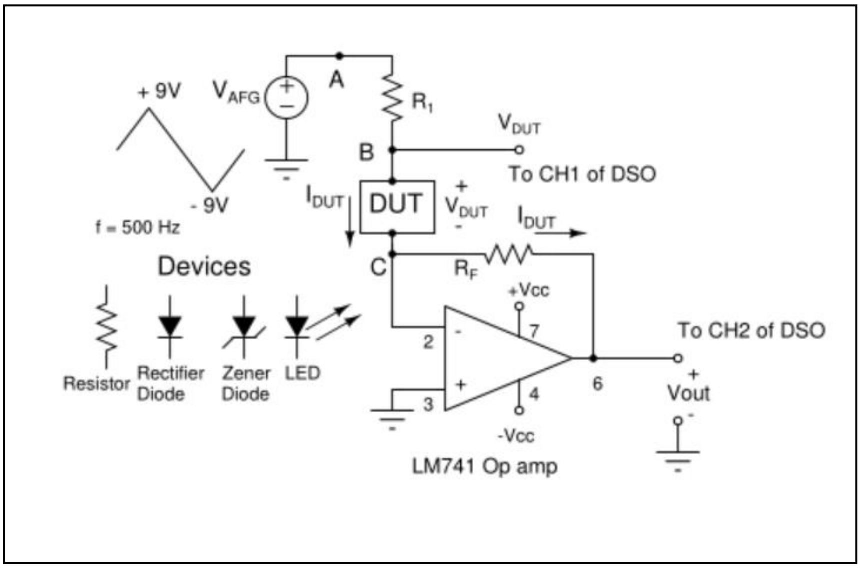
C) The input $v_{in}(t)$ is a square wave with the maximum and minimum levels of +2 V and −2 V. The output $v_{out}(t)$ will be a square wave with the maximum and minimum levels +12 V and −12 V.

D) If the connections to the op amp input terminals are interchanged, the circuit will not work as a linear amplifier.

E) If the connections to the op amp input terminals are interchanged, the circuit will work as a non-inverting amplifier.

Answer(s): __________

3&4) The current-to-voltage converter circuit of Expt 2 is shown in the figure. Given: R_1 = 10 kΩ, R_F = 20 kΩ, $+V_{cc}$ = +12 V, $-V_{cc}$ = −12 V.



A rectifier diode is connected as the device-under-test (DUT) with its cathode at terminal B and anode at terminal C. The diode I-V characteristic has a forward voltage drop of 0.6 V, and negligible reverse saturation current. Calculate the current through the device (I_{DUT}) and the voltage across it (V_{DUT}) at the instant when V_{AFG} = +5.6 V.

I_{DUT} = __________ mA

V_{DUT} = _________ V

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5) In the circuit shown above, R_1 = 10 kΩ, R_F = 20 kΩ, $+V_{cc}$ = +12 V, $-V_{cc}$ = −12 V. A resistor of 2 kΩ is connected across the nodes B and C as the device-under-test (DUT). Calculate output voltage (V_{out}) at the instant when V_{AFG} = −3 V.

V_{out} = __________ V

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