MS101 Makerspace
2022-23/II
Expt 3: Op amp Circuits (Ver 1.1)

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 rectifier diode, a Zener diode and an LED using op amp based current-to voltage converter.

List of components:

LM 741 Op amp, Rectifier diode, Zener diode, LED, 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 offers three independent and isolated power channels, allowing you to power circuits with different references or polarities.

For details of the basic operations of the power supply, please refer to the user manual file: '**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 of a channel (CH1, CH2 or CH3)**
   a. We will be using this power supply to obtain the +Vcc and -Vcc voltages for the LM 741 Op amp.
   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 green colour 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 sets 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. 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.
   e. Similarly, set 12 V on CH2.
   f. You need not set the CH3 output. This channel can be set only up to around 5 V.
   g. 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.
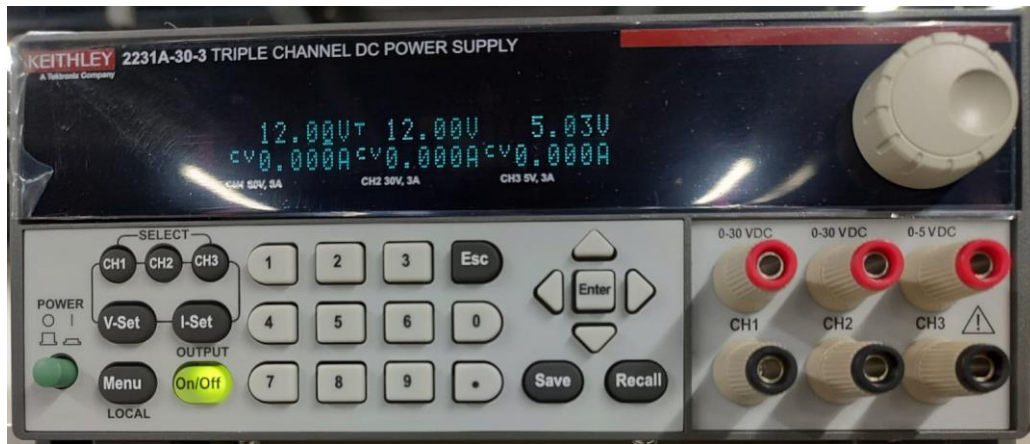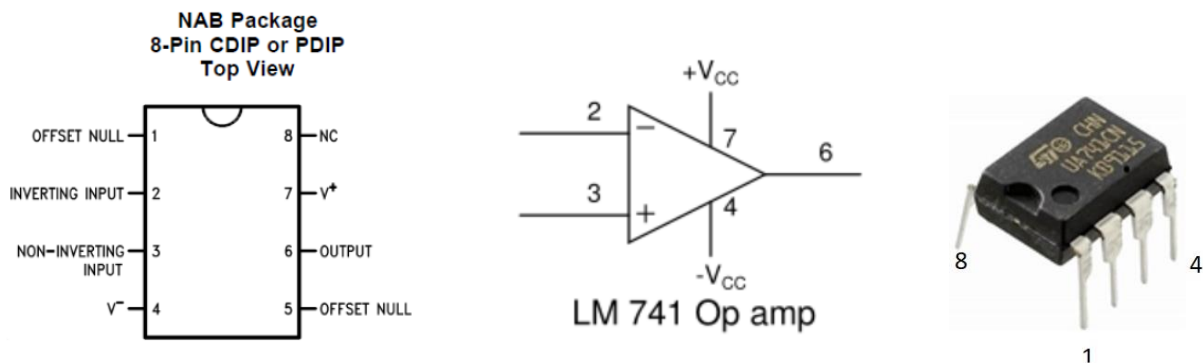
Fig. 1 Keithley Model 2231A-30-3 Triple Channel Programmable DC Power Supply (Front panel image)

Part B – LM 741 Operational Amplifier

Note: NC: no connection.

   (a) Pinout details   (b) Op amp symbol with pin numbers   (c) 741 Op amp image

Fig.2 Pinout diagram and details of the LM 741 Op amp

LM741 Operational amplifier (Op amp) is the most commonly used Op amp IC. Its pin out is shown in Fig.2. Basic parameters (nominal values) of the LM741 Op amp 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 LM 741 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.

Part C – Op Amp Inverting Amplifier

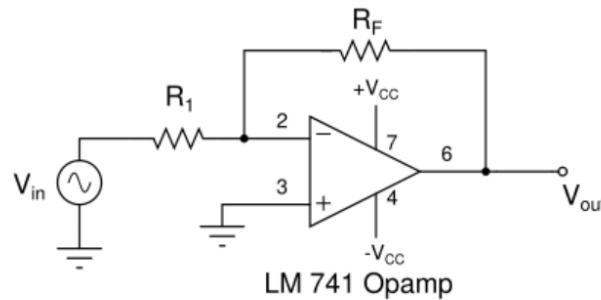Circuit values: + Vcc = + 12 V, - Vcc = - 12 V; R_1 = 10 kΩ, R_F = 470 kΩ

Fig. 3 Op amp inverting amplifier

C.1 Experiment:

i) **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 instantly damaged at power ON.**
    b. **Students who do careless wiring (wrong IC orientation and wrong V_{cc} connections) will be penalized.**

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 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 Op amp power supply is ON.

Observation and Measurement:
a) 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).
b) Enable the AFG output by pressing the '**Out On/Off**' button.

c) Now you should be able to see both V_{in} and V_{out} waveforms on the DSO. Measure the peak-to-peak output voltages. (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 power supply and the AFG Off).

d) Once the waveforms are correctly displayed, sketch the V_{in} and V_{out} waveforms.

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.

Part D – V-I Characteristics of 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 to display the V-I characteristics of a rectifier diode, a Zener diode, and an LED.

Op amp based Current-to-Voltage Converter Circuit

Circuit diagram to be used for the 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 are going to use the DSO in X-Y mode. Normally, the X axis on the oscilloscope represents time. However, in X-Y mode, the input to one channel becomes the X axis while the input to the other channel becomes the Y axis. Since, we are going to plot VI characteristics of various devices, the applied voltage will be the X axis. We sweep the voltage range using a triangle wave generated by the Tek AFG 1022 Arbitrary Waveform 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. In a 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 diode. For the shown polarity of the diode, the connected diode will be forward biased during the +ve half cycle of the test signal, and reverse-biased during its -ve half cycle. Because of the negative feedback through resistance R_F, the V- 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 diode, V_{Diode}.

C) Current-to-Voltage Converter

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

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

Before using the X-Y plot feature, it is important to observe the V_{Diode} and I_{Diode} 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_{diode} 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_{Diode} will be the same as the input signal, but I_{Diode} will be zero. However, for the Zener diode the diode voltage will be same as the input signal till the V_{Zener} voltage (i.e. $I_{Diode} = 0$ before Zener breakdown), after which the Zener diode current will increase exponentially for small increases in the reverse voltage.

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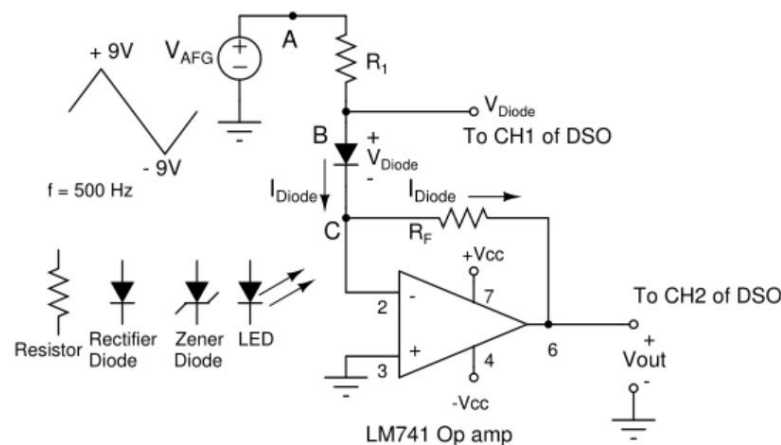

Fig. 4 LM741 Op amp based current-to-voltage converter for obtaining the V-I characteristics of diodes

Experiment
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.

- **CASE A**: **A 2.2 kΩ Resistor as the Device**
  We will use a 2.2 kΩ resistor as the first device 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.
      Note: With reference to Fig.4, $I_{Diode} = I_{Res}$; $V_{Diode} = V_{Res}$.

c) Adjust the AFG settings to obtain a 500 Hz triangular test signal with 18 Vpp (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 make 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.

Case A: 2.2 kΩ Resistor as Device - Observation and Measurement

a) 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.

b) Enable the AFG output by pressing the '**Out On/Off**' button.

c) Observe the V_{Res} and I_{Res} w.r.t time on the DSO.

    a. $V_{Res} = V_{AFG}$ [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.

d) 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).

e) Choose the scales of both CH1 and CH2 to be 1 V/div.

f) Put the DSO in the X-Y mode by pressing the 'Acquire' button under 'Horizontal' and then choose XY Display on (i.e. Acquire > (more page 1/2) > XY Display On).

g) Calculate the peak V_{Res} and I_{Res} values for the 2.2 kΩ resistor case. Verify the values and sketch the XY waveform in your Lab Notebook.

Case B: IN4007 Rectifier Diode V-I Characteristic

Experiment

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). 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.

    a. For the rectifier diode case the typical waveform you would see in the XY mode is shown below:
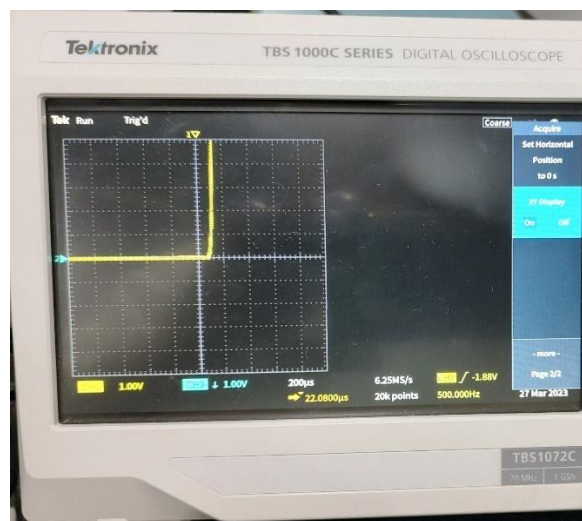

    b. Note the Yellow and Blue GND indicators showing the correct alignment in the XY mode. This way the origin will be at the middle of the DSO screen. The diode cut-in voltage can now be measured.

e) Sketch the XY waveform 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).

Case C: Zener diode V-I Characteristic

<u>Experiment</u>
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) Once again observe the XY plot of the given Zener diode.
e) The typical XY plot you will observe for the Zener diode is shown below.
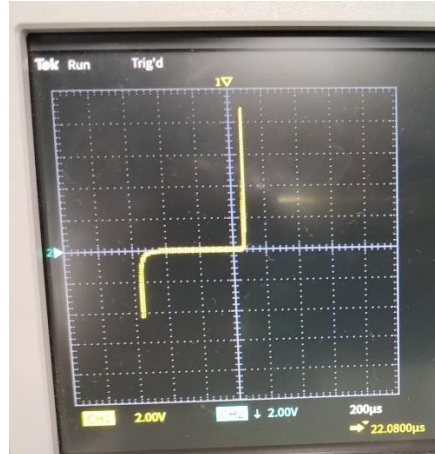
f) Sketch the XY waveform obtained by you in your Lab Notebook.
g) From the displayed XY plot, measure the cut-in voltages (in V) for both forward and Zener regions and the maximum currents in mA.

Case D: LED V-I Characteristic

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 the cathode. As in the previous cases connect cathode at point C and anode at point B.
c) After connecting the LED correctly, switch ON first the Keithley Power Supply outputs and then the AFG output.
d) Once again observe the XY plot of the given LED.
e) Sketch the XY waveform in your Lab Notebook.
f) From the displayed XY plot, measure the cut-in voltage (in V) of the LED and the maximum current in mA.