Lab 6 - Operational Amplifiers II

Objectives

In this lab, you will design and build more complex op-amp circuits and use them to measure small signals from sensors. You will also use PSpice to simulate the behavior of these circuits.

Laboratory Equipment

You will use the following components:

- Op-amps
- Resistors
- Rectifying diodes (1N4007)
- Light-emitting diodes

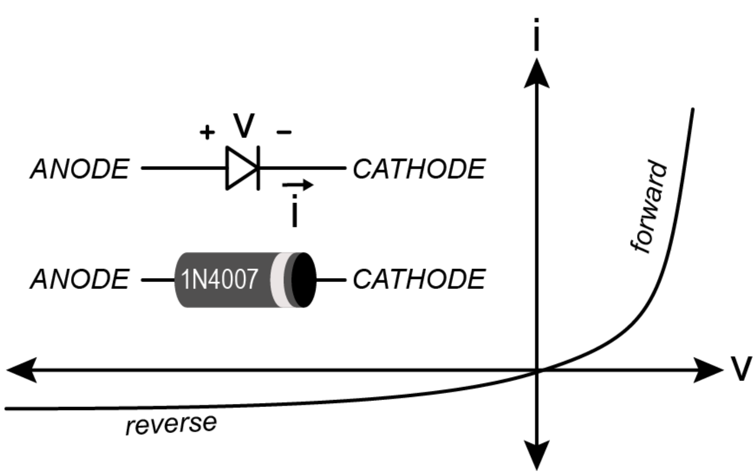
All measurements can be performed using:

- Digital multimeter
- ADALM2000 (Scopy)

Background

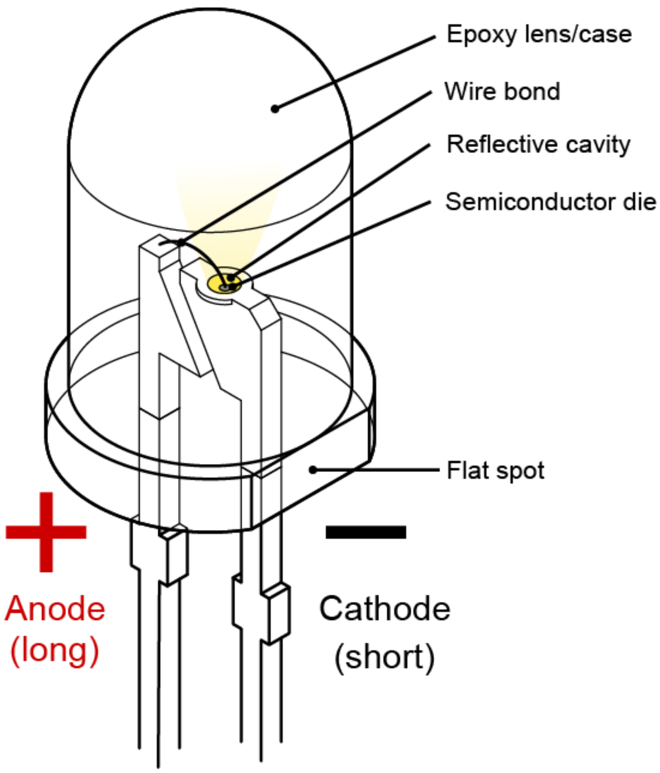
Diodes

A diode is a two-terminal semiconductor device that is formed by joining a p-type and n-type semiconductor. Unlike resistors, capacitors, and inductors, diodes are nonlinear devices -- meaning that the current and voltage are not related to one another by a simple linear relationship.



The following figure shows (schematically) the relationship between the current and voltage for a typical diode. Because of the asymmetry in the i-v relationship, the diode behaves differently when the voltage is applied in the reverse direction. Therefore when using diodes in your circuit, it is important that you connect with the right polarity. All diodes are clearly marked (typically with a bar) on the “minus” terminal, which is called the “cathode”. When the diode is biased in the forward direction, a positive current flows from the anode to the cathode. When the voltage is applied in the reverse direction, the current is much smaller. Because of this strong asymmetry, diodes are often used to inhibit current flow in the reverse direction, for example, in rectifying AC-to-DC power converters.

In this lab, you will take advantage of an interesting feature of diodes: the i-v relationship changes slightly depending on the temperature of the diode. This effect can be exploited to make a simple solid-state temperature sensor. However, because the change is small, you will need to use an op-amp circuit to amplify the change to a level that can be easily measured.



LEDs

Another common diode is the light-emitting diode (LED), which uses a direct bandgap semiconductor like GaAs or InGaN. Light-emitting diodes have an i-v relationship that is similar to that of a rectifying silicon diode, however, they emit light when current flows in the forward direction. The LEDs used in your kit are the familiar glowing indicators that are commonly found in electronic appliances, however more powerful LEDs are now widely used in automotive headlights, and by virtue of cost, efficiency and longevity, have now replaced incandescent, halogen, neon, and fluorescent light bulbs.

The following figure shows a typical diagram of a packaged LED. The two electrical leads have different lengths and the anode (+) is the longer of the two. The base of the epoxy lens also typically has a flat bevel that indicates the cathode (-) side of the LED.

In the lab, you will take advantage of the fact that an LED can also operate in the reverse direction, that is, it can produce a reverse voltage or current when light is incident on the device from above. Because the LED was not intended or designed to efficiently collect incident light, the resulting electrical signal is very small. You will therefore use an op-amp circuit to convert this nano-ampere current into a measurable output voltage.

Adding AC Signals

We have learned that any sinusoidally-varying (AC) voltage $v(t) = V_m\cos(\omega t+\varphi)$ can be entirely described by the three quantities:

1. Amplitude V_m [Volts] (> 0)

2. Frequency ω [rad/s] (> 0)
3. Phase φ [radians] ($-\pi < \varphi \leq \pi$)

An equally general way to represent an arbitrary sinusoidally-varying signal is in terms of cosine and sine components:

$v(t) = A\cos(\omega t) + B\sin(\omega t)$

where the two coefficients A and B can be positive or negative, and are related to the Cartesian coordinates of the complex phasor representing v(t).

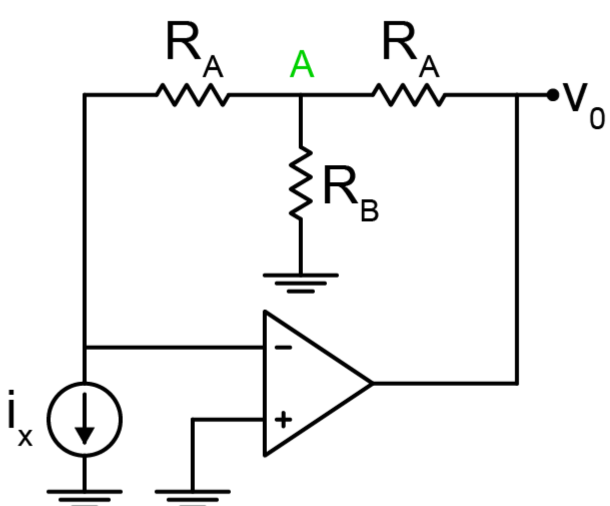
In this lab, you will use an op-amp summing circuit to add together a cosine and a sine function and verify that the resulting waveform has the expected magnitude and phase.

Pre-lab Preparation

Light Detection

A light-emitting diode is a semiconductor device that emits light when you pass a current through it. It can also operate in the reverse direction -- it can produce an electrical current when you shine light on it. However, a typical LED is a very inefficient light detector, primarily because of the small size of the active area. Even under direct bright light, the photocurrent produced in an LED is typically smaller than 1 µA. However, it is possible, using op-amp circuits, to amplify this miniscule photocurrent from an LED to produce an output voltage that you can measure on a digital meter.

In the following circuit, the illuminated LED is modeled as a current source i_x:

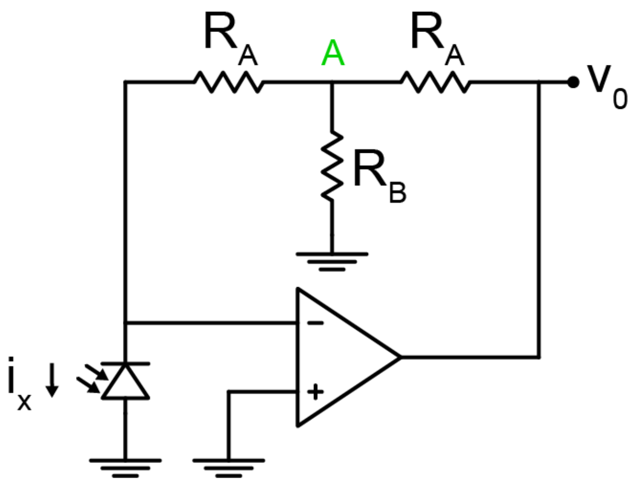


Derive an expression for the output voltage v_0 in terms of the input current i_x. Then select values for R_A and R_B in the above circuit so that the output voltage is approximately

- $v_0 = (10^7 \text{ V/A})\, i_x$

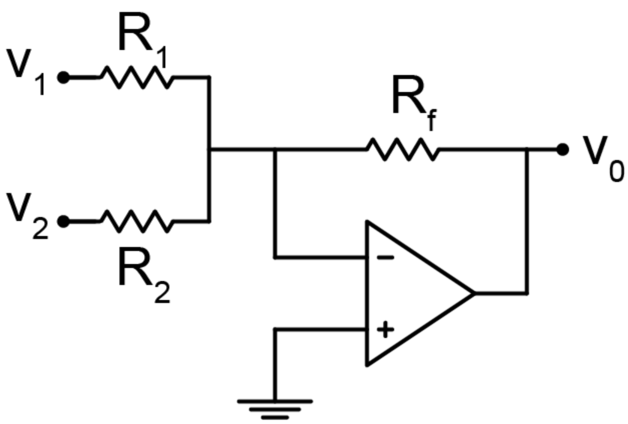
- You may only use resistor values that are [available in your kit](#)

Build and assemble the circuit that you designed in the preceding steps, but instead of the current source, insert one of the LEDs from your kit:



Summing Amplifier

Design a summing amplifier with the following characteristics:

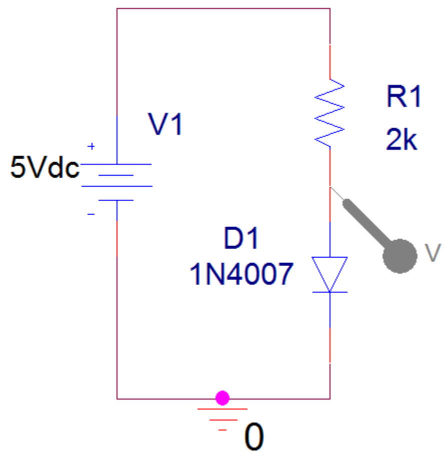


- Takes two input voltages $v_1(t)$ and $v_2(t)$ and produces an output $v_0(t) = -3[v_1(t)+v_2(t)]$
- Has an input resistance of 10 kΩ for each of the two inputs (i.e., the input current i_1 and input voltage are related by $v_1/i_1 = 10$ kΩ)
- Use only resistors that are [available in your kit](#).

Sensing Temperature with a Diode

The forward voltage measured across a diode depends upon the temperature, and in this experiment, we will use this effect (with an op-amp difference circuit) to build a temperature sensor.

Simulate the following circuit using Pspice:



(You can search for the PSpice part "1N4007" which is a standard rectifying diode that is found in your kit.)

Add a voltage probe to measure the diode voltage, and set the simulation profile to "DC Sweep", with the following parameters:

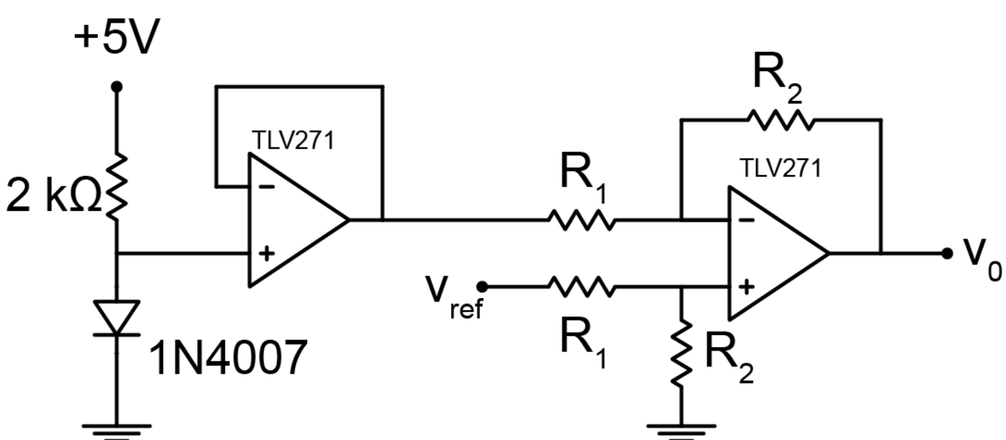
- Sweep the temperature (T)
- Temperature sweep range from 0 degrees C (32 F) to 30 degrees C (86 F)
- Step size 1 degree C

Your simulations should show that the voltage across the diode is approximately 0.6 to 0.7 volts, but that it changes by about 60 mV over this temperature range. Submit a copy of your simulation.

Now design an op-amp circuit that produces an output voltage v_0 that is proportional to the diode temperature in degrees C:

- v_0 = (40 mV/C) x T [in Celsius]. (i.e., at 0 C, v_0 = 0 V and at 30 C, v_0 = 1.2 V)

You can use the following combination of a buffer amplifier (which senses the diode voltage without diverting significant current) and a difference amplifier.



The tunable input voltage v_{ref} should be chosen to subtract the offset voltage, and the resistors R_1 and R_2 should be selected from the values available in your kit, to achieve the desired scale ratio. Do not use any resistors in your design that are smaller than 1 kΩ in size.

Do not worry if you cannot achieve exactly 40 mV/C. Specify your chosen values for R_1, R_2, and the offset voltage v_{ref}, and the resulting temperature scale factor (which should be on the order of 40 mV/C)

Instructions

Light Detection

Test the light-detection circuit that you designed and assembled in the pre-lab activities, which uses an op-amp with T-network feedback to amplify the reverse photocurrent that is produced when light shines on an LED:

- Test the circuit initially by measuring the output voltage v_0 using your digital multimeter, while shining light directly onto the LED. You should be able to produce a measurable voltage using the flashlight feature available on a typical smartphone. Because LEDs are encased in a transparent acrylic dome, you will measure the strongest signal for light incident directly from above, so that the incident light gets focused onto the LED active area.
- Try with a couple of different LEDs from your kit, and find the one that gives you the largest signal. (Best practice is to power off the op-amp before connecting/disconnecting components) Take note of the largest attainable output voltage that you can observe.
- Once the circuit is working, use the ADALM2000 voltmeter to record output voltage while moving the light back and forth across the LED. Here are the recommended settings:
  - 60-second history
  - Data logging on (choose output filename)
  - Overwrite
  - Timer: 1 s (this will take one measurement per second)
- Save your data sequence as a CSV file, and make sure that you have captured the maximum attainable output voltage for your light source.

Summing Amplifier

Assemble the summing amplifier that you designed for the pre-lab exercise and connect the two inputs $v_1(t)$ and $v_2(t)$ to the two waveform generators.

- Configure the two waveform generators to produce sinusoidal waveforms with the following characteristics:
  - Frequency = 10 kHz, for both channels
  - Waveform = sinusoidal
  - Amplitude of v_1 = 300 mV
  - Amplitude of v_2 = 400 mV
  - Phase: $v_2(t)$ leads $v_1(t)$ by 90 degrees
- Measure $v_1(t)$ and $v_2(t)$ and record the resulting waveforms (both screenshot and data points)
- Measure both $v_1(t)$ and the output $v_0(t)$ (both screenshot and data points).

Difference Amplifier

Assemble the diode temperature sensor amplifier that you designed for the pre-lab exercise

- Use an adjustable / programmable DC input voltage for v_{ref}:
    - If you are using the ADALM2000/Scopy, you can use the signal generator in "Constant" mode to produce a programmable DC output voltage.
- With the circuit configured, adjust the offset voltage v_{ref} until the output voltage v_0 shows the correct reading that you expect to see for 25 C (room temperature)
- Take one of the remaining 1N4007 diodes from your kit and hold the body firmly between your fingers/hands, to warm it up to body temperature. Hint: if you do not trim the leads of the diode, you should be able to observe the temperature change by simply pinching the diode between your fingers while it is in the circuit.
    - If you are working from home, you can also try putting one of the diodes in the freezer, or warming one gently with a hair-dryer.
- Replace the diode with the warmer (or colder) diode and carefully observe the output voltage as the diode cools (or warms) back to room temperature.
- Use the Scopy voltmeter and data logger to record the output voltage of your circuit while the diode cools (or warms) back to room temperature. Here are the recommended settings:
    - 60-second history
    - Data logging on (choose output filename)
    - Overwrite
    - Timer: 1 s (this will take one measurement per second)

Post-lab Analysis

Be certain to include plots of all three circuits along with complete descriptions.

For the LED circuit:

1. Describe your method for illuminating the circuit as accurately as you can (e.g. did you use direct sunlight? If you used a flashlight, do you know how many lumens it produces? If you used a light bulb, how many watts & what temperature?)
2. Describe / plot the variation in output voltage with LED color. Which worked the best and which the worst? Speculate as to why there was the variation you saw.
3. Compare your results with at least three other classmates and summarize similarities and differences in the results. Speculate as to why there was a variation.

For the inverting summer circuit:

1. Compare the measured result to the analytic calculation. Describe quantitatively the difference between the results. To what do you attribute any differences? Are you speculating or is your opinion backed by data? Explain.
2. If you played with frequencies besides 10 kHz at what frequency(ies) did the behavior of the op-amp circuit change. To what do you attribute the changes?

3. If you played with other amplitudes or other pulse shapes (e.g. square waves or triangle waves), describe the behavior of the op-amp output. Was the output as you expected?

For the temperature sensor (diode) circuit:

1. What reference voltage was necessary to calibrate your circuit? Could you predict the needed reference voltage based on the diode forward voltage? If so, how? If not, why not?
2. Estimate the calibration of your circuit. You should be able to get your ambient temperature from a thermometer or a thermostat. Typical skin temperature (when not lowered by the ambient temperature) is about 33C. Refrigerators are typically around 5C and freezers are around -15C. Many modern fridges actually display internal temperatures, so if that’s the case for you, your estimates will be more accurate.)
3. Estimate the temperature sensitivity of the diode. For a current of ~2 mA, the sensitivity should be around $dF_v/dT \sim -1.8$ mV/C (the change in forward voltage with temperature). How does this compare to your result? To what might you attribute discrepancies in the measured value and this estimate?