
Lab 4

Operational Amplifiers (OP-Amps) I

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1 Goals

The Gaussian Beams Lab

In this lab, you learn about mounting optics and photodetectors and try out some techniques that are generally useful in optics labs and elsewhere. In particular, you will set up a simple optics system for measuring the width of your laser beam and in the process will have to mount and align the laser and optics.

EA1P1

At the end of this activity you will be able...

1. ...to explain the merits of different ways to estimate the ***statistical*** uncertainty in common measurements like a DC voltage reading.
2. ...to explain which of the methods actually give an estimate of the standard deviation, which over/underestimate the uncertainty, and which are just a rough estimate of the uncertainty.
3. ...compute the uncertainty in a derived quantity using the uncertainties in the measured quantities (error propagation).
4. ...add error bars to a plot as a visual representation of uncertainty.

2 Lab Notebook

The lab notebook will play an important role in this course. You will use your notebook for keeping records of many things including

- Answering pre-lab questions from the lab guide
- Answering in-lab questions
- Recording data
- Including plots of data
- Analysis and results
- Diagrams and pictures
- Procedures of experiments that you design

The lab notebook will be an important part of your grade because learning to keep a good lab notebook is an important part of your professional development. You may find it helpful to write up many of your notes on the computer, for example, within Mathematica or another program. This is fine. However, before your notebook is turned in, the notes, plots, and analysis should be transferred to

the lab notebook by printing and taping the pages or keeping them in a three-ring binder. There will also be formal lab reports and oral presentations, but these will be restricted to a limited portion of the experimental work you have conducted in the lab.

3 Definitions

Optic – Any optical component that manipulates the light in some way. Examples include lenses, mirrors, polarizing filters, beam splitters, etc.

Optomechanics – This category includes optics mounts and the components to align them. Examples in the lab include post, post holders, bases, lens mounts, adjustable mirror mounts, rotation mounts, and translation stages.

4 Setting up the Laser and Mounting Optics

Your group should find an empty optical breadboard workstation in one of the five optics bays in G-214. Spend some time to explore the space and familiarize yourself with the components.

When you start working in the lab you should have an empty optics breadboard. The shelf above the breadboard should have

- An oscilloscope
- A waveform generator
- Triple output DC Power Supply
- Set of ball drivers
- Optics caddy to hold optics already mounted on 0.5" posts
- Set of 1/4-20 and 8-32 screws, setscrews, washers, and nuts

4.1 Question 1

1. Get a laser and power supply from the "He-Ne Laser" drawer in the colored drawer cabinet found in your chosen or assigned optics bay (each of the five optics bays has been color coded). You'll also need two sets of laser tube mounts which you can find in the same drawer. The bottom mount first gets mounted to an optical post and then the top of the mount can be assembled with 1/4-20 socket head cap screw and nut. After both sets of tube mounts are attached to the laser, insert the optical posts into post holders and attach the assembly to the optical table.

2. Each person in your group is responsible for assembling a mounted lens or mirror as shown in Figure 1. In the end, you will need at least 2 mirrors to complete the next task. It's very important that you **do not handle optical components** (lenses, mirrors, polarizers, wave plates, beam splitters, etc.) **with your bare hands**. The oils on your skin can damage the optics and degrade the light in your experiment. Always handle these components while using **latex/nitrile gloves or finger cots**.

As you are mounting the optics, choose the heights so that the laser hits the center of each optic and the beam is parallel to the table.

4.2 Walking a beam

Mount two 3D printed beam alignment discs onto the optical table at the same height above the table.

1. Use only two mirrors to get the beam to pass through the center of each disc. This technique is commonly called "walking a beam." Having two mirrors allows you to independently adjust the angle and position of your beam.
2. Draw a diagram in your lab notebook of the configuration of your laser, mirrors, and alignment discs.

4.3 Lens alignment

1. Using your setup from 4.2, insert a lens (after the mirrors) into the beam path to change the divergence/convergence of the beam but keep its propagation direction the same.
2. When this condition (the beam propagation is unchanged) is met, where does the beam intersect the lens?

Note: This is the preferred method of adding a lens to an optical set up.

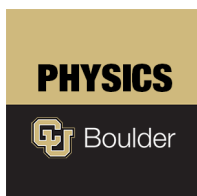


Figure 1: Mounting assemblies for a mirror (left) and a lens (right).

5 Modeling Characteristics of the Photodetector

The goal of this part of the lab is to understand a lot about the specifications given on the datasheet for the Thorlabs PDA36A (or PDA36A2) Switchable Gain Amplified Photodetectors. It is important to realize that data sheets (also called spec sheets or specification sheets) provide a model for the realistic behavior of the device. This model can be tested and improved, a process more commonly called “calibration.” Note that there are **two** power switches, one on the power supply and one on the photodetector. The photodetector will respond to light with the power off but it won’t work well and changing the gain will have little effect.

5.1 Basic function of the amplified photodetector

1. Spend a few minutes (no more than 10) to write an explanation using words and diagrams to explain the physical mechanism for how the photodetector converts light into voltage. You may use the manufacturer’s specifications sheet, trustworthy online resources, a book, etc. The specification sheet available at www.colorado.edu/physics/phys4430/phys4430_sp18/datasheets/Thorlabs_PD
2. Use the data sheet to estimate the conversion of watts of light into amps of current for Helium-Neon red wavelength (632.8 nm) and for the frequency doubled Nd:YAG laser (Green laser pointer wavelength, 532 nm).
 1. How would you convert “amps per watt” into “electrons per photon”?
 2. What is the electron/photon conversion efficiency for the red HeNe laser and green doubled Nd:YAG lasers?
 3. Is this number less than, equal to, or greater than one? What does this number tell you about how the photodiode works?

5.2 Calibrating the photodetector offset and gain

Calibrating the photodetector is especially important when you take a data set that uses multiple gain settings. Having an accurate calibration of the gain and offset will let you stitch the data together accurately.

1. Here you will encounter gain values that are presented on a logarithmic dB (decibel) scale, which is obtained by taking $20 \times \log(V_{out}/V_{in})$. For example, 20 dB of gain corresponds to electronic voltage amplification by a factor of 10. A dB scale could also be defined as $10 \times \log(P_{out}/P_{in})$, where P is the power. Explain the conversion between these two scales and why this makes sense.

2. Calibrating the offset voltage (the output of the photodetector when no light is incident upon the device).
 1. Calibrate the offset of the photodetector as a function of gain setting.
 2. Quantitatively compare it to the specifications given in the table. Is your measured value within the specified range given on the PDA36A or PDA36A2 photodetector data sheet?
 3. What measures did you take to eliminate stray light? Were your measures sufficient for an accurate calibration?
3. Calibrating the gain.
 1. Is it possible to measure the V/A gain for each setting, or can you only measure the change in gain as you switch the settings? Why? Note that this lab only requires relative gain.
 2. Make a measurement of the gain or relative gain for most of the gain settings. If you need to adjust the laser power, try blocking part of the beam. Note, you will need to make two measurements at one gain setting when you block the beam. What systematic error sources are of most concern?
 3. Quantitatively compare your results with the range of values given on the data sheet. Do you believe your results provide a more accurate estimate of the photodetector gain than the data sheet? Why or why not?
 4. Using the appropriate spec sheet and your measurements, what is the power of your laser? Does this agree with the laser power shown on the laser?
 5. Hypothetically, how would you measure the absolute gain?

5.3 Follow up

1. Write mathematical expressions that converts the incident power (the light) P_{in} to the photodetector voltage V and the photodetector voltage V to input power P_{in} . Take into account all relevant parameters such as the photodetector gain setting (in dB) and offsets.

6 Measuring the Beam Width

The goal of this section is to develop a measurement technique and analysis scheme to measure the width of a laser beam. The scheme will let you measure the width in one dimension. The technique is most useful for beams that have an approximately Gaussian intensity profile. You will improve and refine this technique in the upcoming weeks of this lab.

The basic scheme involves measuring the power in the laser beam as the beam is gradually blocked by a razor blade using a setup similar to Figure 2.

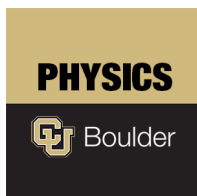


Figure 2: Razor blade mounted on a translation stage.

6.1 Question

1. Suppose a laser beam has a Gaussian intensity profile $I(x, y) = I_{max}e^{-2(x^2+y^2)/w^2}$, and is incident upon a photodiode. What is the expression for the power hitting the photodiode when a portion of the beam is blocked by a razor blade?
 1. Draw a diagram showing the beam and the razor.
 2. Using the above expression for $I(x, y)$, write the mathematical expression for the power incident on the photodiode as a function of razor position. Note, to address this question, you will need to become familiar with the Error Function, $erf(x)$. What assumptions, if any, did you need to make in evaluating the integral? Hint: if you are moving in the x direction, what is going on in the y direction?

6.2 Before you take data: Create an analysis function to fit a test set of data

Note: Nonlinear least squares fitting is covered in Mathematica Activity 2 available on the course website. There is also a YouTube video available on least squares fitting at www.youtube.com/compphysatcu.

- a. What is the functional form for your fit function?
 - b. Is it a linear or nonlinear fit function? Why?
 - c. What are the fit parameters? Why do you need this many?
 - d. How do the fit parameters relate to the beam width?
 - e. Download the data set from: www.colorado.edu/physics/phys4430/phys4430_sp18/sample_data/Test_Profile_
- i. Make a plot of the data.
 - ii. Make a fit and plot it with the data.
 - iii. Check that the fit looks good and you get a beam width of. If you get a different value, check with your instructor to understand the problem. What is the uncertainty on your measurement?

6.3 Build your setup for measuring the beam width of your laser

1. Draw a detailed schematic of the setup (from the laser all the way to the photodetector). Do not use a lens for this measurement.
2. After assembling your experiment, but prior to taking a lot of data, how can you quickly determine if the measurement is working?
3. Is it preferable to use a digital multimeter or oscilloscope? Why?
4. Use the measurement scheme to take data of power vs position of the razor. Pay attention to the units of the translation stage. Pick a position where your beam has a measurable width, and measure it. Justify your choice.

6.4 Analysis of the random uncertainty sources

1. What are possible sources of random uncertainty in the photodetector voltage?
2. How would you estimate the uncertainty in the photodetector voltage measurement?
3. What is the largest source of uncertainty? Why?

6.5 Analysis of the real data

1. Use the analysis procedures verified in Question 8 to find the beam width for your data. Be sure to include the uncertainty.
2. Plot your fit together with your data to make sure it is good.

7 Introduction to Measurement Uncertainty

When attempting to establish the validity of our experimental results it is always important to quantify the uncertainty. Measurement uncertainty wasn't invented to make lab classes tedious, rather it is a core part of any experimental work that gives us a way to quantify how much we trust our results.

A simple and rigorous way to make a measurement and estimate its uncertainty is to take N measurements $\{y_1, y_2, \dots, y_N\}$ and estimate the value by the mean:

$$\bar{y} = \frac{1}{N} \sum_{i=1}^N y_i$$

The estimated uncertainty (standard deviation, σ_y , or variance, σ_y^2) of any one measurement is given by

$$\sigma_y^2 = \frac{1}{N-1} \sum_{i=1}^N (y_i - \bar{y})^2$$

.

While the uncertainty in the mean value $\sigma_{\bar{y}}$ is smaller and is given by

$$\sigma_{\bar{y}}^2 = \frac{\sigma_y^2}{N}$$

.

The remainder of this week's lab will discuss a variety of practical considerations about using uncertainty in the lab.

7.1 Estimating the mean and uncertainty

The next four questions cover a basic measurement that was essential in the Gaussian Laser Beams lab. **In a group of 2 or 3, find a lab bench with a laser and turn it on immediately. It might take 5 minutes for the laser to warm up.** Use the photodetector to measure the DC optical power.

7.2 Measurement and uncertainty using the multimeter

Note: It may be possible to answer questions 1 and 2 at the same time if you use a BNC "T" to send the voltage to the multimeter and oscilloscope at the same time.

Make a table of estimated DC voltages from the laser and the corresponding uncertainties using the following methods

1. "Eyeball" the mean. "Eyeball" the amplitude of the random fluctuations.
2. **If your multimeter has the capability**, set the multimeter on max/min mode to record the V_{max} and V_{min} fluctuations over a certain time period. You can estimate the mean by $(V_{max} + V_{min})/2$ and the uncertainty by $(V_{max} - V_{min})/2$.
3. Record the instantaneous voltage reading on the multimeter N times and calculate the estimated uncertainty from the standard deviation.
4. What is the resolution intrinsic to the multimeter according to the spec sheet here (No measurement required) How does this compare to the observed uncertainty in parts a-c?

7.3 Measurement and uncertainty using the oscilloscope

Continue the previous table of estimated DC voltages from the laser and the corresponding uncertainties using the following methods. For each method comment on if and how it depends on the setting for the time scale or voltage scale on the oscilloscope.

1. “Eyeball” the mean. “Eyeball” the amplitude of the random fluctuations (no cursors or measurement tools).
2. Use the measurement function on the scope to record the mean and RMS fluctuations.
3. Use the cursors to measure the mean and size of fluctuations.
4. Record the voltage from the oscilloscope N times and calculate the estimated uncertainty from the standard deviation.
5. A comparison with the data sheet is difficult because so many factors affect the observed noise in the oscilloscope. You can find some information here. There is information about the resolution and the DC measurement accuracy.

7.4 Summary of Questions 1 and 2 (make sure to support your answers for each question):

1. Did any methods overestimate the uncertainty?
2. Did any methods underestimate the uncertainty?
3. How reliable was “eyeballing”?
4. Did the time scale or voltage scale affect any of the oscilloscope measurements? If yes, how? Does this tell you anything about how to use the scope?
5. Suppose the light into the photodetector was not constant during the measurements (due to variations of the laser, room lights, etc.). In which estimates of the uncertainty will this be included?
6. Which method(s) should give a true estimate for the uncertainty?

7.5 Measurement using the NI USB-6009 DAQ

- a. Is the USB data acquisition device more like the multimeter, or more like the oscilloscope? (Just think back to your experience using the DAQ last time. No data taking for this part.)
- b. How would you go about estimating the uncertainty when using your DAQ?

7.6 Writing numbers and their uncertainty

The convention used in this course is that we

- 1) only display one significant digit of the uncertainty (two are allowed if the first significant digit is a 1)
- 2) display the measurement to the same digit as the uncertainty.

The numbers 1543, 576.330.04, and 245.11.4 follow the convention. However, numbers copied from the computer are often displayed as “machine precision” with no regard for significant digits.

Question 5

Mathematica generated the following fit parameters and corresponding uncertainties:

How should the two Mathematica fit parameters above be rewritten?