Lab 6

Optical Communication Link

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Contents

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1 Goals

In this lab, you will design and build a photometer (optical detector) based on a silicon photodiode and a current-to-voltage amplifier whose output is proportional to the intensity of incident light. First, you will use it to measure the room light intensity. Then you will set up and investigate an optical communication link in which the transmitter is a light emitting diode (LED) and the receiver is your photodiode detector.

Proficiency with new equipment:

- Diodes, LEDs, photodiodes, and transimpedance amplifiers

Modeling the physical system:

- Model the sensitivity of a photodiode
- Develop a model of a photometer measurement system

Applications:

- Build a calibrated photometer
- Build an optical communications link

2 Definitions

Intensity - power per unit area; units are W/cm^2 and symbol (for this lab) is N.

3 Diodes

A diode is a semiconductor device that has two terminals, an anode and a cathode. These terminals are represented by (-) for the cathode and (+) for the anode on the diagram in Figure 1. Diodes are made out of n-doped and p-doped semiconductors. Visit this PhET simulation for a good example of how these work.

The fundamental property of a diode is its tendency to conduct electric current in only one direction. The diode can be operated in three regions. The first region, called forward biased, is when the cathode has a higher potential relative to the anode. Once this potential difference is greater than some

threshold voltage (about 0.6 V for silicon diodes) the diode conducts with almost zero resistance and has a constant 0.6 V drop across it. The second region of operation is where the cathode has a lower potential relative to the anode. This region is called reversed biased and essentially no current can flow. Finally, if the potential difference from the cathode to the anode is negative and larger than some breakdown voltage, the diode will again conduct. Regular diodes are not used in the break down region, but Zener diodes are used for this purpose.
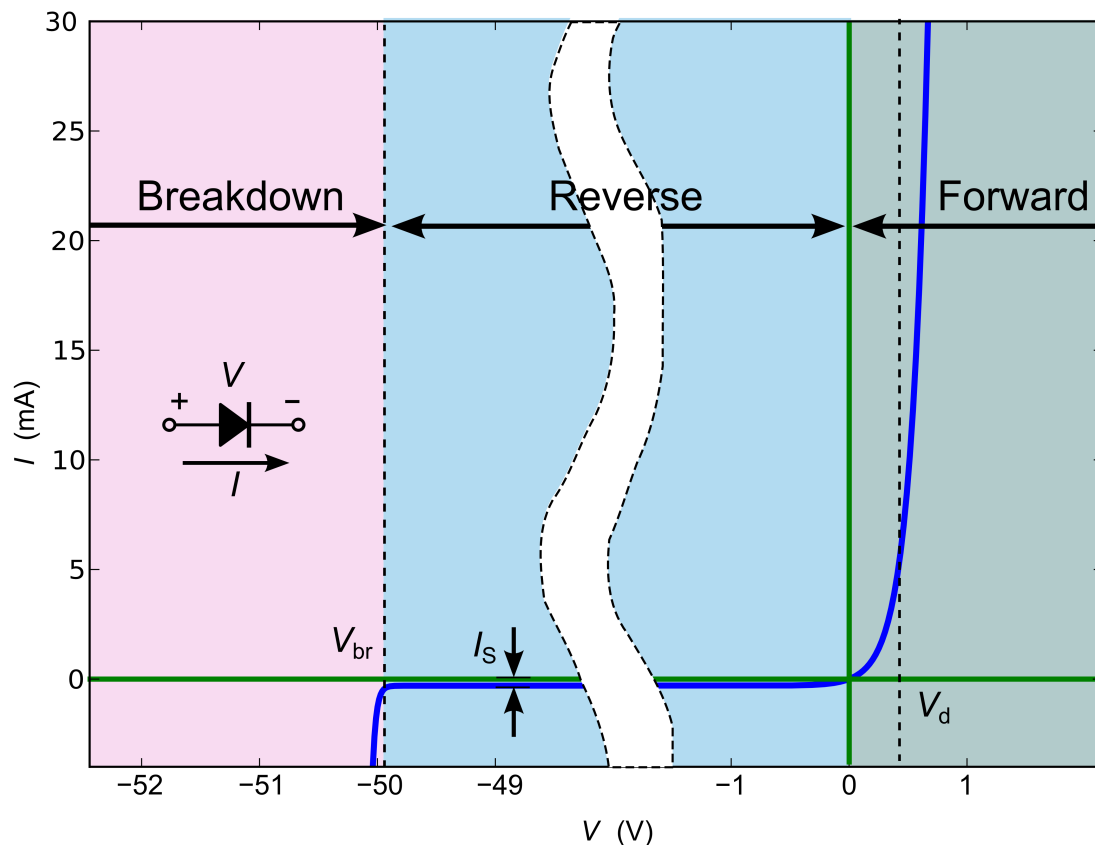
**Figure 1:** Diode characteristics

3.1 Light emitting diode (LED)

The HLMP-C625 light emitting diode used in this lab acts electrically like any other diode. However, unlike regular diodes it also emits light when forward-biased due to direct radiative recombination of electrons and holes. The forward voltage drop is about 1.9 V rather than 0.6 V because the LED is made of AlInGaP instead of silicon.

3.2 Photodiode
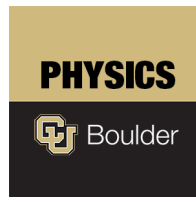
Figure 2: Diagram and schematic symbol for a PIN silicon photodiode.

The PD204 photodiode used in this experiment is a p-intrinsic-n (PIN) silicon diode operated in reverse bias. A sketch of the photodiode structure is shown in Figure 2. The very thin p-type conducting layer acts as a window to admit light into the crystal. The reverse bias voltage maintains a strong electric field throughout the intrinsic region forming an extended depletion layer. The depletion layer should be thicker than the absorption length for photons in silicon in order to maximize the efficiency. An incident photon whose energy exceeds the bandgap energy can be absorbed to produce an electron-hole pair by photoelectric excitation of a valence electron into the conduction band. The charge carriers are swept out of the crystal by the internal electric field to appear as a photocurrent at the terminals. The photocurrent is proportional to light intensity over a range of more than 6 orders of magnitude.

The photodiode sensitivity S_λ is the proportionality factor that links how incident optical power P in Watts to a generated current I in Amperes. The photodiode sensitivity S_λ carries units of A/W.

$$I = S_\lambda P$$

It is important to keep in mind that here, Amperes is the current flowing in the electrical circuit, whereas Watts refers to the incident optical power, NOT an electrical power somewhere in the circuit.

What would S_λ be for an ideal photodiode in which every photon hitting the photodiode generates one electron? Since each photon of light at wavelength λ carries an energy $E_\lambda = hc/\lambda$, the rate of photons hitting the photodiode is $R = P/E_\lambda$ photons/second. But for an ideal photodiode, every photon generates one electron with charge e that then flows out of the photodiode. Therefore, the rate of charge flowing out of the photodiode per second (i.e. the current!) is $I = eR = P\,(\lambda e)/(hc)$. However, in a real photodiode, not every photon gets absorbed and generates an electron. We call the probability that an incident photon at wavelength λ generates an electron, the quantum efficiency of the photodiode q_λ with possible values between 0 and 1 such that $S_\lambda \leq q_\lambda\,(\lambda e)/(hc)$. At $\lambda = 690$ nm (red), the ideal sensitivity (i.e. $q_\lambda = 1$) would be 0.56 A/W, a fairly easy number to remember.

The quantum efficiency also depends on λ, so photodiode manufacturers typically will provide the

actual S_λ in the data sheet. Because the PD204 photodiode comes with a curved lens, the data sheet specifies the short circuit current $I_{SC} = 10\,\mu A$ at an incident intensity of $1\,mW/cm^2$ at λ = 940 nm. The lens has a diameter of $d = 0.3\,cm$ or an area of $0.071\,cm^2$. So, an incident intensity of $1\,mW/cm^2$ corresponds to a total power of 71 μW of optical power hitting the photodiode. The sensitivity is then:

$$S_{940} = \frac{I_{SC}}{71\,\mu W} = 0.14\,A/W$$

Note that this means the quantum efficiency at 940 nm is only 0.18, not so great.

The sensitivity at other wavelengths λ is given on the data sheet in terms of the peak sensitivity S_{940} at 940 nm times a correction factor called the relative spectral response, or RSR:

$$S_\lambda = S_{940}\,RSR(\lambda)$$

Figure 3 shows the RSR from the PD204 data sheet. You can see the maximum sensitivity is around 940 nm.
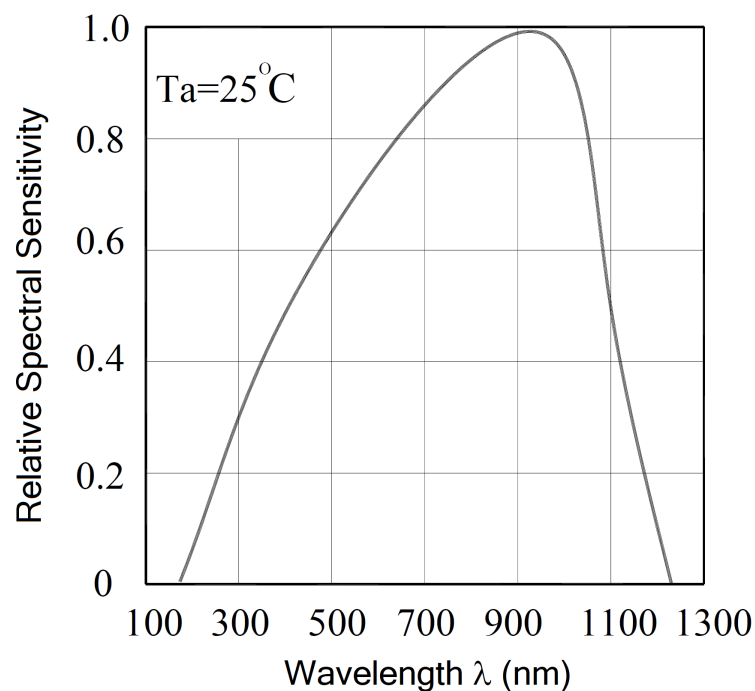
Figure 3: PD204 Relative Spectral Sensitivity

4 Current to Voltage Amplifier (Transimpedance Amplifier)

In an ordinary inverting amplifier, the input voltage is applied to a resistor, and the amplifier generates an output voltage in response to the current that flows through the input resistor to the virtual ground at the negative op-amp input. A current-to-voltage amplifier (Figure 4) is an inverting amplifier with the input current I_{in} supplied by the photodiode and applied to the inverting op-amp input. Since no current flows into the op-amp input, the output voltage must be $V_{out} = -I_{in}R_F$. The ideal (Golden Rules result) low-frequency gain of a current-to-voltage amplifier is

$$G = \frac{V_{out}}{I_{in}} = -R_F$$

This gain has the units of impedance i.e., Ohms, and it is often called a transimpedance gain. The current-to-voltage amplifier is also called a transimpedance amplifier. This type of amplifier is very common in research labs, and is used to amplify the current from photodiodes, photo multiplier tubes, ion detectors, etc.
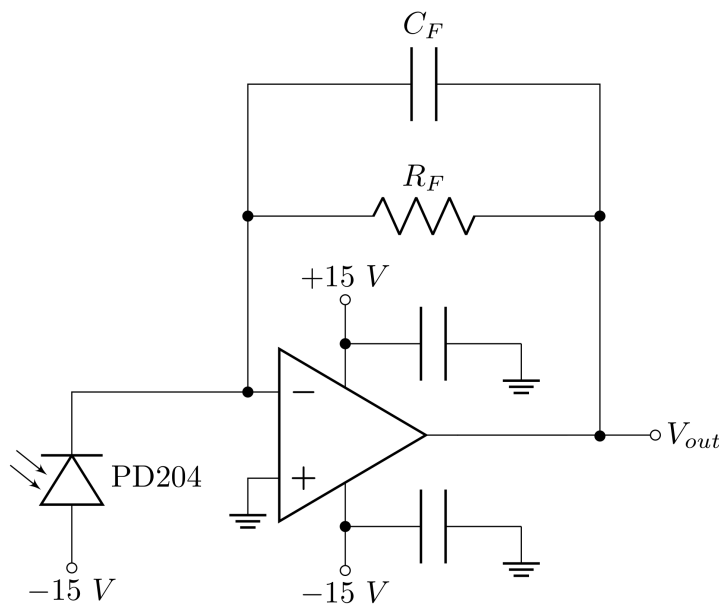
Figure 4: Photodetector circuit

In our photometer circuit the current I_{in} flows through the reverse-biased photodiode when it is illuminated (it flows out of the op-amp negative input node and the resulting V_{out} is positive). The feedback capacitor C_F enhances stability, i.e., it helps to avoid spontaneous oscillations of the op-amp by reducing the bandwidth of the amplifier (just like an active low-pass filter).

5 Optical Communication Link

The basic optical communication link is composed of two circuits (Figure 4 and Figure 5). The circuit in Figure 5 uses an AC voltage source to produce a light signal from the LED. The circuit in Figure 4 is the photometer, composed of a photodiode connected to a transimpedance amplifier to convert the light into a measurable voltage.
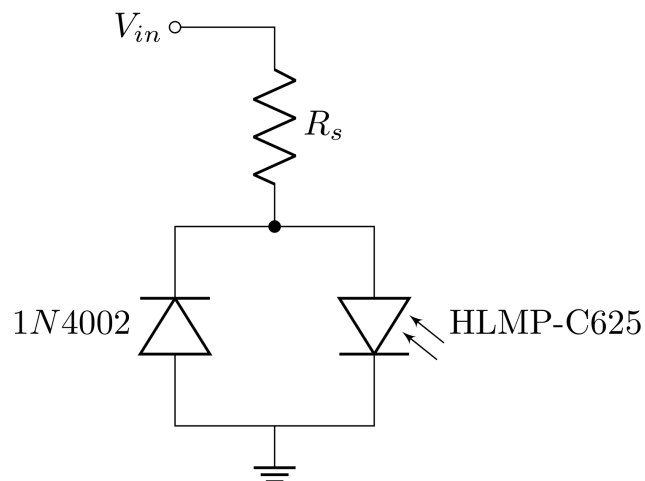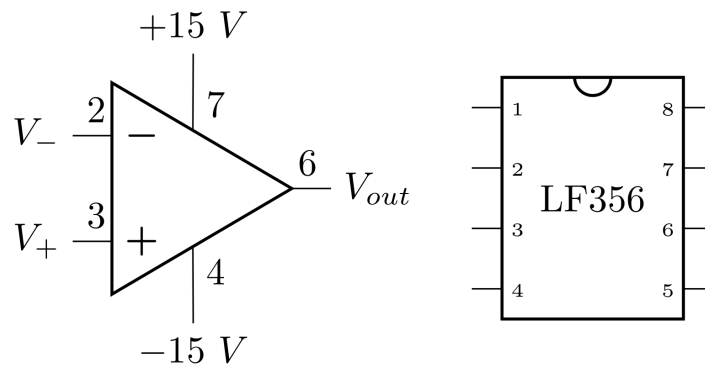
Figure 5: Optical communication link circuit

6 LF356 Pin Out and Schematic

All op-amp circuits start out by making the basic power connections. Op-amps are active components, which means they need external power to function, unlike passive components such as resistors and capacitors.

Figure 6: LF356 schematic and pin-out

7 Useful Readings

1. Steck Sections 2.2.1, 3.1, 3.3, 3.4, 3.6, Problem 7.5 (pages 246-246)

2. Fischer-Cripps Chapter 4, especially Sections 4.18-4.19

3. Horowitz and Hill 2nd Ed., Sections 1.25-1.27, 15.02, and page 184

8 Prelab

Answer the following questions using Mathematica for the plots. You can use either Mathematica for the rest of the questions as well or do them by hand. **Make sure to have the Mathematica notebook for your lab section as well.**

8.1 Simple diodes

1. Consider the circuit in Figure 7. If the diode is ideal with a threshold voltage of 0.6 V and a break-down voltage of 50 V, predict the behavior of the current I (consider clockwise current to be positive) and V_{out} as a function of the source voltage V_{in}. Make a table of the predicted I and V_{out} for the following values of V_{in}: -2 V, 0 V, +0.5 V, +0.6 V, +0.7 V, +1 V, +2 V, +4 V.

2. Now, consider the case where V_{in} is a sine wave with a 3 V amplitude (6 V peak-to-peak) centered on V_{in} = 0 V. Predict V_{out} and I as a function of time and sketch your predictions (by hand or with Mathematica) over 3 periods.

8.2 Transimpedance amplifier

1. For the current-to-voltage amplifier in Figure 4, choose a value for the feedback resistor R_F so that an incident white-light (λ = 555 nm) optical power of P = 71 μW produces an output of 10 V.

2. The small feedback capacitor C_F is used to suppress spontaneous oscillations. The transimpedance gain of the amplifier at any particular frequency is $-Z_F$, where Z_F is the effective impedance of the parallel $R_F C_F$ circuit. The gain rolls off at high frequencies with a bandwidth of $f_B = 1/(2\pi R_F C_F)$, just like any low-pass filter. The bandwidth will suffer if C_F is too large. What is the bandwidth f_B if C_F = 10 pF?

3. What are the DC values of the voltages at the + and - inputs and at the output of the op-amp for zero light on the photodiode? Consider the ideal situation where the diode allows zero current when there is no light hitting it. (In reality, about 10 nA of "dark current" flows through the diode even with no light on it.)

8.3 Optical communication link

1. To drive the transmitter, the function generator will be adjusted to produce a square wave with a high level of 8 V (unloaded) and a low level of 0 V. The high-level (8 V) should give a 20 mA forward current in the LED, and the low level (0 V) should give 0 mA. **Find the value of the series resistor Rs that gives the correct current.** The data sheet lists the LED forward voltage drop at 20 mA to be 1.9 V (instead of 0.6 V for silicon diodes). In addition, do not forget to model the function generator as an ideal voltage supply with a series output impedance of 50 Ω, which is the true output impedance regardless of the "impedance setting" on the function generator. You will want to draw a circuit diagram with all of the components (modeling the output impedance as an extra resistor) and then use Kirchoff's rules to generate an equation that you can solve for R_S.

8.4 Lab activities

1. Read through all of the lab steps and identify the step (or sub-step) that you think will be the most challenging.

2. List at least one question you have about the lab activity.

# 9 Introducing Diodes
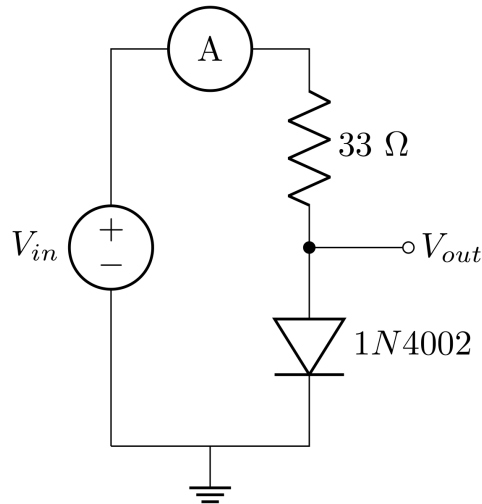
Figure 7: Simple diode circuit

9.1 Determine the I-V characteristics for a silicon diode

1. Build the circuit in Figure 7 using the silicon diode 1N4002.

2. Measure the current I and the voltage across the diode (V_{out}) for different values of V_{in} from –3 V to +3 V. You need to use the DMM to measure the voltage across the diode. To maximize accuracy, you would use another DMM to measure current. But reading the current directly from the power supply is fine. Be sure to take many data points (at least 10) to map out the characteristic curve of the diode, with a few extra points around V_{in} of 0.6–0.9 V. How does the result compare with your predictions from section 8.1.1? How does it compare with Figure 1?

3. Specifically consider the points at V_{in} = +0.5 V, +0.8 V, and +2.0 V. What is the power dissipated in the diode and in the resistor for these values? Remember $P = IV$ and I is the same for both components, but V is not.

4. Now, change V_{in} from the DC voltage source (power supply) to the AC voltage source (function generator) and input a 1 kHz sine wave with a 3 V amplitude (6 V peak-to-peak) Record the resulting V_{out} waveform and compare with your prediction in section 8.1.2.

9.2 Determine the I-V characteristics for a light emitting diode

1. Now, replace the silicon diode with a red LED (HLMPC625). Repeat section 9.1.2, but take the extra points in the region where the current begins to rapidly increase. Be sure to read the spec sheet for the LED and don't exceed the DC current limit. Take note whether the LED is emitting light and give a qualitative description of the amount of light. How does the LED behave differently in the circuit from a silicon diode? Does the LED's light output seem to be proportional to voltage or current, or some combination?

10 Test with Inverting Amplifier
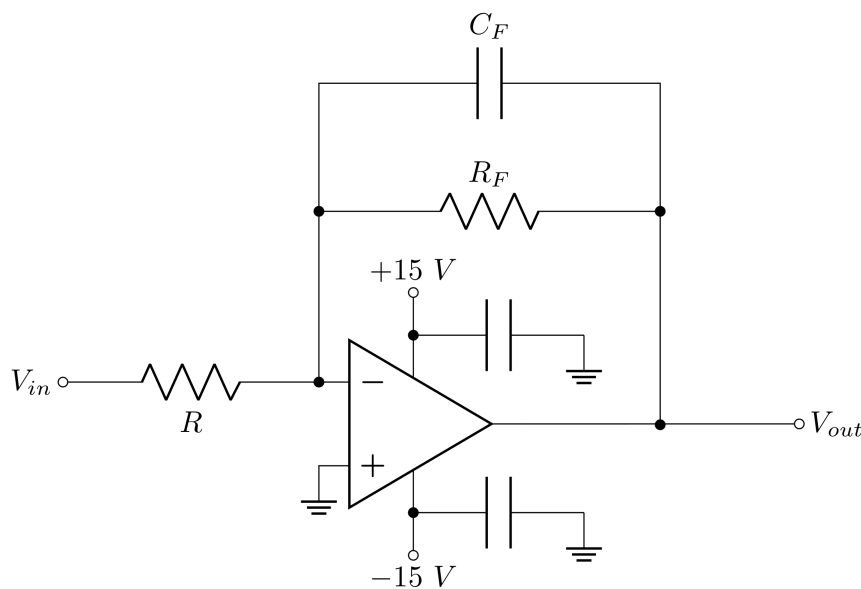
Figure 8: Inverting amplifier circuit

1. We will first build the amplifier in a normal voltage amplifier configuration to test the setup and all the connections. Build the inverting amplifier circuit shown in Figure 8. Use a value for $R_F = R$ close to what you found in 8.2, and a 10 pF capacitor C_F in parallel with the feedback resistor to avoid spontaneous oscillations. Draw the schematic in your lab notebook and record the values of the components.

2. Predict the low frequency gain and 3 dB frequency of the circuit. HINT: Look at your prelab answers. This will be the $R_F C_F$ time constant from 8.2; in this circuit the time constant will be determined by the feedback resistor and capacitor (not the input resistor). Design a test

to ensure the amplifier is working as predicted at low frequency (much lower than the cutoff). Don't bother testing the high-frequency behavior.

11 Room Light Photometer

1. Reconfigure your voltage amplifier to the transimpedance amplifier circuit shown in Figure 4. Pay attention to the direction of the photodiode. You can use your DMM set to the "diode setting" to determine which side of the diode is the cathode.

2. Verify that it changes as a function of the amount of incident light on the photodiode, for instance, by putting your hand over the photodiode to shade it from the room lights. Look at the output voltage on an oscilloscope. What is the period of the waveform produced? What is it you think you're seeing?

12 Optical Communication Link

12.1 LED emitter

1. Set up a light emitting diode type HLMP-C625 as the transmitter on a separate small circuit board according to the schematic in Figure 5. Be sure to protect the LED with a series resistance that prevents the forward current exceeding 20 mA. HINT: You calculated the required resistance in the prelab. Also, the LEDs have a nominal breakdown voltage of 5 V, which, if exceeded, can damage the LED. Therefore, to prevent this from happening, connect a regular diode in parallel with the LED but with opposite polarity. This will protect the LED from a large negative voltage.

2. Set up the function generator to produce 5 Hz square waves with the low voltage level 0 V and the high voltage of 8 V. You can accomplish this by using the DC offset setting of the function generator. Connect this to the oscilloscope and the LED circuit. Make sure the oscilloscope shows a square wave that goes from 0 V to 8 V and that you see the LED flashing 5 times per second before moving on.

12.2 Measure the output of the LED with the photometer

1. Place the LED transmitter close to the photodiode and verify that the photodiode sees the light from the LED. The LED is directed forward so make sure to orient both the LED and photodiode so they are pointing at each other to maximize the amount of light detected. You can bend the wire leads to get both devices pointed horizontally. You can check the alignment by using a piece of white paper to see if the red illumination is centered on the photodiode.

2. Observe the input driving signal and the output of the receiver on the scope using DC coupling for both signals. Make sure the received signal is due to the red LED, and not from an electrical connection. How did you determine that it was working? You may want to increase the frequency to about 100 Hz to allow the scope to update faster. You can also try switching to AC coupling for the receiver to see if it is easier to see the signal.

3. Determine the frequency limitations of your photometer. We did this in previous labs by measuring the frequency dependence of sine waves to find where the gain dropped by 3 dB. This method is only correct for sine waves. For square waves, we can use another method. A low-pass filter in the time domain is an integrator. This means it charges or discharges exponentially with a time constant of RC. Measure the time it takes for the signal to rise from the base level (room lights) to $(1-1/e)$ of the maximum value or to fall from the maximum value to $1/e$ of the difference between the maximum value and the base level. This gives the time constant RC. As the 3 dB frequency is $f_B = 1/2\pi RC$, you can determine f_B. Does this measurement agree with your model predictions?

4. Measure the output of the transimpedance amplifier (in Volts) of the transmitted light versus distance from a few cm to about 0.5 meter. How does the background light from the room affect the signal? Explain how you made this measurement. Estimate the the photodiode sensitivity S_λ at the wavelength 625 nm of light emitted by the LED. Plot the power in Watts hitting the photodiode as a function of distance.

13 Summary and Conclusions

Write a two-paragraph summary in your lab notebook of what you learned and any important takeaways.

## Appendix A: Some Related Concepts About Measuring Light

The sun has a power output (radiant flux) of $P = 3.85 \, x \, 10^{26}$ watts. Assuming a transparent atmosphere and a 1 m by 2 m solar panel perpendicular to the sun that absorbs 100% of the light, how much power is received? Consider that the entire $3.85 \, x \, 10^{26}$ W is distributed evenly on a hypothetical sphere with radius $1.50 \, x \, 10^{11}$ m (distance from sun to Earth). Since we know the area of a sphere is $4\pi r^2$, we can calculate the irradiance or intensity (power per area) as $N = P/4\pi r^2 = 1360 W/m2$. Since the solar panel has an area of 2 m^2, the power delivered to the solar panel is 2720 W.

There are additional concepts and units that are made necessary by the fact that the eye is not uniformly sensitive to all wavelengths and we are often interested in how humans perceive things. The

luminous flux is measured in units of lumens (lm) and is basically the same as the power (measured in watts) except that the spectrum of emitted light is weighted by the eye's response. The conversion from radiant flux (power) in watts to luminous flux in lumens is given by:

$$F(lm) = 683 \, y(\lambda) \, P(W)$$

The dimensionless quantity $y(\lambda)$ is the photopic standard luminosity function and is shown in Figure 9 and tabulated in the Datasheets section of Canvas. At λ = 555 nm, where the eye is most sensitive, $y(\lambda)$ = 1. Therefore, two sources with the same luminous flux will have the same subjective brightness to a human observer (even though the outputted power may be different). This kind of color corrected unit is helpful if you want to design a control panel with lots of colored lights, and you want them all to have the same perceived brightness. We may also be interested in the luminous flux per unit area (similar to intensity). This is measured in units of lux, where 1 lux = 1 lm/m^2.
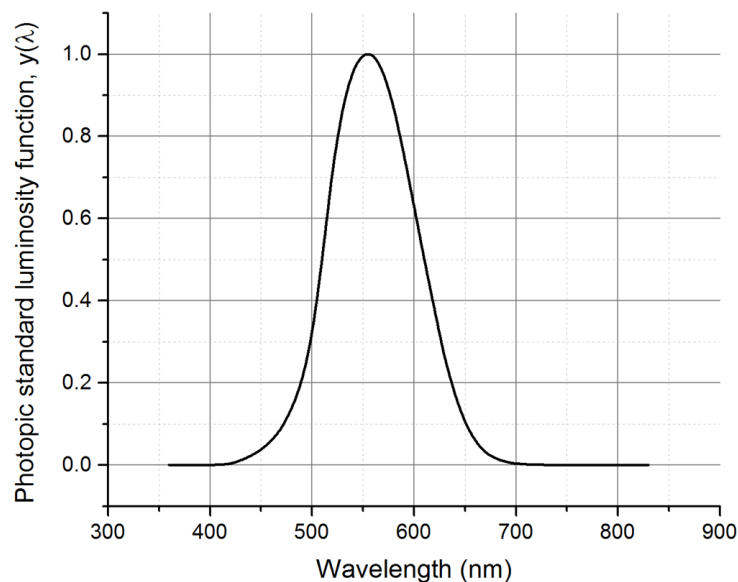
Figure 9: The photopic standard luminosity function

Appendix B: Light Output in Lumens for Various Light Sources

Table 1: Electrical power consumption of select light sources as a function of light output.

Light Output (lm)	Tungsten Filament (W)	Halogen (W)	CFL (W)	LED (W)
200	25		4	3
450	40	29	10	6
800	60		14	9
1100	75	53	19	12
1600	100	72	26	15
2400	150		40	26
3100	200		60	32