OPTICAL COMMUNICATION LINK

LAB 6 INTRO: INTRODUCTION TO LEDS, PHOTODIODES, AND TRANSIMPEDANCE AMPS

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

DEFINITIONS

Intensity – power per unit area, unit: W/cm^2
Luminous intensity – power *perceived* by the eye emitted per unit solid angle, unit: mcd (millicandela)
Luminous flux – total power emitted as perceived by the eye, unit: lumen

DIODES - GENERAL

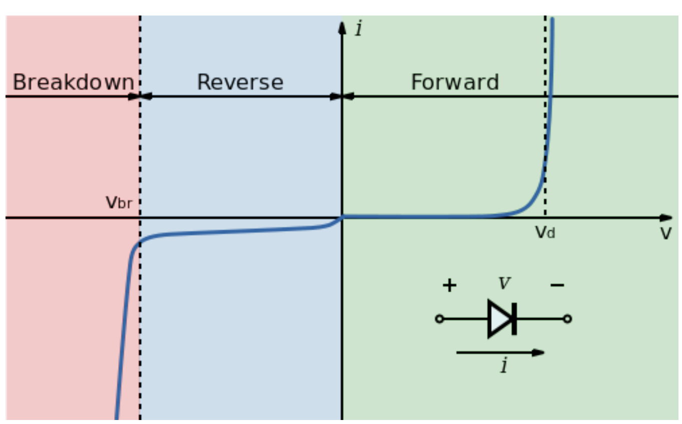

Figure1: Diode Characteristics

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. For a good example of how these work, see: https://phet.colorado.edu/en/simulation/semiconductor

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 (~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.

LIGHT EMITTING DIODE (LED)

The HLMP-C625 light emitting diode acts electrically like any 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.

To describe the output of a light source like our LED, it is helpful to introduce the notion of solid angle. Consider a transparent sphere of radius r, and suppose that an area A on the surface of the sphere is painted white (Figure 2). We then say that the whited-out region subtends a solid angle of Ω steradians (sr), where $\Omega = A/r^2$. According to this definition, the whole sphere subtends a solid angle of 4π sr. One steradian is an area of r^2, just as one radian is an arc of length r.

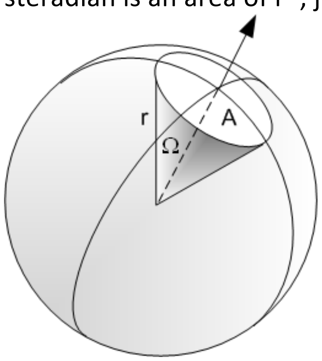

Figure 2: Solid Angle depiction.

The concept of solid angle is essential in separating the two units in which light is customarily measured. Both the lumen and the candela originated in the 18th century when the eye was the primary detector of electromagnetic radiation.

The lumen (lm) is a measure of the total light power emitted by a source. You might then expect that there is a conversion factor between lumens and Watts, and you would be right: its value is 683 lm/Watt. However, things are a bit more complicated because this conversion factor is only correct for light with a wavelength of 555 nm, the yellow-green color that our eyes are most sensitive to. For other colors the conversion factor is multiplied by a dimensionless number $y(\lambda)$ called the photopic standard luminosity function. A plot of $y(\lambda)$ is shown in Figure 3 and a tabulation of this function can be found on the course website under the *Useful Docs Section* at the bottom: photopic standard luminosity function.
The point of this is that two sources described by the same number of lumens (the same "luminous flux") will have the same subjective brightness to a human observer. This kind of color corrected unit is very 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. To summarize, if the luminous flux of your source is described as F lumens,

then you convert this to Watts using this formula:

$$F(\mathrm{W}) = \frac{1}{683 \cdot y(\lambda)} F(\mathrm{lm}) \tag{1}$$

Notice that more Watts are required for a given luminous flux as the color gets farther and farther away from yellow-green, to make up for the declining sensitivity of the eye. Note: This is really just a conversion from one unit to another.

However, this is not the whole story for describing light sources, because the amount of light emitted varies with direction, and how much light we intercept in a given direction will depend upon how much solid angle our detector covers. Thus we need a measure of light power per solid angle, and this unit is called the candela, equal to one lumen/sr. A light source that emits one candela in every direction emits a total of 4π lumen, since there are 4π sr in the whole sphere. The quantity measured by the candela is called the "luminous intensity". If you look at the data sheet for our HLMP-C625 LED you will see that it uses the unit "mcd" or millicandela to describe the brightness. The values given are for light emitted along the axis of the LED. For other directions see the Spatial Distribution graph in the data sheet. By dividing Eqn. 4 above by the solid angle we can rewrite it as a relation between the luminous intensity J in mcd and the power per unit solid angle:

$$J(\mathrm{mW/str}) = \frac{1}{683 \cdot y(\lambda)} J(\mathrm{mcd}) \tag{2}$$

Again: Note that this is really just a conversion from one unit to another.

Suppose now we place our photodiode a distance R from the LED, and we want to find the intensity N(mW/cm^2) at the photodiode. We first find J in millicandela on the LED data sheet. We then convert J(mcd) to J(mW/sr), using Equation 2 and y(λ) for the appropriate wavelength. (For our LED, y(650 nm)=0.107.) Finally we divide J(mW/sr) by R^2 to get N(mW/cm^2).

$$N\left(\frac{mW}{cm^2}\right) = \frac{1}{683\, y(\lambda)} \frac{1}{R^2(cm^2)} J\ (mcd)$$

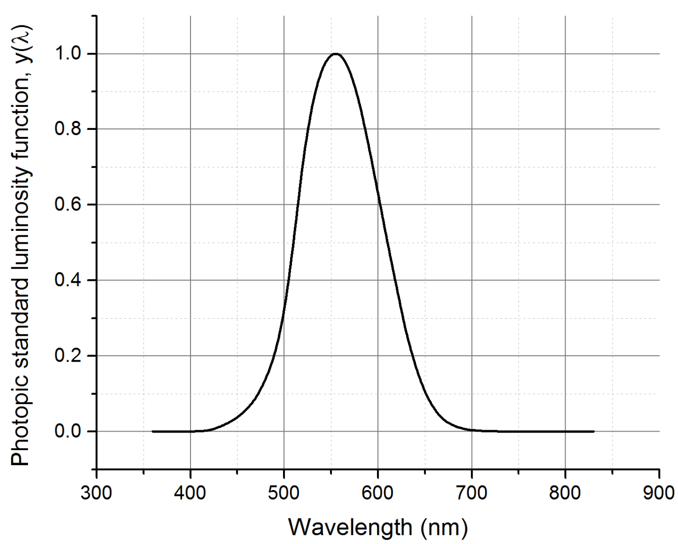

Figure 3: y(λ) as a function of wavelength.

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 4. 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. Any incident photon whose energy exceeds the band-gap energy is 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.

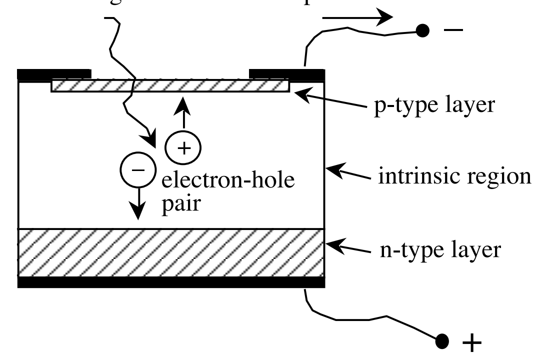

Figure 4: Diagram and schematic symbol for a PIN silicon photodiode.

The photodiode sensitivity $S\lambda$ (in units of μA/(mW/cm^2)) is defined as the photocurrent per unit light intensity incident on the photodiode. It is a function of the light wavelength λ. For light intensity (in mW/cm^2) the photocurrent I (in μA) is given by

$$I = S_\lambda N. \quad (3)$$

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

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

Figure 5 shows the RSR from the PD 204 data sheet. You can see the maximum sensitivity is around 940 nm.

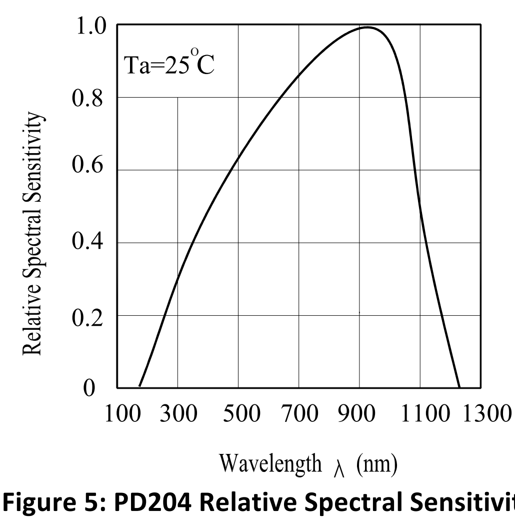

Figure 5: PD204 Relative Spectral Sensitivity

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 (Fig. 6) 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 or transimpedance gain. The current-to-voltage amplifier is sometimes called a trans-impedance 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.

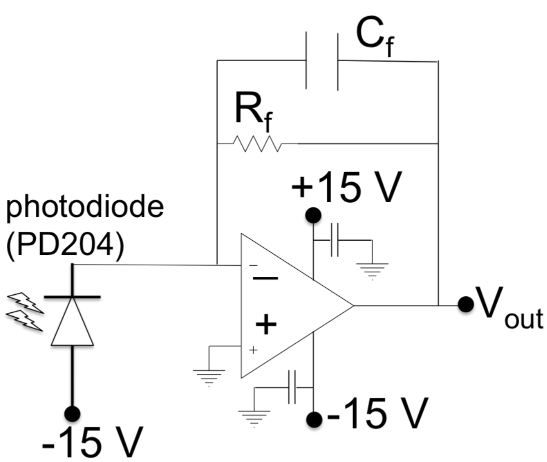

Figure 6: Photodetector circuit.

In our photometer circuit the current I_{in} flows through the back-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).

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.

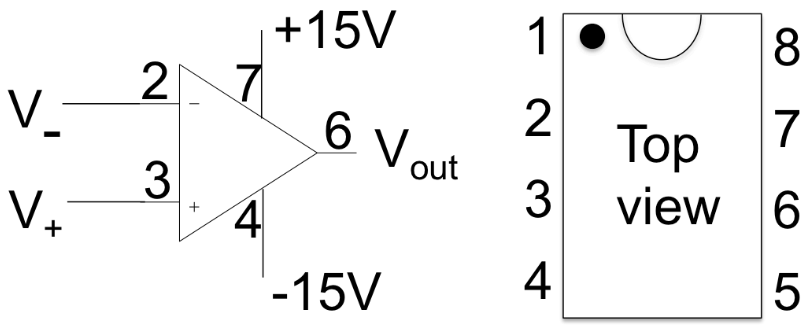

Figure 7. LF356 pin-out and schematic.

USEFUL READINGS

1. Data sheets for the PD204-6C/L3 silicon photodiode and the HLMP-C625 AlInGaP light emitting diode are available at the course web site.
2. Optional reading on diodes: FC Chapter 4, particularly Sections 4.18 & 4.19
3. For general background on optoelectronics, see H&H Section 9.10.

LAB PREP ACTIVITIES

Answer the following questions using Mathematica. **Bring an electronic copy of your notebook to lab, preferably on your own laptop.**

Question 1	**Room Light Photometer** a. Estimate the sensitivity, S_λ, in units of μA/(mW/cm^2) of the PD204 photodiode to the fluorescent lights in the lab. The peak sensitivity at 940 nm is 10 μA/(mW/cm^2). See the photodiode data sheet posted on the course web site or the plot above to determine the RSR at the appropriate wavelength. The mean wavelength of the white fluorescent lights is about 550 nm. Consider if 550 nm makes sense… is there a way you could estimate the mean? b. What intensity of white light in mW/cm^2 do you expect is incident on your photodiode on the lab bench when it is facing upwards i.e., towards the fluorescent lights? Each fluorescent light tube produces approximately 4W of visible light. You can assume that half of it (~2W) is emitted downwards into 2π sr. c. Be sure to state your assumptions explicitly for part (b). How many bulbs did you model and at what distance from the detector was each bulb? What wavelength are you assuming? Etc. State at least three key assumptions in your model prediction.

Question 2	**Trans-impedance Amplifier** a. For the current-to-voltage amplifier in Fig. 6, choose a value for the feedback resistor R_F so that an incident white-light intensity N of 1.0 mW/cm^2 produces an output voltage of 10 V. b. The small feedback capacitor C_F is used to suppress spontaneous oscillations. The trans-impedance gain of the amplifier at any particular frequency is $-Z_F$, where Z_F is the effective impedance of the parallel R_FC_F circuit. The gain rolls off at high frequencies with a bandwidth of $f_B=1/(2\pi R_FC_F)$, 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? c. 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 the full model, ~10 nA of dark current flows through the diode even with no light on it.) d. What would the voltages be if the photodiode leads were accidentally reversed to make it forward biased? *Hint: In this case the diodes acts like a short circuit with a 0.6 V drop across it.*
Question 3	**Optical Communication Link** a. Assume we have an HLMP-C625 LED being run with a current of 20 mA as in Fig. 9 (left). Use the typical value of luminous intensity at 20 mA (See the LED datasheet on the course website to find the typical luminous intensity). Compute the intensity N (in units of mW/cm^2) incident on a detector place R cm away from the center of the transmitted light beam. Plot the intensity on the photodiode as a function of R for reasonable distances of 1-50 cm. b. Plot the expected output voltage from the optical receiver as a function of the distance between the detector and the LED. Remember to recalculate the sensitivity of the detector for the wavelength of light from the LED, which is 650 nm for the ones we use in lab. c. To drive the transmitter, the function generator will be adjusted to produce a square wave with a high level of 10 V (unloaded) and a low level of 0 V. The high-level should give 20 mA forward current in the LED, and the low level should give 0 mA. Find the value of the series resistor R_S 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.
Question 4	**Lab activities** a. Read through all of the lab steps and identify the step (or sub-step) that you think will be the most challenging. b. List at least one question you have about the lab activity.

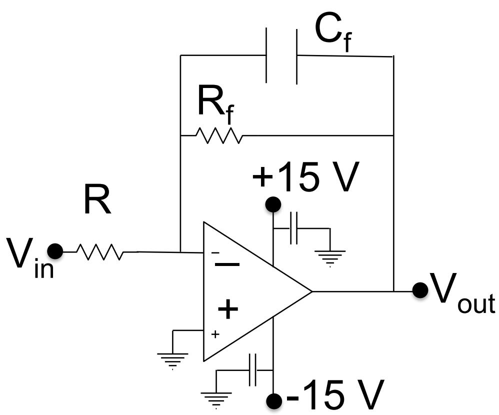

Figure 8: Inverting Amplifier

Step 1	**Test the amplifier (inverting configuration)** a. We will first build the amplifier in a normal voltage amplifier configuration to test the set up and all the connections. Build the inverting amplifier circuit shown in Figure 8. Use a value for R_F = R and close to what you found in Lab prep problem 2, and a few pF of capacitance C_F across the feedback resistor to avoid spontaneous oscillations. Draw the schematic in your lab book and record the values of the components. b. Predict the low frequency gain and 3dB frequency of the circuit. *HINT: Look at your lap prep solutions. This will be the R_fC_f time constant from (2b prelab); this circuit the time constant will be determined by the feedback resistor and capacitor (not the input resistor).* Design a test to make sure the amplifier is working as predicted at low frequency. Describe your procedure, the data you acquired, and if the data fit the model.
Step 2	**Room light photometer** a. Reconfigure your voltage amplifier to the trans-impedance amplifier circuit shown in Fig. 6. Pay attention to the direction of the photodiode. You can use your DMM set to the "diode setting" to determine which side of the diodes is the cathode. b. Measure the average intensity of light from the fluorescent lamps in the lab from the output of your photometer circuit. How does your result compare with your Lab prep estimate? Keep in mind that the estimate you made of the light intensity was very rough, and also note that the data sheet only gives a "typical" value of the sensitivity of the photodiode. How could you refine your model to more accurately represent your system or your physical system to more accurately represent your model? List two possible refinements and complete at least one. Explain why you think this refinement could allow you to getter better model-measurement agreement. Report on what you did, your new measurements/model predictions, and if you were successful in getting better agreement.

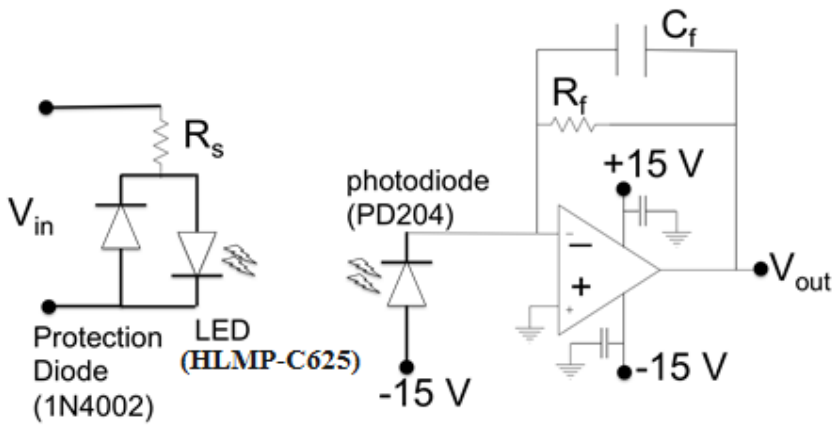

Figure 9: Optical communication link. Left: LED emitter circuit, Right: Photodetector circuit

Step 3	**LED emitter** a. Set up a light emitting diode type HLMP-C625 as the transmitter on a separate small circuit board according to the schematic in Fig. 9. You will eventually drive the input voltage with the function generator (See step 3b.) 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 Lab prep.* Also, connect a protection diode in parallel with the LED but with opposite polarity. This will prevent you from accidentally running the LED at with a large negative bias voltage, causing it to break down. b. Before connecting it to the LED transmitter circuit, set up the function generator to produced 1 kHz square waves with the upper voltage level at 10V and the bottom voltage at 0V. You can accomplish this by using the DC offset setting of the function generator. Now connect the function generator output to the LED transmitter circuit. Can you see the LED turn on?
Step 4	**Measure the output of the LED with the photometer** a. Place the LED transmitter at a distance where you expect a measurable signal from the photodiode. Use your prelab calculation to determine a good distance. What criteria did you use to determine this distance? The light from 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 check alignment by using a piece of white paper to see if the red illumination is centered on your photodiode detector. c. Observe the input driving signal and the output of the receiver on the scope using dc coupling for both signals initially. Make sure the received signal is due to the red. How did you determine that is was working? You may eventually want to switch to AC coupling on the scope to remove the large DC offset due to the room lights.

	d. Determine the frequency limitations of your photometer. To measure the 3 dB bandwidth, measure the 1/e rise time of the leading edge of the square wave signal from the photometer. Use the rise time to calculate the 3 dB bandwidth. Does this measurement agree with your model predictions? Whenever you use your photometer, you will want to make sure the light intensity is not varying faster than your 3 dB cutoff frequency.
Step 5	**Compare with Prediction and Refine Model** a. Measure the intensity of the transmitted light and compare with your prediction versus distance. How does the background light from the room affect the signal? Explain how you made this measurement. Does your measurement agree with your prediction? b. State explicitly what criteria you used to determine if they agree. If your model predictions and measurements do not agree, list all of the model and physical system refinements you could try to get better agreement. Try at least one of the refinements. Explain why you think this refinement could allow you to getter better model-measurement agreement. Report on what you did, your new measurements/model predictions, and if you were successful in getting better agreement.