EXPERIMENT 10
CHARACTERISTICS OF THE PHOTDIODE

OBJECTIVES:

The objective of this experiment is to understand and measure some of the many important characteristics of the photodiode. The photodiode characteristics that will be studied in this experiment are responsivity, I-V characteristics and linearity.

EQUIPMENT REQUIRED

1- Optical power meter: INFOS, Model # M100.
2- HeNe laser: Coherent, Model # 31-2090-000.
3- Optical bench (¼ m).
4- Horizontal and vertical stages (Used to carry and align the HeNe laser).
5- Laboratory jack.
6- Multimeter.
7- Power supply.
8- Decade resistor box.
9- 160 Ω resistor.
10- Medium area silicon photodiode (RS Part Number: 651-995).
11- Polarizer/Analyzer pair.
12- Large carton box with a pinhole.

PRELAB ASSIGNMENT

Read the introduction to this experiment, before you attend the laboratory.

INTRODUCTION:

The photodiode is an essential element in fiber optics communication systems. It is similar to the ordinary semiconductor diode, with one exception: it responds to light. The symbol used for the photodiode is the same as the symbol of the ordinary diode, as seen in Figure 1. The diode voltage V_d is defined with + polarity on the p terminal and the diode current I_d is defined to flow through the diode from the p to the n terminal, which is identical to the standard definitions of the voltage and current of the ordinary diode.

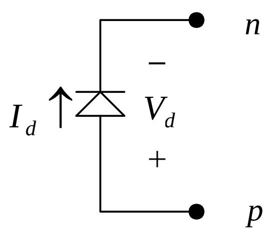

Figure 1: Photodiode Symbol, Showing Definition of the Photodiode Current and Voltage.

The *simplest* way to use a photodiode for the purpose of light detection is to leave its terminals open-circuited, as shown in Figure 2(a). This is an example of the so called *photovolatic* mode of diode operation. In this simple circuit, the photodiode conducts no current (because of the open circuit). When the incident light power P_i is zero, V_d is also zero. However, in this circuit, when $P_i > 0$, a small (at most a fraction of a volt), but measurable voltage V_d appears across the photodiode. This voltage is termed *photovoltage*, because it is caused by the incident light power and it disappears when the incident light power becomes zero. The value of V_d depends on P_i as well as on the incident light wavelength λ. An important example of the application of the photovolatic mode is in solar cells.

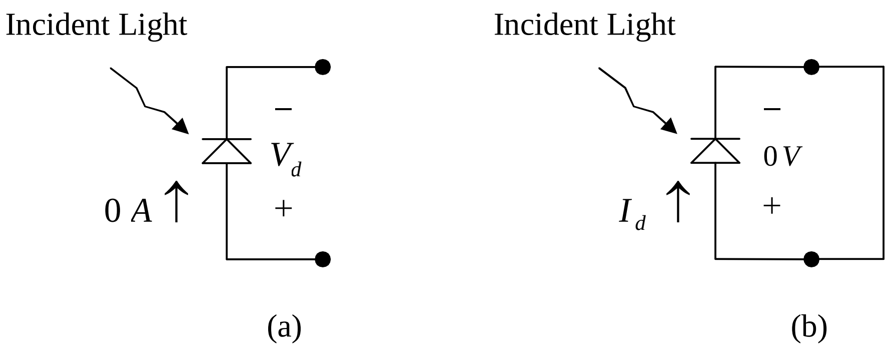

Figure 2: (a) Open Circuited and (b) Short Circuited Photodiode Circuits.

The circuit shown in Figure 2 (b) is an example of the *photoconductive* mode of diode operation. In this circuit, because the photodiode is short circuited, the diode voltage V_d is forced to be zero. The diode *produces* electric current I_d in response to the incident light. The current I_d is called the *photocurrent*, because it caused by the incident light power and it disappears when the incident light power is zero. This photocurrent is *proportional* to the incident light power P_i. In general, the higher the light power is, the higher the photocurrent I_d is. We can then view the photodiode in this circuit as a device that coverts light energy to electric current. The *actual* direction of the photocurrent is opposite to the one shown in Figure 2 (b). Thus, when the photodiode *operates in the photoconductive mode*, I_d is *always* a negative quantity. Let us then define the current $I_p \equiv -I_d$. Because I_p is positive, it is easier to use in our forthcoming discussion and the experimental work to be done.

For fiber optics communication, the photoconductive mode of operation is used to covert communication signals carried by light to signals carried by electric current. Thus, in this laboratory experiment, we will concentrate on the photoconductive mode of photodiode operation. The relationship between the incident power P_i and the induced current I_p is given by:

$$I_p = \overline{R}P_i \qquad (1)$$

Where $\bar{R}$ is the photodiode responsivity (see Appendix C). The variation of $\bar{R}$ with λ for the medium area photodiode used in this experiment is shown in Figure 3.

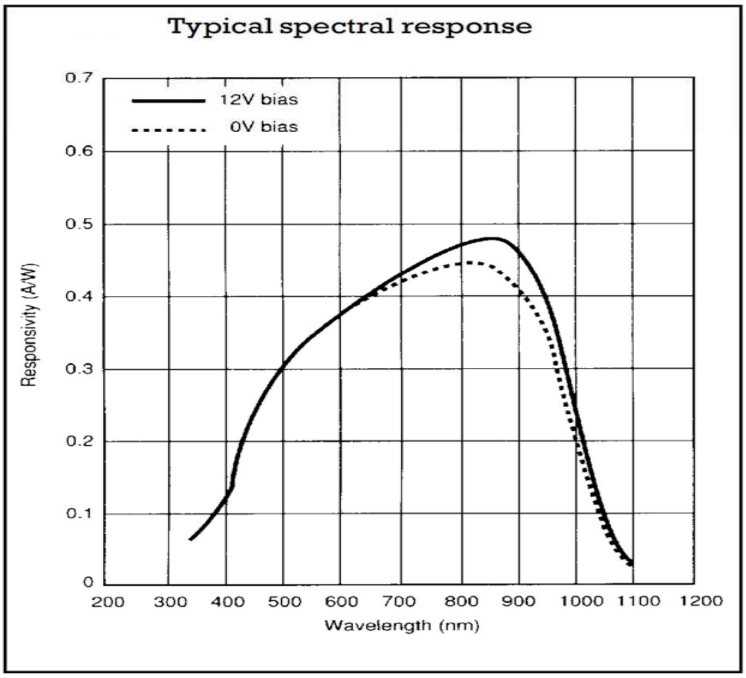

Figure 3: Responsivity Versus Wavelength for the Medium Area Photodiode.

For normal operation, the photodiode is *reversed biased* (i.e. $V_d < 0$). The responsivity $\bar{R}$ of the diode is *largely independent* of the bias voltage, *as long as the diode is reversed biased.* When the diode has zero bias (i.e. $V_d = 0$), $\bar{R}$ decreases slightly below the reversed bias value. This effect can be seen clearly seen in Figure 3, where the 12 V indicated in the figure refers to the value of the reverse bias voltage. However, when the diode is *forward* biased, $\bar{R}$ begin to drop, reaching negligible values when the forward is sufficiently high. It is thus important to keep in mind that the diode *responsivity decreases drastically when the diode is forward biased.* This important feature of the photodiode will be observed in this experiment.

Now, consider the circuit shown in Figure 4, which a simple and practical circuit for light detection. The supply voltage V_s is kept positive. Using Kirchhoff's voltage law and Ohm's law, we have:

$$V_d = V_L - V_s \qquad (2)$$

$$V_d = I_p R_L - V_s \qquad (3)$$

Let us assume that the incident optical power is fixed at a certain level P_i. When the load resistance R_L equals zero, $V_d = -V_s$. Since $V_s > 0$, then $V_d < 0$ and thus in this case the diode is reversed biased. Since P_i is fixed, we also expect I_p to also be fixed, as long as the diode remains reverse biased. When R_L increases, the voltage

$V_L = I_p R_L$ also increases. Thus we can continue to increase V_L by simply increasing R_L *as long as the photodiode remains reversed biased*. However, at some point, $I_p R_L$ will exceed V_s causing the diode to be forward biased and becoming less and less responsive to the incident power (i.e. $\bar{R}$ starts to decrease, causing I_p to decrease). In short, the *maximum* obtainable value of the load voltage $V_L = I_p R_L$ is slightly larger than the value of V_s. Thus, for this circuit, the following relationship applies:

$$(V_L)_{\max} \approx V_s \qquad (4)$$

This important relationship will be verified in this experiment.

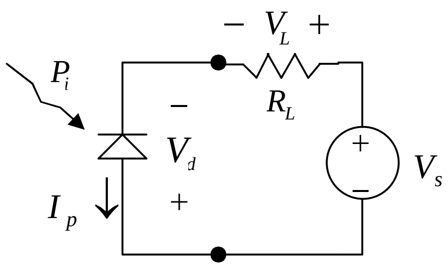

Figure 4: Practical Simple Circuit for Light Detection.

PROCEDURE:

Part A: **Using the Photodiode in Light Power Measurement and Diode Responsivity.**

1- Connect the circuit shown in Figure 5.
2- Turn the HeNe laser on and keep it approximately 1m from the photodiode.
3- Align the laser so that the center of the laser beam is approximately normal and in the middle of the light sensitive of the photodiode. Notice that laser beam is completely within the light sensitive area of the diode, so that *all* the laser power is sensed by the diode.
4- Use an object to block the laser beam and read the ammeter reading. Record the value in table 1.
5- Remove the object and read the ammeter reading. Verify that the induced current *actually* flows through the diode from the n terminal to the p terminal, not the other way around. Record the results in table 1.
6- Use Figure 3, equation (1) and the ammeter reading of step (5) to estimate the output power of the HeNe laser. Record the value in table 2.
7- Compare your result with the HeNe Laser specifications. Discuss the results and draw some conclusions.

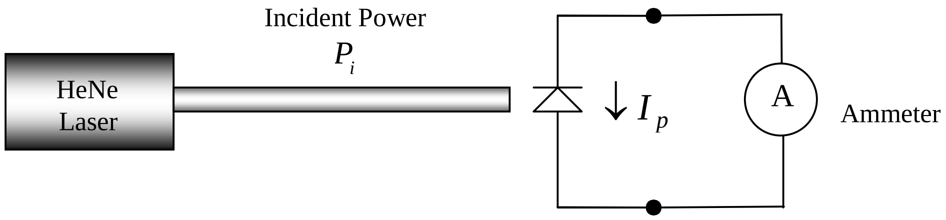

Figure 5: Setup Used for Measuring the Power Emitted by a HeNe Laser Source.

Condition	I_p (mA)	Actual Direction of I_p
Laser Blocked		From n to p
Laser Unblocked		From p to n

Table 1: Photocurrent Current Measurement for Part A of the Experiment.

$\bar{R}(\lambda = 0.633\mu m)$ in (A/W)	I_p (mA)	HeNe Laser Power (mW) (Experimental)	HeNe Laser Power (mW) (Manufacturer's Specification)

Table 2: Photodiode Responsivity and Estimated Power of the HeNe Laser.

Part B: Practical Circuit for Light Detection and Photodiode IV Characteristics.

1- Connect the circuit shown in Figure 6 and repeat steps 1) and 2) of part A.
2- Set V_s to 0 Volts [Disconnect the leads from the power and connect them together to produce a short circuit, which is equivalent to $V_s = 0V$. *Turning the power supply off or setting the power supply voltage to zero does not work well in this case*].
3- Set the decade resistance R to $0\,\Omega$ and then measure V_L and record its value in table 3.
4- Repeat step 3 for $R = 100\,\Omega$, $200\,\Omega$, until the third column of table 3 is filled. *To simulate $R = \infty$, remove the lead that connects the decade box to the $160\,\Omega$ resistor.*
5- Calculate the photodiode current and voltage and record them in table 3.
6- Connect the circuit to the power supply and set V_s to 5 Volts [You should use a digital volt meter to measure V_s to set it precisely to 5V. [*Do not rely on the power supply meter for this measurement*]. Record the *precise* value of V_s in the top row of table 4.
7- Set the decade resistance R to $0\,\Omega$, then measure V_L and record its value in table 4.
8- Repeat step 8 for $R = 100\,\Omega$, $200\,\Omega$, until the third column of table 4 is filled.
9- Calculate the photodiode current and voltage and record them in table 4.

10- Repeats steps 6 through 9, for $V_s = 15V$ (precise) and record the results in table 5.

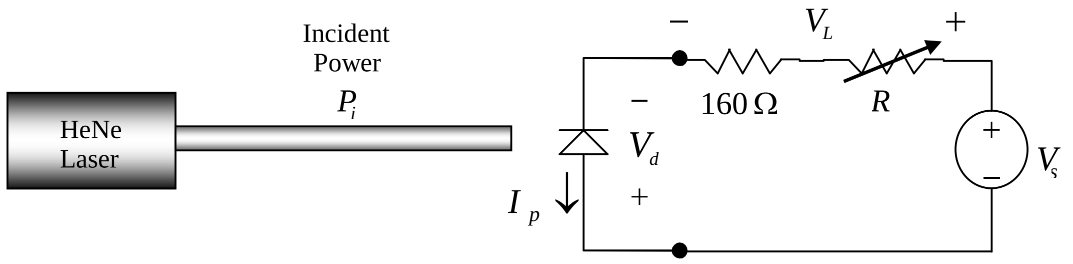

Figure 6: Circuit Diagram for Part B.

$R(\Omega)$	$R_L = R + 160(\Omega)$	V_L (V)	I_p (mA)	V_d (V)
0	160			
100	260			
200	360			
300	460			
400	560			
500	660			
600	760			
700	860			
800	960			
900	1060			
1000	1160			
10000	10160			
∞	∞			

Table 3: Measured Load Voltage Versus Load Resistance for $V_s = 0V$.

V_s (Measured) = Volts				
$R(\Omega)$	$R_L = R + 160(\Omega)$	V_L (V)	I_p (mA)	V_d (V)
0	160			
100	260			
200	360			
300	460			
400	560			
500	660			

600	760			
700	860			
800	960			
900	1060			
1000	1160			
1100	1260			
1200	1360			
1300	1460			
1400	1560			
1500	1660			
1600	1760			
1700	1860			
1800	1960			
1900	2060			
2000	2160			
10000	10160			
∞	∞			

Table 4: Measured Load Voltage Versus Load Resistance for $V_s = 5V$.

V_s (Measured) = Volts				
$R\,(\Omega)$	$R_L = R + 160\,(\Omega)$	V_L (V)	I_p (mA)	V_d (V)
0	160			
100	260			
200	360			
300	460			
400	560			
500	660			
600	760			
700	860			
800	960			
900	1060			
1000	1160			
1100	1260			
1200	1360			
1300	1460			
1400	1560			

1500	1660			
1600	1760			
1700	1860			
1800	1960			
1900	2060			
2000	2160			
2100	2260			
2200	2360			
2300	2460			
2400	2560			
2500	2660			
2600	2760			
2700	2860			
2800	2960			
2900	3060			
3000	3160			
3100	3260			
3200	3360			
3300	3460			
3400	3560			
3500	3660			
3600	3760			
3700	3860			
3800	3960			
3900	4060			
4000	4160			
5000	5160			
10000	10160			
∞	∞			

Table 5: Measured Load Voltage Versus Load Resistance for $V_s = 15V$.

Part C: Photodiode Linearity.

[<u>IMPRTANT</u>: FOR THIS PART OF THE EXPERIMENT, THE LASER MUST BE TURNED ON FOR AT LEAST ONE HOUR BRFORE RELIABLE MEASUREMENTS CAN BE TAKEN].

1- Refer to the experimental setup shown in Figure 7.
2- Set the following circuit setting: $R = 1K\Omega$ $(R_L = 1160\Omega)$ and $V_s = 5V$.

3- Insure that the beam is reasonable centered within the light sensitive area of the diode.
4- Insert a polarizer/analyzer pair between the laser and the photodiode.
5- Set the *analyzer* angle θ_p to 90^o.
6- Rotate the *polarizer* until V_L is minimized. The light incident on the photodiode should be too weak to see with the naked eye.
7- Set the *analyzer* angle θ_p to 10^o. Now, the light beam is visible again.
8- Cover the circuit with the carton box in such away that the laser beam passes through the center of the pinhole. [*Take care not to disturb the circuit while placing the box*].
9- Now, measure V_L and record its value in table 6.
10- Repeat step 9 for $\theta_p = 20^o$ and all remaining values of θ_p shown in table 6. [*Note that the step size for* θ_p *is not fixed*].
11- Remove the circuit and replace it with the optical power meter. Set the meter to dBm and $\lambda = 0.85\,\mu m$.
12- Adjust the position of the optical power meter for maximum power reading. [*DO not remove the cover of the power meter*]. There is no need to use the carton box in this case.
13- Set the analyzer angle θ_p to 10^o and record the power meter reading in table 6.
14- Repeat step 13 for $\theta_p = 20^o$ and all the remaining values of θ_p shown in table 6.
15- Calculate the current I_p and record its value in table 6.
16- Convert the power meter readings to mW and record the values in the fifth column of table 6.
17- Plot I_p versus the optical power in mW.
18- On the *same graph*, draw a straight line that best fits the experimental graph, and then comment on the linearity of the photodiode.
19- Why did we use a polarizer/analyzer pair? What function do they serve in this part of the experiment? Why did we use a box cover in the first part? Discuss the experimental results and write some conclusions.

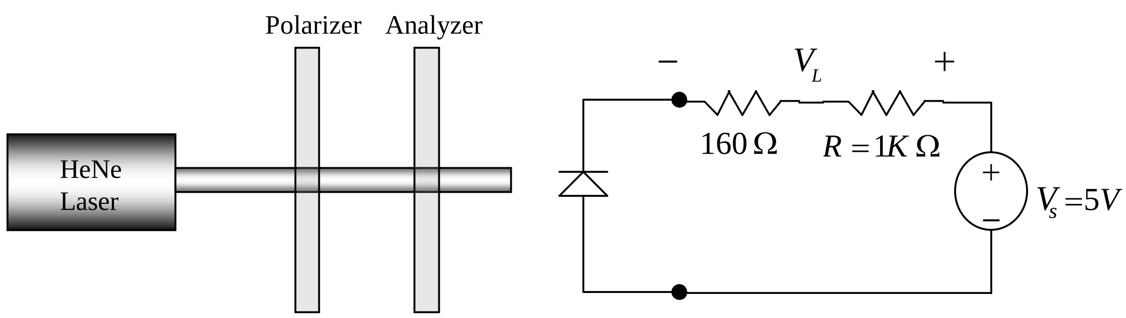

Figure 7: Setup Used for Photodiode Linearity Measurements.

θ_p (Degree)	V_L (V)	PdBm	I_p (mA)	P (mW)
10				
20				
30				
35				
40				
45				
50				
55				
60				
65				
70				
80				
82				
84				
86				
88				
90				

Table 6: Experimental Data for Part C.

REPORT REQUIREMENTS:

Part A: The requirements for part A were already stated in the procedure.

Part B:

1- *On the same graph*, plot V_L versus R_L for the cases $V_s = 0V$, $V_s = 5V$ and $V_s = 15V$.

2- Comment on the maximum voltage obtainable in each case. Compare the results with the theoretical prediction of equation (4).

3- *On the same graph, plot* I_p *versus* R_L for the cases $V_s = 0V$, $V_s = 5V$ and $V_s = 15V$.

4- Comment on the behavior of I_p. Is it always constant? If not when is it constant and when is it not constant?

5- *On the same graph, plot* the photodiode IV characteristics (i.e. V_s versus I_d, *not* V_s *versus* I_p) for the cases $V_s = 0V$, $V_s = 5V$ and $V_s = 15V$.

6- Comment on the resulting graphs. In what way are they different and in what way are they similar?

7- In order to enrich your report, ask yourself the following questions which will help you in developing comments and conclusions appropriate for this part of the experiment.

- Does the photocurrent (increase or decrease) (rapidly or slowly) with the forward bias?
- Do you see approximately straight lines in the IV characteristics?
- Can we model the photodiode as an optical power-dependent current source? If yes, what conditions must be satisfied for the validity of this model?
- Do you expect the IV characteristics of the photodiode to change when the incident optical power changes? Explain.
- Do you expect the IV characteristics of the photodiode to change when the incident light wavelength changes? Explain.
- When $V_s = 0V$, do we obtain a complete or partial IV characteristic? Explain.

PART C: The requirements for part C were already stated in the procedure.

QUESTIONS:

1- Suppose the incident power is extremely low, but measurable, what changes and precautions should be done in part B of this experiment to make it successful?

2- The circuit shown in Figure 4 is much more practical for fiber optics communication than the one shown in Figure 2 (b). Explain why, giving as many reasons as you can think of. [Hint 1: current is harder to deal with than voltage. Hint 2: Different circuits require different voltage levels].

3- When does the circuit used in part B operate in pure photovolatic mode?

4- Using the experimental results, estimate the maximum obtainable voltage V_d when the photodiode operates in the photovolatic mode.

5- Imagine that you were asked to design a photodetector circuit for use in an optical fiber communication system operating at $\lambda = 1.55\ \mu m$. Is the photodiode used in this experiment a suitable choice? Justify your answer.

6- In part B of the experiment with $V_s = 15\text{V}$, estimate the range of load resistance R_L in which we can model the photodiode (approximately) as an ideal current source?

7- In part B of the experiment with $V_s = 15\text{V}$ and $R = 200\,\Omega$, use the experimental data to predict the load voltage V_L when the incident power is reduced by a factor of 2.

8- Answer question (6), assuming the incident power is reduced by a factor of 1000.

9- In part B of the experiment, with $V_s = 5\text{V}$ and $V_s = 15\text{V}$, the photocurrent I_p remains almost independent of R_L in a certain range of R_L. However, with $V_s = 0\text{V}$, I_p does not remain constant as R_L changes, even for low values of R_L. Briefly explain why this is so. [Hint: Find out what the bias of the photodiode is when $V_s = 0\,\text{V}$. Is it forward or reverse biased?].

10- Assuming we can model the photodiode as an *optical power-dependent* current source, develop an appropriate approximate mathematical model for this source [i.e. $I_p = \text{constant} \times P_i$, find the approximate value of the constant at $\lambda = 0.633\,\mu m$]. Use the experimental data and the known responsivity of the diode for this purpose.