Photodiode and Light Beam Polarization

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I. INTRODUCTION

To explore the polarization of light, we used a wire grid polarizer, photodiode, laser, and voltmeter. We investigated various phenomena such as Malus' law and "crossed" polarizers. We also used a plexiglass block to determine Brewster's angle.

A. Theoretical Background

The solutions of Maxwell's equations consist of waves of vibrating electric and magnetic fields. The most general solution is given by

$$\overrightarrow{E} = E_{01}\hat{x}cos(\omega t - kz + \phi_{01}) + E_{02}\hat{y}cos(\omega t - kz + \phi_{02}) \quad (1)$$

which propagates in the $\hat{z}$ direction with frequency ω.

The polarization of this electromagnetic wave refers to the vibration of $\overrightarrow{E}$ in the $x - y$ plane, and linear polarization occurs when $\phi_{01} = \phi_{02} = \phi_0$. Then

$$\overrightarrow{E} = (E_0\hat{e})cos(\omega t - kz + \phi_0), \quad (2)$$

where $\hat{e}$ is the polarization vector and points in the direction of vibration of the electric field. [1]

Polarizers produce linearly polarized radiation. [1] A wire-grid polarizer drives an oscillating current through the component of the electromagnetic field that is parallel to the metal wires of the wire-grid polarizer. [1] The polarizer is constrained by its wire spacing, which must be small compared to the wavelength of the incident radiation.

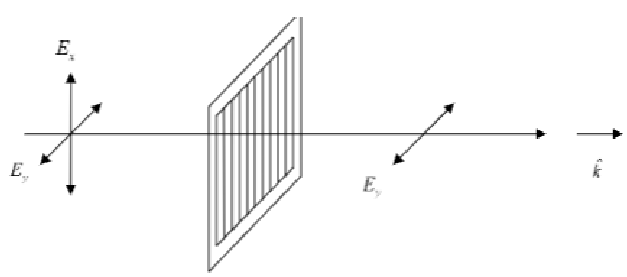

FIG. 1. Wire grid polarizer [1]

B. Malus' Law

When an electromagnetic wave propagates through two polarizers in sequence, the fraction of intensity transmitted through the second polarizer is given by

$$I_t = I_i cos^2(\theta) \quad (3)$$

known as Malus' law. [1] Therefore the intensity of a beam can be attenuated by adjusting the angle of the two polarizers. [1]

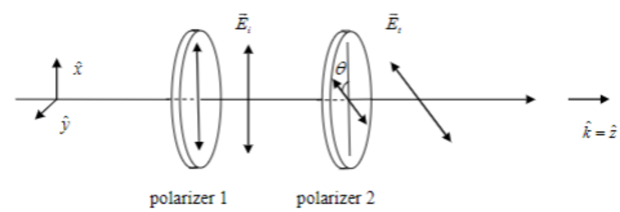

FIG. 2. Malus' law [1]

C. Photodiodes

When two types of semiconductors, p-type and n-type, are placed in junction with one another, current will flow in one direction but not the opposite.

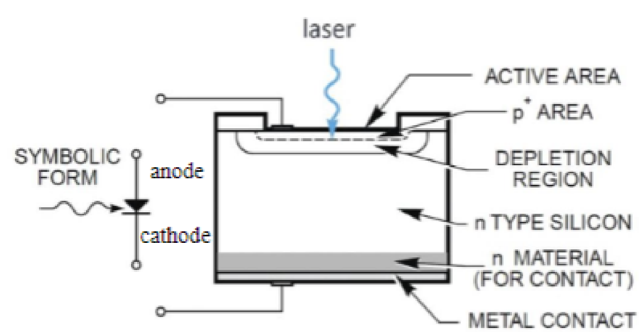

FIG. 3. Silicon photodiode [1]

II. EXPERIMENTAL PROCEDURE

We first built the circuit shown in figure 4 on a breadboard. We used three double A batteries in a battery

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holder. We then used our three wire voltmeter to measure the voltage between two resistors. We used three different resistors with resistances of 523 $\Omega \pm 1\%$, 1.00 $k\Omega \pm 1\%$, and 2.00 $k\Omega \pm 1\%$ and checked each paired together.

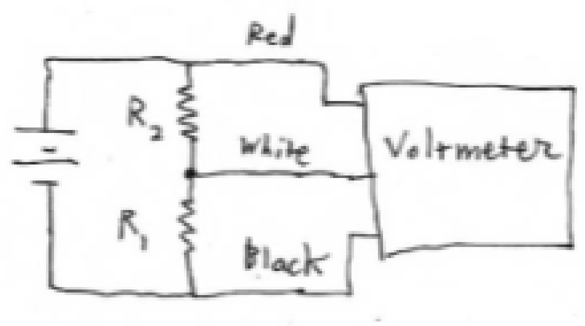

FIG. 4. Circuit with a voltmeter, batteries, and two resistors [1]

A. Photodiode

Next, we created a holder for our laser and photodiode by cutting holes in pieces of foam and placing them in slots in wooden blocks. We then aligned our laser beam with our QDT2030 photodiode which was connected in series with a 100 Ω resistor. We incorporated the photodiode into our breadboard circuit with a 1.00 $k\Omega \pm 1\%$ resistor as indicated in figure 5. We measured the current using our voltmeter for forward-biased and reverse-biased diode connections.

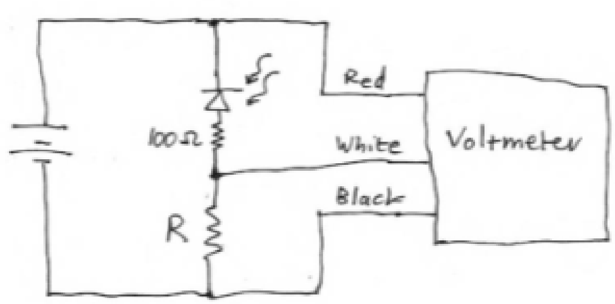

FIG. 5. Photodiode reverse bias circuit [1]

Next we turned on the laser so that the light was incident upon the sensitive area of the photodiode, therefore maximizing the signal.

B. Polarization

To determine if our laser was polarized, we created holders for our polarizer sheets. We cut holes in pieces of foam board and placed then in slots of wooden blocks after positioning the polarizers between the holes. We then placed a polarizer between the laser and our photodiode. We then rotated the polarizer and observed what effect this had on our measured intensity.

C. Malus' Law

Next, we chose two polarizers and used our laser and photodiode to confirm Malus' law. We began by placing one polarizer between our laser and photodiode, and adjusting the incidence so that the signal was maximized. We then chose another polarizer, and measured the power as a function of angle between the polarization axes.

D. Three Polarizers

Next, we again directed our laser beam through two polarizers, and adjusted the second polarizer so that the measured intensity was minimized, yielding "crossed" polarizers. We then placed a third polarizer between these two polarizers and rotated it 360°, observing what effect this had on the intensity. We recorded the angle of maximum and minimum transmission.

E. Brewster's Angle

In order to observe Brewster's angle, we added a plexiglass block to our set up as depicted in figure 6. We then varied the angle of the polarizer and plexiglass block, recording the incident angle which resulted in low intensity of the reflected beams. We also recorded the polarization angle at which this occurred. Next, we observed what effect changing the polarization while remaining at Brewster's angle had on the reflected beam.

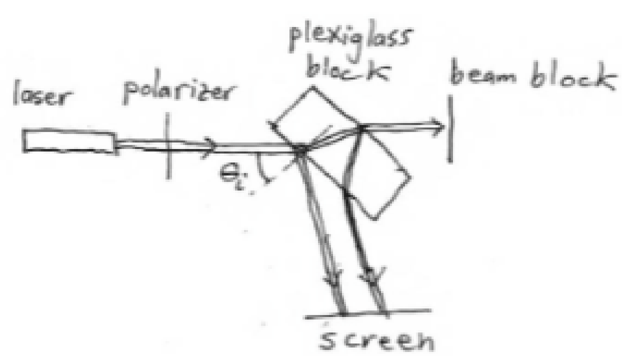

FIG. 6. Experimental setup to measure Brewster's angle [1]

III. DATA AND ANALYSIS

A. Voltmeter

Table I lists the voltages recorded for each pair of resistors.

TABLE I. Potential Difference Between Resistor Pairs

R_1, R_2 ± 1%	Voltage [V] ± 0.01V
1.00 $k\Omega$, 523 Ω	3.12
2.00 $k\Omega$, 523 Ω	4.62
2.00 $k\Omega$, 1.00 $k\Omega$	4.50

B. Photodiode

We found that the photodiode did act as ordinary diode when no light was incident upon it. We also noted that the diode conducted current in forward bias but not reverse bias. We did measure that the voltage across the resistor was less than the battery voltage for forward bias. This could potentially be due to our incident beam being larger than the 1.245 millimeter by 1.245 millimeter collecting area of the photodiode.

C. Polarization

When rotating the polarizer sheet, we noted that the measured intensity varied, therefore we discovered that our laser was linearly polarized.

D. Malus' Law

A graph of our recorded power as a function of θ for two polarizers in series fit to a $cos^2(\theta)$ function is shown in figure 7. We confirm that within our bounds of uncertainty, Malus' law holds.

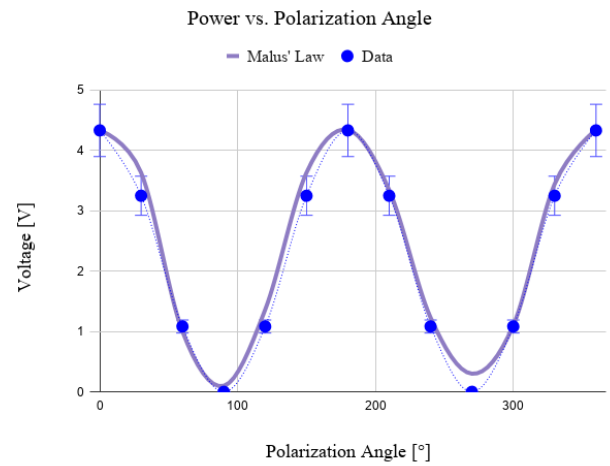

FIG. 7. Power of laser beam incident upon photodiode through two polarizers as a function of polarization angle

E. Three Polarizers

We found that by rotating the third polarizer 360°, the intensity decreased from 0° to 90°, increased from 91° to 180°, decreased from 181° to 270°, and again increased from 271° to 360°.

Our measured angle of maximum transmission was 180°± 0.02°, and minimum was 270°± 0.02°. In order to understand how light can pass through when the third polarizer is added even though it was previously blocked by the two polarizers, the quantum-mechanical view of the system must be adopted. The photons that previously passed through the two polarizers do not retain any information from past measurements. [2]

F. Brewster's Angle

We measured Brewster's angle to be 55°±0.02° and the polarization of the beam for minimum reflection to be 90°±0.02°. Our value of Brewster's angle does not agree for the theoretical value for the plexiglass block within our bounds of uncertainty. Our value was within 1.78%± 0.04% of the theoretical value of Brewster's angle.

When varying the polarization but leaving the plexiglass block at Brewster's angle, we noted that the reflected beam increased and decreased in intensity.

If the beam of light incident upon the plexiglass block at Brewster's angle was unpolarized, the polarization of the reflected light would be partially polarized.

IV. CONCLUSION

A systematic error in this experiment is that we neglected the index of refraction of air. We also did not make our measurements within a vacuum. [1] [3]

The values could be determined more accurately by repeating the measurements. [3] A systemic source of error was that the polarization and incidence angles could not be measured directly since we did not have a protractor and instead had to be calculated from length measurements which could only be measured with a precision of 1 millimeter. The data could also be made more precise by using a voltmeter with more values known than the 10 millivolt limited voltmeter used. Another issue in this experiment is that the voltmeter was constrained to values less than 10.00 Volts. [1]

To improve this experiment, more advanced equipment could be used such as a digital multimeter with various functions as opposed to the three wire voltmeter employed.

Issues in this experiment could have arisen due to measurement error. [3] The deviation values were also not decided precisely. [3]

[1] D. Heinzen, Photodiode and light beam polarization, (2020).

[2] R. P. Feynman, *The Feynman Lectures on Physics*, Vol. 3 (Addison Wesley, 1971).

[3] P. Bevington and D. K. Robinson, *Data Reduction and Error Analysis for Physical Sciences*, 3rd ed., Vol. 2 (McGraw-Hill Education, 2002).

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[7] G. C. King, *Vibrations and Waves*, 1st ed. (Wiley, 2009).