# Physics Lab 2020-1
## Characteristic study of Photodiode and Diode laser
## (Final Lab Project)

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# 1 Introduction

Photodiodes and diode laser are semiconductor devices used routinely in various optical experiments. Diode lasers are used as sources of polarised coherent light for many experiments such as interferometery and diffraction, while photodiodes are used as detectors of light intensity. Thus, it is important to study the characteristics of both devices before they are utilised. In this experiment, I have studied the beam characteristics of a diode laser, and the properties of a photodiode in a circuit.

# 2 Aim

In this experiment, I aimed to study:

- the profile of a diode laser beam, including the spread of intensity across the beam, the spot size, and the divergence angle.
- the polarisation of the diode laser.
- the IV characteristics of a photodiode at different incident light intensities.
- the variation in current in a photodiode as the incident light intensity is changed.

# 3 Theoretical Background

## 3.1 Overview: Diodes

Diodes are two terminal semiconductor devices that are ubiquitous in modern electronics applications. An ideal diode is one that conducts current in only one direction. It acts as a short circuit (0 ohm resistance) for the region of conduction (positive voltage and positive current), and as an open circuit (infinite resistance) for the region of non-conduction (reverse bias potential). Diodes are mainly made of semiconductor material, which has unique conduction properties, particularly a level of conductivity between that of a conductor and an insulator. The semiconductors most commonly used in electronic components are silicon and germanium, both of which are tetravalent atoms and form a regular lattice. Each has four valence electrons, and forms covalent bonds with four other atoms. Despite this being a lower energy state, in some cases a valence electron with sufficient kinetic energy might break the covalent bond and become a 'free' electron. Very pure and refined semiconductors in which the only free electrons are those arising from this natural occurrence are known as intrinsic semiconductors, and the electrons are intrinsic *carriers*. As the temperature of this material in increased, more electrons have sufficient kinetic energy to break the covalent bonds, become free electrons, and conduct current. Thus, at higher temperatures, these materials have lower resistance, giving them a negative temperature coefficient (unlike conductors, which have a positive temperature coefficient).

The mechanism of how the electrons conduct current is understood through the idea of energy bands. Each electron has discrete energy levels that are permissible states, which depend on the material and the atomic structure. In general, an electron further from the nucleus occupies a higher energy level than one closer to the nucleus, so the free electrons occupy a higher energy level known as the conduction band, than the electrons in the covalent bonds state, which occupy the lower valence band. The separation between these two bands, which is the width of the forbidden gap (states the electron cannot occupy) determines the nature of the material. At the lowest possible energy, all electrons occupy the valence band. If the forbidden gap is very large, electrons would need a very high energy (much higher than room temperature) to move from the valence band to the conduction band. This is the case for insulators, which have very high resistance. If the conduction band and valence band overlap, and the forbidden gap is essentially zero, electrons can easily move around from the valence band to the conduction band and carry current, even with very little kinetic energy. This is the case for conductors, which have very low resistance at room temperature. If the forbidden gap takes some intermediate value, then at room temperature, some electrons have sufficient kinetic energy to transition to the conduction band and carry current. Additionally, as the temperature is increased, the number of electrons with this energy increases and more electrons move into the conduction band, reducing the resistance. This is the case for intrinsic semiconductors. The energy width of the forbidden gap can also be reduced in semiconductors by adding impurities, which is known as doping.

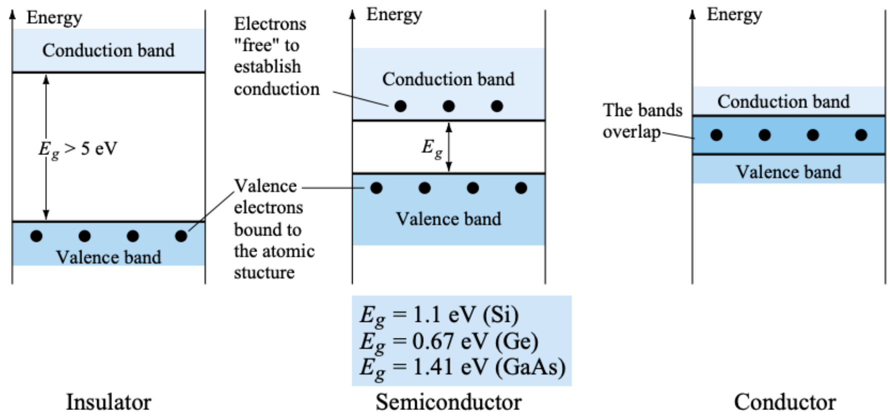


Figure 1: Image illustrating energy band gaps in different materials. Image credit: Boylestad.

*n*-type materials are created by doping the semiconductor with an element that has five valence electrons, such as antimony, arsenic or phosphorous. This introduces an additional electron that is not associated with a covalent bond, that is more loosely bound and can more easily move into the conduction band. In terms of the energy levels, this can be understood as the impurity element adding an additional 'donor energy level' in the middle of the forbidden gap. Electrons in this band require lesser energy to transition into the conduction band, so this introduces additional charge carriers without adding any overall charge to the material.

*p*-type materials are created by doping with an element that has three valence electrons, such as boron, gallium, or indium- called acceptor atoms. The addition of these elements, leaves a 'hole' where an electron ought to sit in a covalent bond. Other electrons can move to occupy this hole, and so it acts as a positive charge carrier. As electrons transfer to hole in series, the hole travels in the direction of the conventional current, and the electrons travel in the direction of electron flow.

In order to form the diode, the n-type and p-type materials are joined together. In the region where they are joined, the free electrons of the n-type material fill the holes in the p-type material, which leaves no charge carriers at the join. This region is thus known as the depletion region, and results in three possible conditions:

- When there is no voltage applied to the diode, the charge carriers must overcome the shielding effects of the depletion region in order to migrate to the other type of material. Given a large number of carriers, a few will cross the depletion region, but the net flow of charge will be zero.
- In the **forward bias** condition (V>0), a positive potential is applied to the p-type material and a negative potential is applied to the n-type material. This causes the electrons from the

n-type and the holes from the p-type to repel from the same potential and recombine with the ions on the respective sides of the boundary, thus reducing the width of the depletion region. As a result, the shielding reduces and the effect of the positive potential on the electron carriers of the n-type material is more significant (as well as the negative potential on the holes). As the forward bias voltage increases, the depletion region will reduce, until at some critical voltage, it is sufficiently small and a large number of electrons cross from the n-type region to the p-type region (and holes cross the other way). At this voltage, the current through the diode begins to increase exponentially.

- In the **reverse bias** condition (V<0), a positive potential is applied to the n-type material, and a negative potential is applied to the p-type material. The electrons in n-type are attracted to the positive potential and leave more uncovered atoms with positive charge at the depletion, and holes in the p-type material leave negative charge. Thus, as the reverse bias voltage is increased, the depletion region grows, shielding the remaining charge carriers and blocking the current from flowing. However, this will not affect the number of holes from the n-type material or the number of electrons from the p-type flowing across the junction, resulting in small current called reverse saturation current $I_s$. This current is very low, and does not change significantly as the reverse bias increases. If the reverse bias voltage is increased beyond the breakdown voltage, the atoms are ionised and the reverse current increases rapidly.

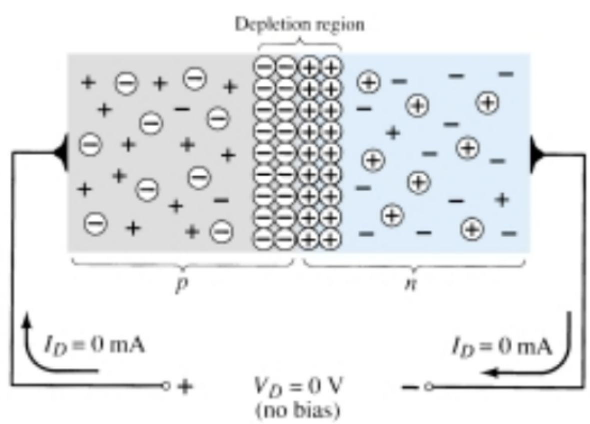


Figure 2: Image of the depletion region formed when there is no bias applied to the diode. Image credit: Boylestad.

In general, and ideal diode obeys the equation below:

$$I_D = I_s\left(e^{\frac{qV_a}{k_B T}} - 1\right)$$

Where $I_s$ is the reverse saturation current, $q$ is the charge of the carrier, $V_a$ is the applied voltage, $k_B$ is the Boltzmann constant, and $T$ is the temperature in Kelvin. The resistance of the diode for a given voltage and current is simply given by Ohm's law:

$$R = \frac{V}{I}$$

## 3.2 Diode lasers

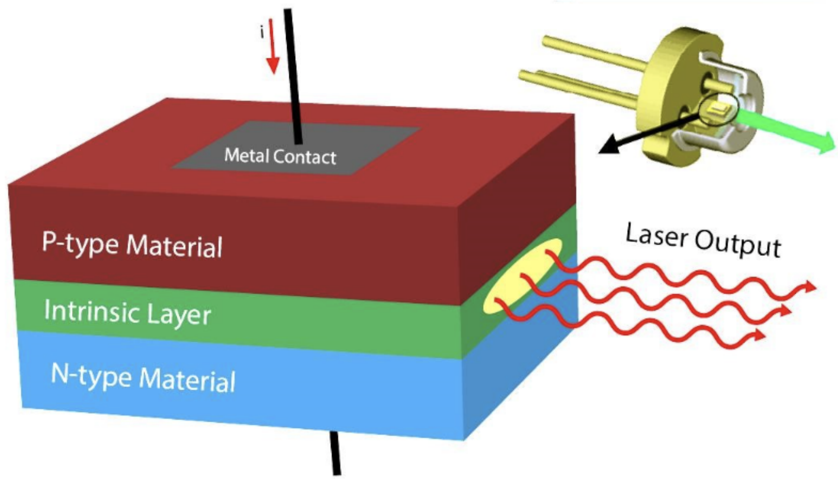


Figure 3: Diagram of a simple diode laser. Image credit: Electronics Hub

Diode lasers are semiconductor optical amplifiers using optical feedback, and are widely used in optical experiments as a collimated, coherent source of monochromatic light. The word 'Laser' stands for Light Amplification by Stimulated Emission of Radiation, which describes the working mechanism. Diode lasers are made out of PIN diodes (made using direct-band gap semiconductors that enable photon emission), which are diodes where there is a region of undoped **I**ntrinsic semiconductor between the p- and n-junctions. When forward bias is applied to the diode, the charge carriers- the electrons and holes- from the n-type and p-type regions are injected into the depletion region. At this point, the process of spontaneous emission begins. A 'free' electron in a higher energy state can recombine with a hole in the depletion region and come to the lower energy state, in the process releasing a photon of energy equal to the energy gap. The photon will have frequency $f = E_{gap}/h$, where $E_{gap}$ is the enrgy gap between the excited and ground state, and $h$ is Planck's constant. In this state, the process is similar to that of an LED or Light Emitting Diode. However, spontaneous emission has many losses associated with it, and in order to maximize the optical power, stimulated emission is preferred.

Ordinarily, an electron can remain near a hole without recombining (i.e. remain in the higher energy state) for some time, which is know as the recombination time. In this state, if a photon with energy equal to the bandgap (one that was generated by spontaneous emission) passes near the electron, it can interact and cause recombination of the electron with the hole, resulting in the generation of a photon with the same frequency, polarization and phase as the previous photon. This is known as stimulated emission, and results in highly coherent and directional light, that does not change phase for a long period of time. This additional photon emitted in the injection region also stimulates further emission. Stimulated emission only occurs above the lasing threshold- which is the minimum excitation level required so that the the optical gain of the laser is exactly balanced by the losses experienced in the laser medium. In order to further maximize the optical power, and ensure the light is collimated, an optical cavity is employed outside the diode junction.

The optical cavity is created either by adding two crystal planes normal to the diode junction, or by having two highly polished and reflective mirrors on either side. This creates an optical waveguide, and the parallel edges form a Fabry-Perot resonator. The photon generated in the injection region is reflected between the two mirrors many times, in order to have it pass as many electrons in the conduction band as possible, thus increasing the number of stimulated emissions by a considerable amount. Additionally, a resonance condition can be created inside the cavity by manipulating the length of the cavity and the reflective medium, so that the light forms a standing wave inside the optical cavity. The increased stimulated emission causes amplification, and when the amplification is greater than the losses (from imperfect reflection, etc.) the diode is said to 'lase'.

An important condition for the maximum optical output is the state of population inversion of the laser gain medium. Population inversion refers to the state where more electrons exist in the higher energy level than in the lower energy level, which cannot occur in ordinary thermal equilibrium. If population inversion exists, the net number of photons produced (say $N$)- that is the number of photons emitted minus the number of photons absorbed during the process- is positive, and the medium acts as an amplifier of light. If $N$ is negative, the medium acts as an attenuater, decreasing the intensity of the light. If $N = 0$, the medium is essentially transparent, having no effect on the intensity of the light. In order to ensure the population inversion state, the method of optical pumping is used, where semiconductor material is used as the gain medium and second laser is used to excite electrons from the lower energy state to the higher energy state, increasing the frequency of emissions. The photons finally leave the laser through a small aperture in the optical cavity, as a highly coherent and monochromatic beam.

As the beam leaves the laser, the light diffracts due to the small size of the aperture and diverges by a large amount. To correct this, a lens is used in front of the aperture, so that the output is a collimated beam of light. Depending on the requirements, different types of lenses can produce different beam shapes, such as circular or elliptical. The light emitted by an ideal diode laser is a Gaussian beam- this means that it is highly monochromatic, and that its intensity distribution is described by a Gaussian spread. Gaussian beams diverge as the propagate- however, diode lasers have a very small divergence angle, since the light is supposed to be well collimated. The intensity profile of the beam in the plane transverse to its direction of propagation is described by the Gaussian function.

$$I(r,z) = \frac{2P}{\pi w(z)^2} \exp\left\{ \frac{-2r^2}{w(z)^2} \right\}$$

Here, $P$ is the total optical power of the beam, $r$ is the radial distance from the center of the beam, and $w(z)$ is the distance from the center of the beam at which the intensity falls to $1/e^2$ of its peak values. As seen, $w$ is a function of $z$, which is the distance from the laser along the path of the emitted beam. The intensity can also be written as:

$$I(r,z) = I_0 \frac{w_0^2}{w(z)^2} \exp\left\{ \frac{-2r^2}{w(z)^2} \right\}$$

Where $w_0$ is the waist radius of the beam, which is the beam radius (as measured above) at the point where it is smallest- that is, $w_0$ is the minimum of the function $w(z)$. The waist radius controls the shape of the Gaussian intensity curve at a given wavelength. As the light propagated further form the laser aperture, the beam spreads out and the radius $w(z)$. The angle at which the beam spreads is known as the divergence angle and is given simply by:

$$\theta_{div} = \lim_{z\to\infty} \arctan\left(\frac{w(z)}{z}\right)$$

The most general form of the electric field of a propagating Gaussian beam from a laser is given by:

$$E(r,z) = E_0 \hat{x} \frac{w_0}{w(z)} \exp\left\{ \frac{-r^2}{w(z)^2} \right\} \exp\left\{ -1 \left( kz + 2\frac{r^2}{2R(z)} - \psi(z) \right) \right\}$$

where $R(z)$ is the radius of the curvature of the beam, and $\psi(z)$ is an additional phase term known as the Gouy phase.

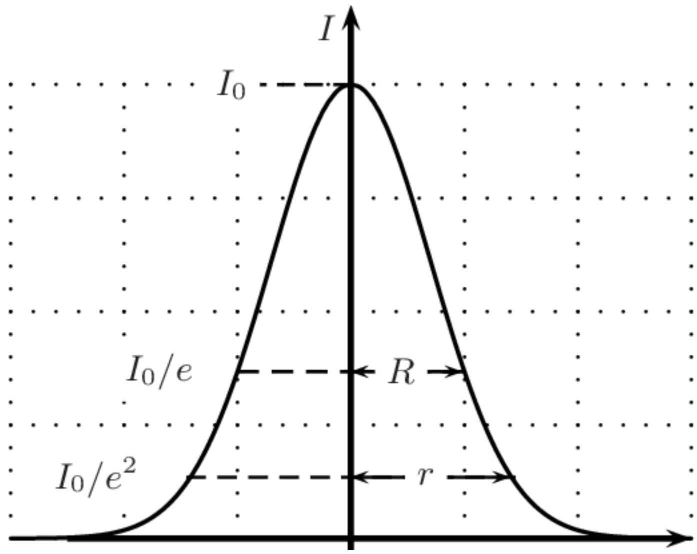


Figure 4: Finding the beam radius from the gaussian graph of intensity versus distance. (Here, r represents the beam radius).

As mentioned above, a diode laser emits polarised light, meaning that all the photons emitted have the electric field polarised in the same direction. However, this is true only for an ideal diode- in reality, the laser beam will be partially polarised, with some small amount of unpolarised light as well. The degree to which the laser is polarised can be found using a polarising filter. When light is incident on a polarising filter, only the component of the light that is polarised along the pass-axis of the filter will be transmitted through, while the rest will be reflected or absorbed. When the incident light is linearly polarised, the intensity of the transmitted light is given Malus' law:

$$I(\theta) = I_0 \cos^{\theta}$$

where $\theta$ is the angle the polarising filter makes with the polarisation of the incident light. If the beam contains some unpolarised light, even at $\theta = 90°$, there will be some measured intensity. We can calculate the degree to which the laser is polarised as:

$$1 - \frac{\text{Minimum intensity observed}}{\text{Maximum intensity observed}}$$

### 3.3 Photodiodes

Photodiodes are important devices in the field of optoelectronics, and are mainly operated in reverse bias. Photodiodes are essentially ordinary diodes, with the p-n junction exposed to incident light via a window or lens. When connected in a circuit in reverse bias, the normal reverse saturation current appears. However, when light above a certain frequency is incident on the semiconductor, the reverse current increases. Photons have energy given by:

$$E = h\nu$$

Where $h$ is Planck's constant, and $\nu$ is the frequency of light. When photons are incident on the diode, electrons in the device can absorb the photon and gain sufficient energy to move from the valence band to the conduction band, which increases the reverse current in the diode. At higher intensities of the light, there are more photons incident on the diode, so more electrons move into the conduction band and cross the depletion band. Thus, in reverse bias, the current produced is proportional to the incident light/radiation power. However, if the frequency is lower than $\frac{E_G}{h}$, where $E_G$ is the energy band gap, then there will not be any current, regardless of the intensity of the incident light, since none of the incident photons deliver sufficient energy to move into the conduction band.

The photocurrent generated when there is no incident light is known as the dark current. When there is some incident light power, the current is given by:

$$I_D = I_s \left( e^{\frac{qV_a}{k_B T}} - 1 \right) - I_P$$

Where $I_P$ is the photocurrent. Thus, the current for the photodiode simply given by the current of a diode shifted by some amount. An important note is that the photodiode should always be operated below the breakdown voltage, since it is operated in reverse bias.

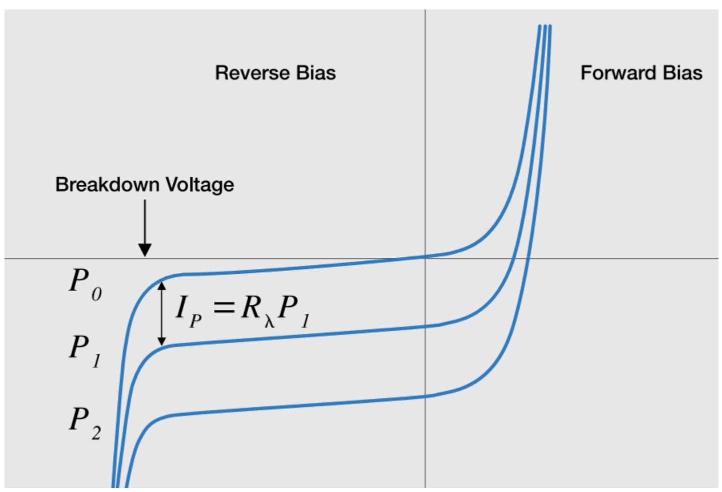


Figure 5: IV characteristic graph of photodiode. Image credit: OSI Optoelectronics: Photodiode

One of the characteristics of a photodiode is the responsivity $R_\lambda$, which is the ratio of the photocurrent $I_P$ to the incident light power at a given wavelength. The responsivity is a measure of the effectiveness of the photodiode in converting light power into electric current.

$$R_\lambda = \frac{I_P}{P}$$

Responsivity can be controlled by adjusting the thickness of the p-n junction substance, and the reflectivity of the coating on top of the device. Other important characteristics of photodiodes are:

- Shunt resistance ($R_{sh}$): Given by the slope of the current-voltage graph near the origin (V=0). An ideal photodiode has an infinite shunt resistance, although practically it is very high ( 100 Mega ohms).
- Series resistance: Resistance of the terminals of the diode, and the the resistance of the depleted semiconductor material. An ideal photodiode has 0 series resistance.
- Junction capacitance: At the p-n junction, the boundaries of the depletion region act as the parallel plates of a capacitor. Thus, there is a capacitance value that is dependent on the reverse bias, and the resistivity of the substrate.
- Noise: There are two sources of noise in a photodiode. The first is shot noise, which is related to a statistical fluctuation in the photocurrent and dark current, given by $I_{sn} = \sqrt{2q(I_P + I_D)\Delta f}$, where $\Delta f$ is the noise measurement bandwidth. The second is Johnson or thermal noise, which is generated due to the thermal energy of the carrier charges, and is given by $I_{jn} = \sqrt{4k_B T \Delta f / R_{sh}}$. The total noise current is $I_{total} = \sqrt{I_{sn}^2 + I_{jn}^2}$. Noise Equivalent Power, or NEP, is the amount of incident light power on a photodetector that generates a photocurrent equal to the noise current.

Some of the common materials used to make photodiodes are silicon, Germanium, Indium-Gallium-Arsenide (InGaAs), Lead(II) Sulfide, and Mercury-Cadmium-Telluride. Out of these, Silicon and Germanium are mainly use to cover the optical range.

# 4 Equipment used

- HOLMARC Diode laser
- HOLMARC Photodiode
- Red LED (Light-emitting diode)- cut-off voltage 1.5 V, maximum input voltage 2 V
- Blue LED- cut-off voltage 2.5 V, maximum input voltage 3 V
- Pinhole photodetector
- Polarising filter
- x-y-z translation stage

- Voltage input source with voltmeter and ammeter
- Variable voltage source (0-12 volts)
- Banana cables
- Ruler
- Optical table
- Cell mount
- Kinematic laser mount

# 5 Procedure

## 5.1 Part A: Beam Profile of Diode Laser

- Set-up the laser on the kinematic laser mount on the optical table. Use a small white card to check that the beam is parallel to the table surface.
- Place the polariser in front of it, and x-y-z translation stage after the polariser, and screw it in. Place the pinhole photodetector in the translation stage, and adjust the laser until the beam falls on the pinhole.
- Switch on the photodetector and laser, and switch the photodetector to the micro ampere mode. Turn the polariser angle until the maximum intensity registered is less than 200 micro-amperes. Record this angle.
- Measure the distance between the diode laser and the translation stage using a ruler and record. it.
- Set the x-, y- and z-axes screw gauges such that the pinhole is at the center of the laser beam, and record the value on each screw gauge. Then, move the x-axis screw gauge only so that the detector moves beyond the beam, and records close to zero intensity.
- Begin moving the screw gauge by 0.25 mm, and record the measure intensity at every point. Keep moving the detector until it has crossed the beam entirely and the intensity has fallen back to zero.
- Move the x-axis back to its original position, then repeat the same process with the y-axis screw gauge, moving the pinhole across the beam in the vertical direction and recording the intensity.

- Move the photodetector to a different distance from the laser- either by moving the z-axis screw gauge, or by unscrewing the stage itself and fixing it at a new distance. Then, repeat the same process of measuring the intensity across the x- and y-axes of the beam.

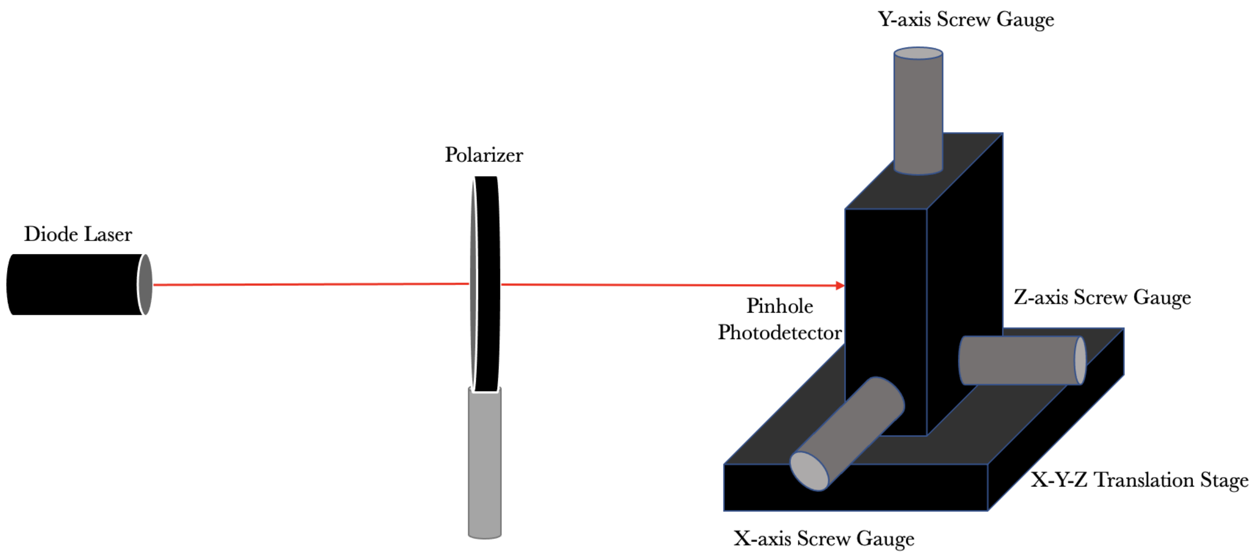


Figure 6: Set-up for measuring the intensity profile of diode laser beam.

## 5.2 Part B: Polarisation of diode laser

- Leave the photodetector fixed at the center of the beam from the previous set up, and all other set-up the same.
- Turn the polariser until the intensity recorded by the photodetector is at maximum. Record this angle and corresponding intensity.
- Change the angle of the polariser by 5 degrees at a time, and record the corresponding intensity at each angle. Continue until the full 360° have been covered.

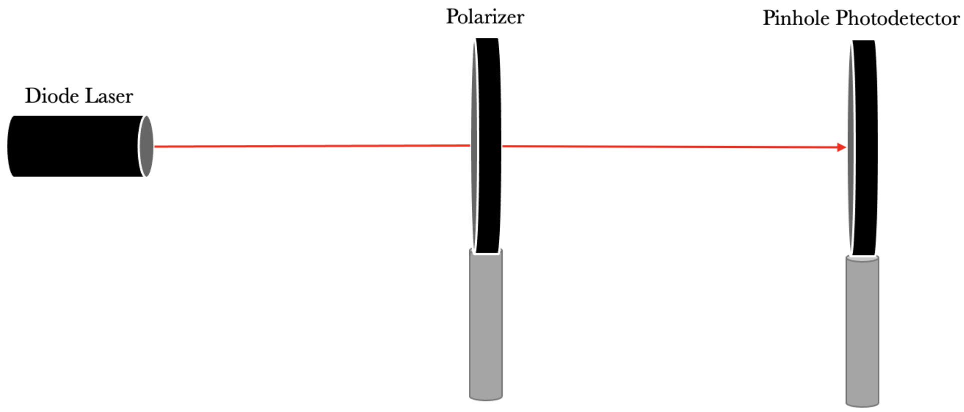


Figure 7: Set-up for measuring polarisation of the diode laser.

### 5.3 Part C: Current and light intensity

- Remove the x-y-z translation stage from the set-up. In front of the polariser, place a cell mount with the photodiode, and connect the photodiode in series to an ammeter.
- Once again, turn the polariser in five degrees increments from 0° to 360°, and record the current measured on the ammeter.
- Remove the polariser and laser diode from the set-up. Place another cell-mount in front of the photodiode very close to it, and attach a red LED to the cell mount.
- Connect the LED to a variable voltage source, and connect an ammeter in parallel to it. Switch on the variable voltage source, and increase it to 1.5V, which is the cut-off voltage for the red LED. At this point, a small point of very dim red light should be visible. Increase it until the ammeter registers some current flowing through the photodiode.
- Increase the voltage to the LED by 0.02 volt increments, and record the corresponding photocurrent. Do not increase the voltage beyond 2.10 volts.
- Connect the photodiode in reverse bias to the variable voltage source of the input-output device (negative of the photodiode to the positive of the source). Connect the voltmeter of the device in parallel, and the ammeter in series.
- Provide some voltage to the photodiode (say 2 Volts). once again, vary the voltage to the LED and record the corresponding photocurrent.
- Repeat the above steps for the blue LED, this time varying the voltage to the LED between 2.5 and 3 volts.

### 5.4 Part D: IV characteristics of Photodiode

- Connect the photodiode in forward bias to the variable voltage source (negative of the photodiode to the negative of the source).

- Turn the voltage to the LED to some value below the cutoff voltage, and the voltage to the photodiode to zero. If there still is some current reading on the ammeter, record it as the dark current.

- Begin increasing the voltage to the photodiode in increments of 0.02 volts from 0 to approximately 0.7 volts, and record the current from the ammeter.

- Then, increase the voltage to the LED, until there is significant incident light power on the photodiode. At 0V, the current on the photodiode should differ from the previous case. Once again, increase the voltage in increments on 0.02 volts and record the corresponding current on the photodiode.

- Repeat the above step from two more higher value of voltage to the LED.

- For each different voltage to the LED, briefly put the photodiode in reverse bias and check the photocurrent in constant across the negative voltage range.

- Plot the curve for each value of LED voltage, with the voltage to the photodiode on the x-axis and the current on the y-axis.

- Repeat the above procedure for both the red LED and the blue LED.

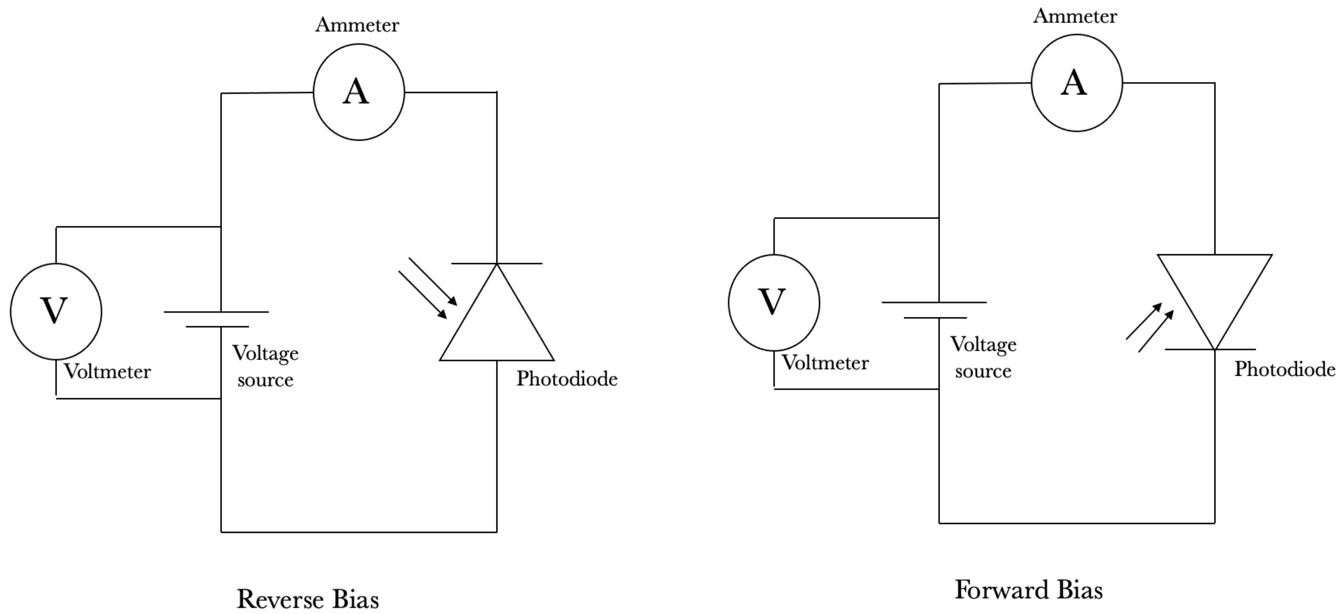


Figure 8: Circuit diagram of forward bias and reverse bias connection of photodiode.

### Precautions

- Do not increase the voltage to the red LED much beyond 2 volts, or the 3 volts for the blue LED, as this will cause them to degrade.
- Do not shine the laser directly in the eyes, as it could cause damage.
- Ensure that all elements are tightly screwed into the optical table before beginning any measurement.
- Do not increase the reverse bias voltage to the photodiode beyond -2 volts, as it could damage the device near the breakdown voltage.

# 6 Observations and Analysis

## 6.1 Part A: Beam Profile of Diode Laser

In the first part of the experiment, The intensity profile of the laser beam was observed, by moving the photodiode across the x- and y- axes. Further, the beam profile was examined at 3d distances from the laser aperture- at 30 cm, 37.5cm and at 45 cm from the laser respectively. To ensure that the full range of intensity was measurable, a polariser was placed in front of the laser. The graphs of the intensity versus the distance moved is given below.

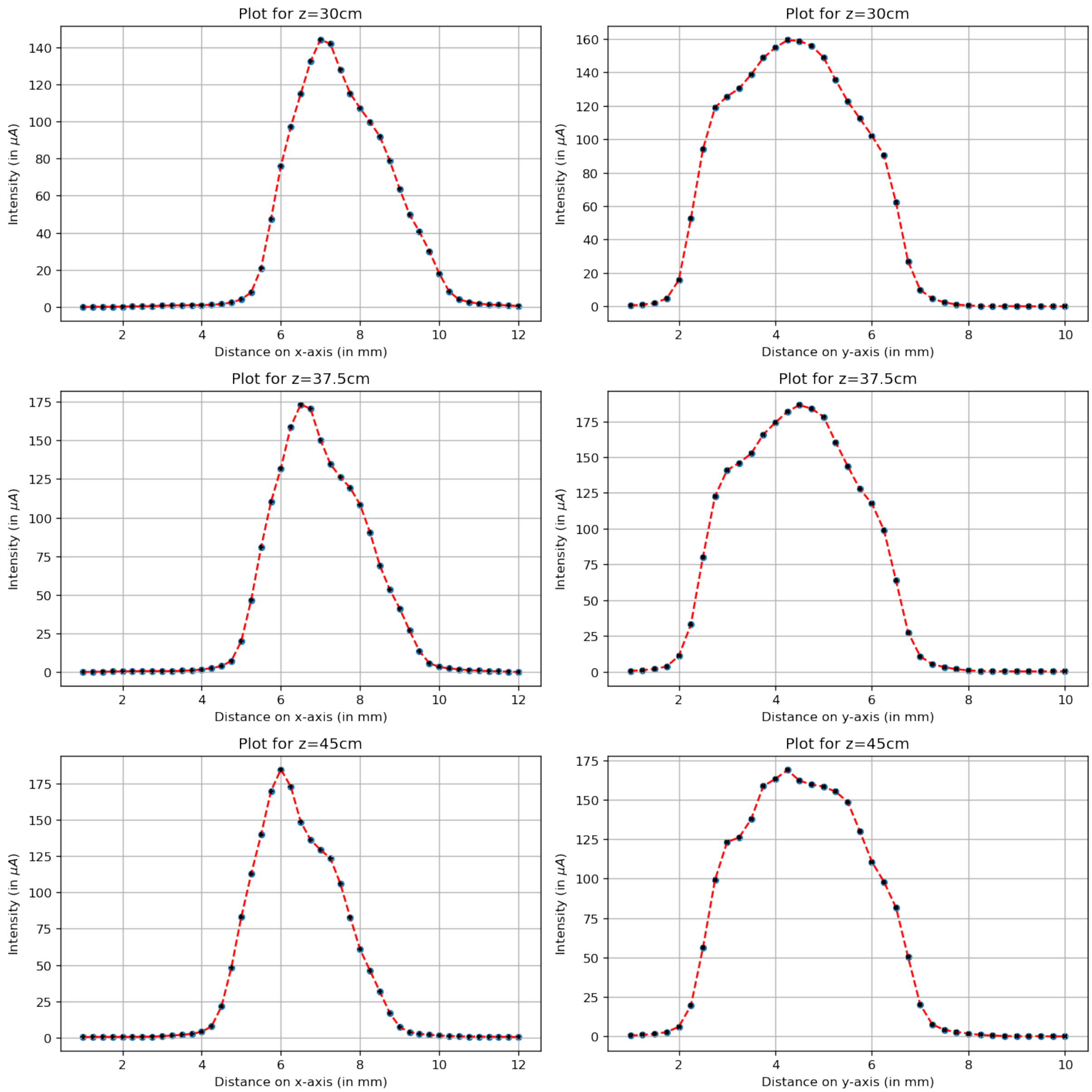


Figure 9: Profile of intensity across the x and y axes of the laser beam, at three different distances from the laser

Since the profile is expected to follow a Gaussian curve, a curve-fit can be done for each of the curves above, to see how well they adhere to the expected graph. The curve-fit was done using the scipy-optimize function in Python.

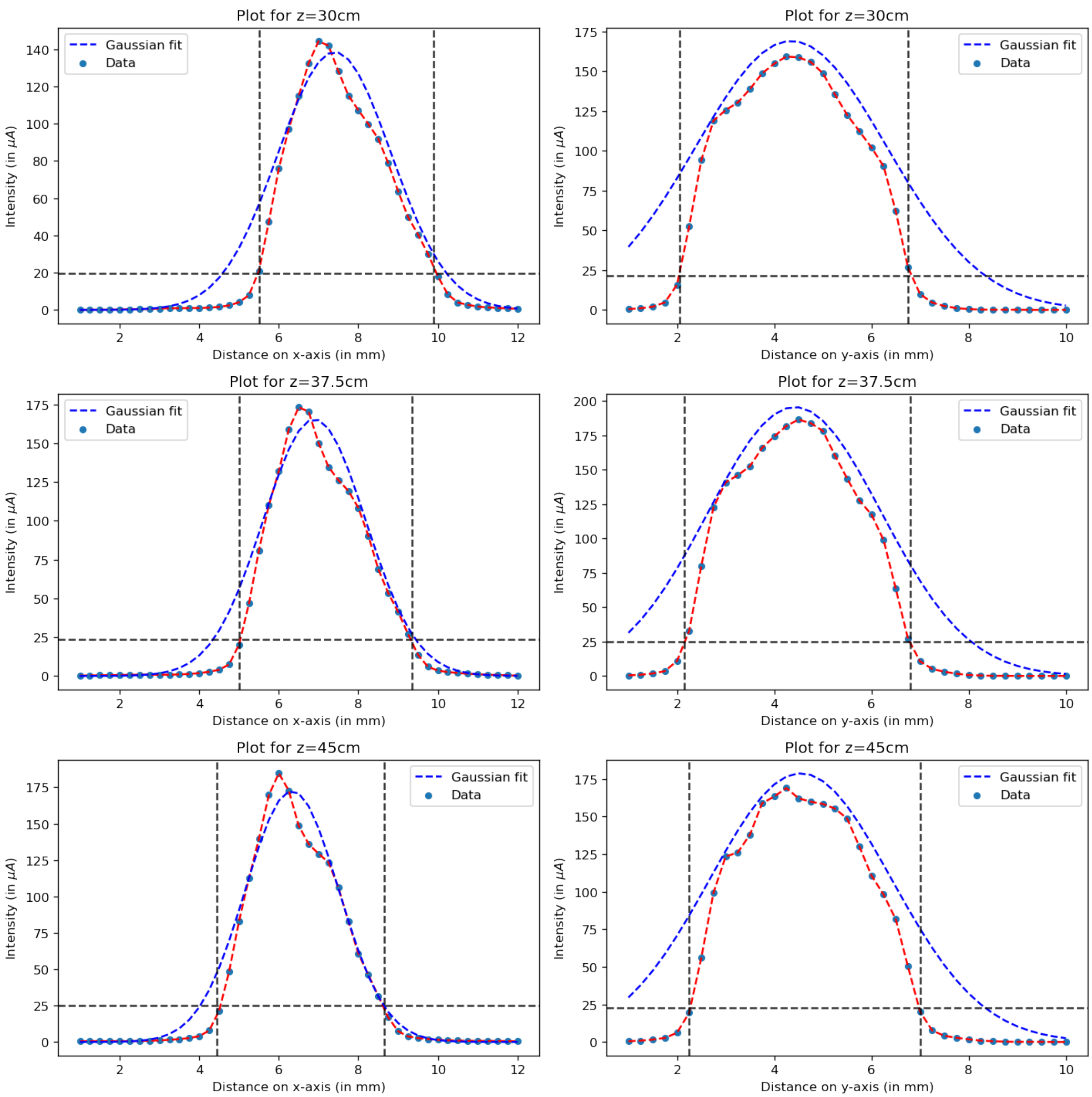


Figure 10: Profile of intensity across the beam at different distances, with Gaussian curve fit and waist radius.

As we can see, the observed profiles differ slightly from the expected shape of the curve. This is in part due to the fact that the curves of observed data are slightly asymmetric, particularly along the x-axis.

The radius $w(z)$ is calculated for each curve by finding the value of $\frac{I_0}{e^2}$, where $I_0$ is the maximum measured intensity, and finding the corresponding values of distance on the x-axis. The difference of these values gives the beam diameter, so we divide by two to get the beam radius.

| | Beam radius (in mm) | |
|---|---|---|
| Distance from laser (cm) | X-axis Profile | Y-axis Profile |
| 30 | 2.20 | 2.35 |
| 37.5 | 2.175 | 2.325 |
| 45 | 2.10 | 3.375 |

Table 1: Table of beam radius obtained for x- and y- axis profiles.

From the table above, we see that there is no clear trend in the y-axis beam radius, and there a very slight decrease in the x-axis radius. From this, we can conclude that the divergence of the laser is very small, and that the error in measurement is more significant.

### 6.2 Part B: Polarisation of diode laser

In order to check the polarisation of the diode laser, the beam is passed through a rotating polarising filter, and the transmitted intensity is recorded. The measured intensity, along with the expected $\cos^2\theta$ curve is given below. The $\cos^2\theta$ curve is plotted with a phase shift of $\pi/2$, since the $0°$ reading was taken at the point of minimum intensity.

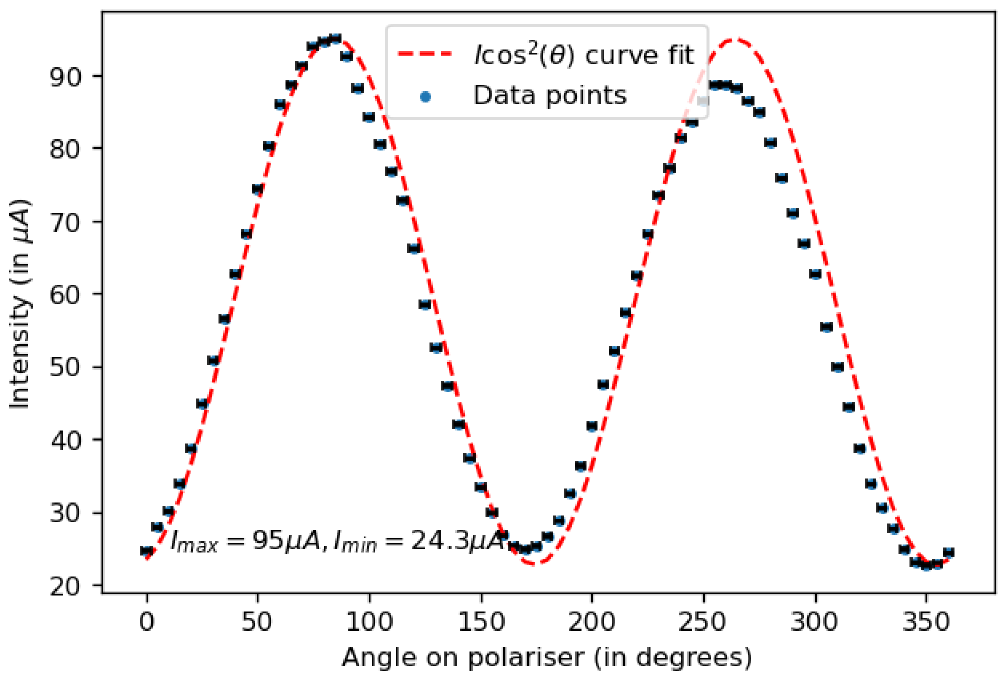


Figure 11: Graph of the intensity detected versus the angle on the polariser, with the starting angle of $195°$ for the minimum intensity

As we can see, the observed trend follows the expected trend quite closely. Additionally, the $\cos^2\theta$

curve is shifted up, and the minimum recorded intensity is greater than zero, which implies that the laser is not perfectly polarised- there is some proportion of unpolarised light produced by the diode laser. The degree of polarisation is calculated as:

$$1 - \frac{\text{Minimum intensity observed}}{\text{Maximum intensity observed}} = 1 - \frac{24.3}{95} = 1 - 0.2558 = 0.7442$$

Therefore, the diode laser is around 74.4% polarised.

## 6.3 Part C: Current and light intensity

In this part of the experiment, the linearity of the photocurrent with the incident light power is checked using to LEDs- one emitting red light and one emitting blue light. The incident light power on the photodiode was varied by changing the voltage supplied to the LED, which increased/decreased the brightness of the emitted light. The graphs for the photocurrent versus LED voltage are given below.

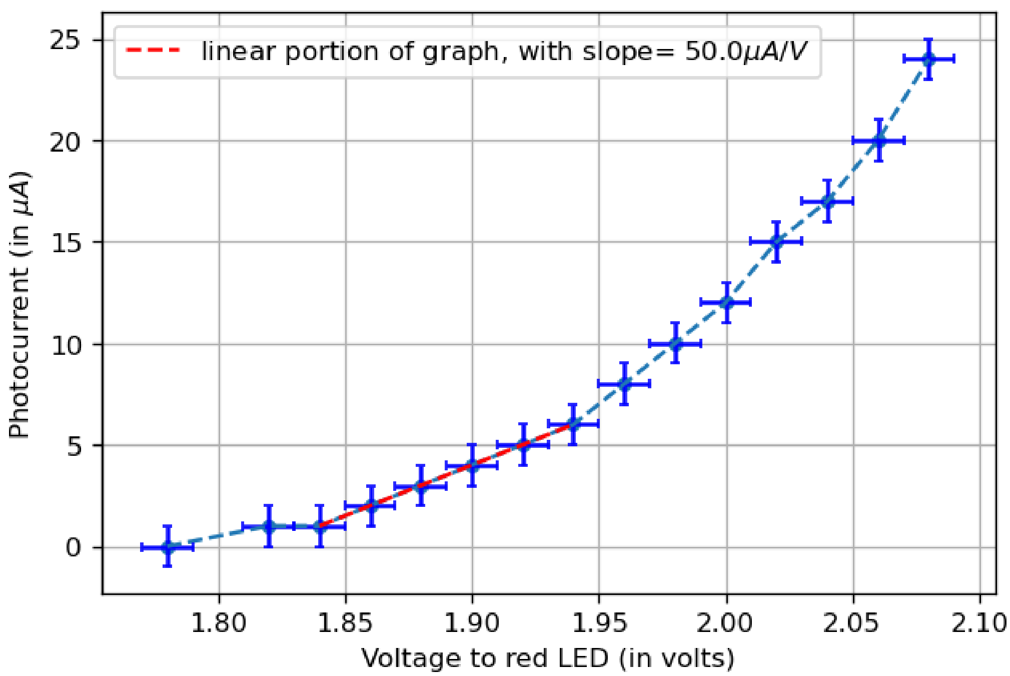


Figure 12: Graph of photocurrent versus LED voltage, for red LED.

Evidently, the trend for the photocurrent does not seem to be linearly related to the power of the red LED light. However, this may have been due to operating the LED on the edge of its permissible range, so it may have been close to the breakdown voltage, causing the non-linear effects. The graph was found to be linear for the portion of the graph well below the upper voltage limit, and the slope of the region of the graph was found to be $50\ \mu A/V$.

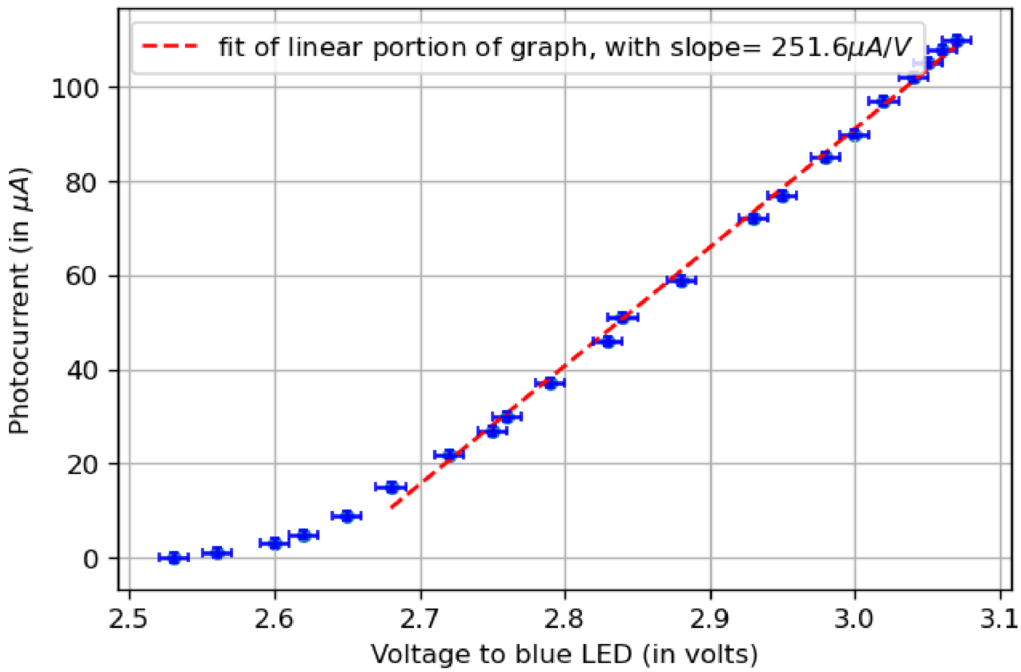


Figure 13: Graph of photocurrent versus LED voltage, for blue LED.

For the blue LED the photocurrent appears to vary linearly with the incident light power, as expected. The slope of the line was found to be $251.6\ \mu A/V$.

## 6.4 Part D: IV characteristics of Photodiode

In the last part of this experiment, I examined the IV curve of the photodiode at different values of incident light intensity, using the blue LED and the red LED. The LED was supplied some constant voltage, then the voltage to the photodiode was varied and the corresponding current was noted.

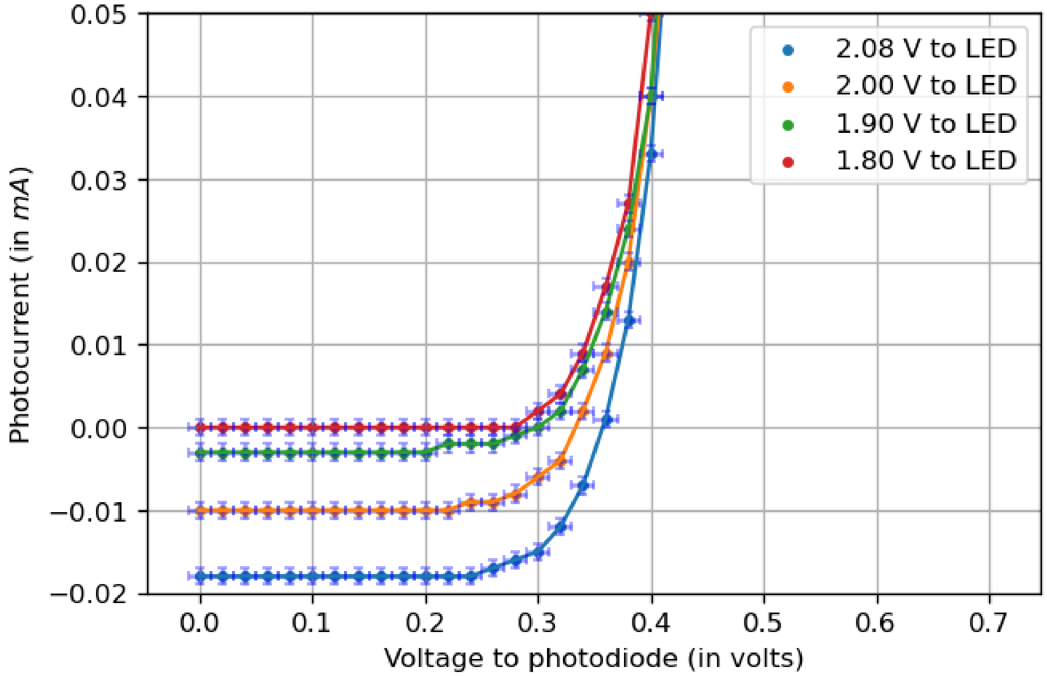


Figure 14: I-V characteristic graph of the photodiode for different incident light power, using the red LED.

From the graph we see that the data obtained follows the expected curve, with a knee voltage around 0.3 volts, after which the voltage rises exponentially. The reverse saturation current is constant up until that point, and varies clearly for different values of light power. A similar graph is obtained for the blue LED as well, shown below:

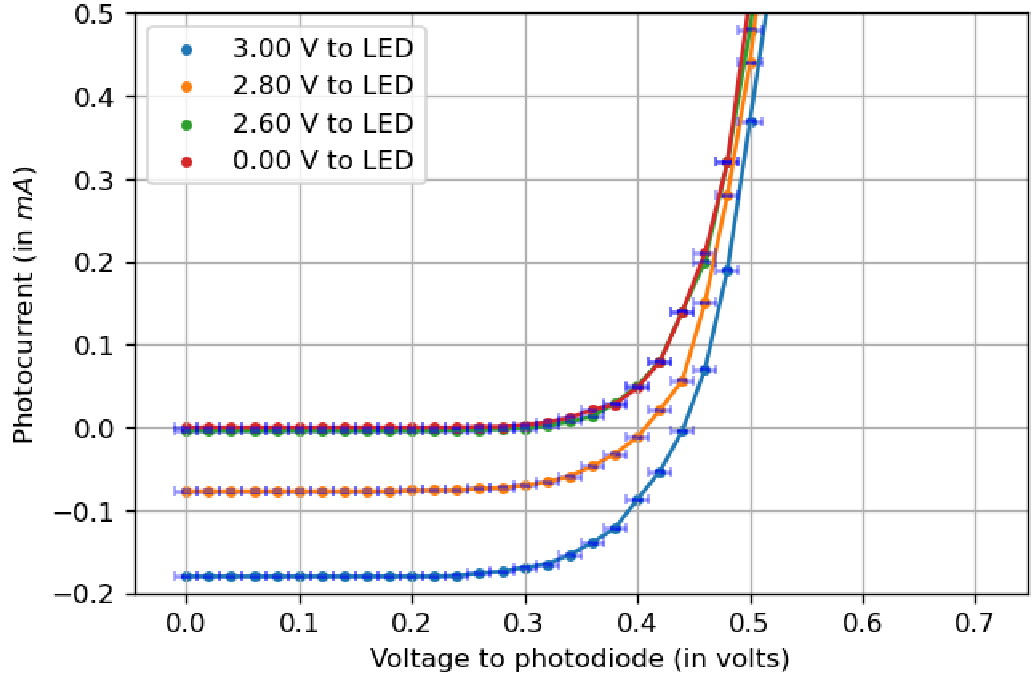


Figure 15: I-V characteristic graph of the photodiode for different incident light power, using the blue LED.

The the photodiode follows the expected curve for both the blue and red LED. However, the curves between the LEDs cannot be compared, as the voltages supplied to each are very different.

# 7 Error Analysis

## Least count of instruments

- LC of pinhole Photodetector- 0.1 $\mu A$
- LC of photodiode voltmeter- 0.01 V
- LC of photodiode ammeter- 1 $\mu A$
- LC of LED voltage source- 0.01 V
- LC of ruler used to measure distance- 0.1 cm

## Sources of Error

- When using the photodiode and LED, although they were kept at close proximity, it was difficult to tell whether the maximum intensity was incident on the photodiode, since the bulb of the LED was at an angle.

- When measuring the intensity profile of the laser beam, at high intensities, the current measured by the photodetector would fluctuate by around 1-2 $\mu A$, which introduces error in the graphed profile.
- If there were imperfections on the polariser plate, such as scratches or dust, it could have altered the profile of the beam as measured by the photodetector.
- As mentioned above, operating the LED at voltages close to the maximum voltage may have caused the LED to behave differently and change brightness non-linearly. This would have affected the data recorded on the photodiode at these voltages.

# 8 Results

In this experiment, various characteristics of diode lasers and photodiodes have been investigated and verified.

- The beam profile of the diode laser across the x and y axes was found to be gaussian in nature, and it was verified that the divergence angle for the laser is very low.
- The diode laser was found to be partially polarised, to about 74.4 %.
- The photocurrent generated by the photodiode was found to vary linear with the incident light power for the blue LED, but not for the red LED.
- The photodiode was found to have the characteristic IV graph of a diode, with the curve being shifted along the I-axis by the incident light power.

# 9 Discussion

- One of the issues faced when trying to verify the linearity of the photodiode was the limited range of voltage available for the red LED. The threshold voltage of the LED was found to be around 1.5 volts, although practically the red LED did not emit significant power until the voltage was increased to around 1.8 volts. As the manufacturer's specification stated that the voltage supplied should not increase beyond 2 volts, this left a very narrow band in which to change the emitted light power. Additionally, the it was very difficult to get a perfectly stable voltage on the external voltage source, and the value typically fluctuated by 0.1 V. Thus, it was difficult to obtain a consistent set of data using this LED. In the graph using the blue LED, it is observed that the graph is initially non-linear at voltages near the threshold voltage, before coming to a linear trend. For the red LED, there was not a sufficient voltage gap between the threshold voltage and the upper limit voltage to obtain a clear linear trend.

- Red lasers are very common in laboratory use for simple optics experiments. Red lasers are often built with a symmetrical lens to focus the beam from the optical cavity. These lenses have different divergences of the transmitted light along the two orthogonal axes, and because of this, the resulting beam is elliptical in shape rather than circular or point-like. However, it is not possible to observe the gaussian beam profile in such a laser, as the shape itself has been altered, and the intensity is found to plateau along the major axis of the ellipse rather than rise and fall smoothly. Thus, although data was collected on the beam profile of an elliptical laser, it is not presented here in the interest of brevity

- When performing the experiment, I had expected to measure a very small divergence angle from increasing beam radii at different distances. However, on analysing the data, the difference in the beam radius was so small, that any increase was likely dominated by the errors in measurement of the intensity (which come primarily from the fluctuating readings at high intensities). Therefore, the only conclusion that can be drawn at this time, is that the divergence of the laser beam is very low, implying that the beam is highly collimated, as expected from lasers. If the experiment were to be repeated I would measure the beam profile at greater distances from the laser, and take a small step size in the distance across the axes to obtain a more accurate beam profile.

- The data obtained on the beam profile has a slight asymmetry, which was even visible in the beam itself. Within the expected circular beam, there was a vertical area of greater brightness that caused the beam intensity profiles to be skewed slightly. In some cases, the intensity was found to rise, fall slightly, plateau and then fall the rest of the way. It is likely that the asymmetrical bright area was responsible for the spike in intensity above the 'plateaued area'. Nevertheless, the overall shape of the beam still resembles the expected Gaussian form.

- Typically, the application of reverse bias to a photodiode is said to improve the linearity of the photocurrent with the incident light power. However, on applying reverse bias, it was found that it made no difference to the variation. This might have been because the aforementioned improvement only applies for specific photodiodes made of particular materials, and is not a general case. This will have to be further investigated. Another point of interest about the bias of the diode is the location of the exponential rise on the IV graph. While performing the experiment, I had been expecting the exponential rise to appear at low reverse bias voltages, as some sources had indicated. However, on applying reverse bias, I found the voltage to be constant throughout. After further research I realised that the curve would have shifted to the right given the incident light, and on applying forward bias, obtained the expected graph.

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