# Diode Laser Characteristics

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**Abstract:** The temperature dependence of laser properties was explored using a diode laser and Peltier cooler. Threshold currents were calculated at various temperatures and comparable to expected results. L-I characteristic plots for seven temperatures were produced to investigate threshold current, slope efficiency, and characteristic temperature. The output beam spatial cross-sectional power distribution was plotted to investigate the beam profile and beam divergence.

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## 1. Introduction

Diode lasers are semiconductor devices that use the p-n junction of a semiconductor diode to create light that is coherent and generally of a single wavelength. Due to the small size, low power consumption, and cost-effective production of these devices, diode lasers have become the most common types of lasers in the world, used in a large variety of components and fields, including electronics, communications, and medical practices. The function of diode lasers is dependent on a variety of properties, including the threshold current, slope efficiency, and characteristic temperature.

When investigating the properties of a diode laser, a plot of the detector output vs. forward current, known as an L-I characteristic, can be used to determine the threshold current and the dependence of the diode laser at various temperatures. When the data is plotted, the point at which there is a significant change in detector output is an indication that the device has reached lasing conditions. The current at which this occurs is the threshold current of the laser.

The slope of the L-I characteristic can determine the efficiency of the diode laser once the diode laser as been supplied with a current higher than its threshold current. No device is 100% efficient, with the best diode lasers available able to convert approximately 50% of the electrical input power into laser light.

Diode lasers are extremely sensitive to temperature, which can influence their functionality and efficiency. By collecting data and plotting L-I characteristics at multiple temperatures between 5°C and 40°C, this temperature dependence is clearly observable, influencing the value of the threshold current for the diode laser as well as the diode laser's efficiency.

A fundamental property of a diode laser is the characteristic temperature of the device. Every laser device has an independent characteristic temperature value, which represents the diode laser's thermal stability. Diode lasers with higher characteristic temperatures are less susceptible to thermal changes of the device and its surrounding environment, yielding a more dependable and stable laser. The characteristic temperature can be empirically calculated using the relation Eq. 1.

$$I_{th} \propto e^{T/T_o} \qquad (1)$$

The characteristic temperature is an important quality for determining whether a diode laser is "good" or not.

The profile of the output laser beam of a laser diode is also of fundamental importance. The cross-sectional power distribution of the beam can be measured to determine the shape of the beam profile. From this information, the divergence of the beam in the parallel and perpendicular to the junction may be determined. The divergence of the laser beam is important for understanding the propagation of the beam through space at extended distances, and why the beam profile takes the Gaussian shape associated with it.

## 2. Background

Lasers are devices that produce coherent light of specific wavelengths by way of stimulated emission of radiation. The term comes from the acronym for "light amplification by stimulated emission of radiation". The process of stimulated emission can be achieved in a variety of was, allowing for different types of lasers to be produced by different methods. The different types of lasers include gas and chemical lasers, solid-state, fiber, free-electron, photonic crystal, and semiconductor lasers [1, 2]. A diode laser is semiconductor device that uses the characteristics of p-n junctions to produce light.

The function of laser diode is similar in principle to a light emitting diode (LED). As an induced current passes through the device, the electrons and holes present in the n-doped and p-doped material layers respectively, are injected into the active layer. When the electrons and holes combine and annihilate, energy is released in the form of a photon. In a light emitting diode, the photons are spontaneously released. However, in a laser diode, the generated photons are used for stimulated emission, interacting with excited electrons to liberate more photons of identical frequency, phase, polarization, and direction of travel [2]. In order for the laser diode to start lasing, the rate of stimulated emission needs to be greater than the rate of absorption of photons, causing a population inversion and an overall optical amplification. The power output of a diode laser is not always constant, and fluctuates with an amount of noise, however these fluctuations are always around a constant total power output [3].

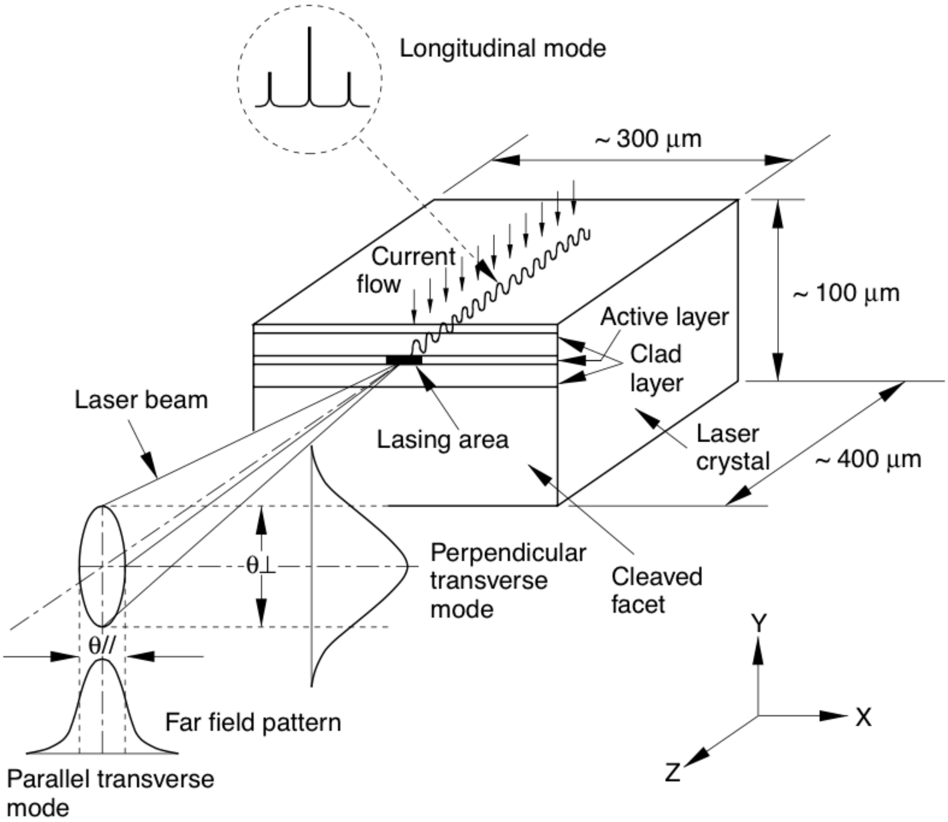



Fig. 1. Schematic of diode laser including current flow, beam profile, and beam divergence angles [4].

Figure 1 shows a detailed schematic of a conventional, double heterostructure diode laser. The cladding layers contain the p-type and n-type doped semiconductor material. In the case of this experiment, this was AlGaInP. The active layer in the middle of the cladding layer, which was GaInP, is the area where the laser light is generated by the previously described process. It should be noted that the divergence of the laser beam and its overall elliptical shape is due to the nature of the lasing area of the laser crystal. Since the lasing area is rectangular in nature, the diffraction creates the elliptical shape, with the small height in the y-axis causing the large perpendicular transverse mode with respect to the smaller parallel transverse mode, which is created due to the comparatively larger length of the lasing area in the x-axis.

The lasing threshold of the device is dictated by the threshold current, which provides the charge carries possessing the electrons and holes. The threshold current, in turn, is dependent on the temperature of the diode laser [5]. The temperature dependence of the threshold current and efficiency of the laser are primary objectives of this experiment and of fundamental importance for the use of diode lasers in real world applications.

Due to their small profile, relatively good efficiency at room temperature, and low power consumption, diode lasers have become the most popular types of laser in the world, and the most widely produced and utilized. Diode lasers can be found in many modern devices and have everyday uses, including multimedia devices, telecommunications, and applications in the medical field.

One of the most known uses for diode lasers in the past decade has been in the use of CD and DVD players. The extremely small profile of the diode laser coupled with its low power consumption make it the ideal device to use to write data to and read data from optical storage devices [1]. The low production costs of diode lasers allow CDs and DVDs to be widely marketable to the general public. Figure 2 shows the diagram of a standard "can" type diode laser. This type of laser can be found in many electronic devices and is useful due to its overall lightweight and compact side.

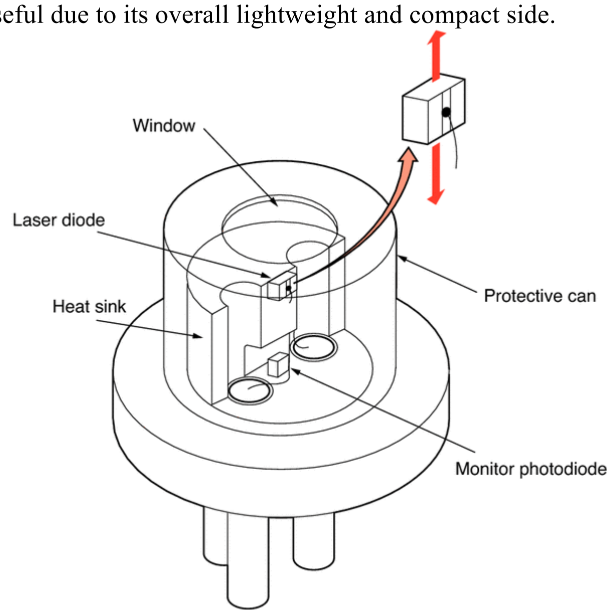



Fig. 2. Diagram of a standard "can" type diode laser [6].

The recent development of Blu-Ray technology has allowed for such storage devices to hold even more data than conventional CDs and DVDs. Such technology is based around diode lasers that emit blue light. Conventional diode lasers usually emit red light, such as the ones used for CD and DVD players, and those used in this experiment, and are based on GaAs. It was not until 1992 that blue diode lasers, based on extremely hard to manufacture GaN (Gallium Nitride), were developed by Shuji Nakamura [7-9]. The difference in the wavelength and color of the emitted light is due to the materials themselves from which the diode laser is produced. GaN has a higher band gap, approximately 3.4 eV, where as GaAs based diode lasers have a comparatively smaller band gap around 1.43 eV at 300K [10, 11]. This band gap difference means that when photons in the GaN semiconductor are generated, they contain more energy, higher frequencies, and thus, smaller wavelengths closer to the blue end of the visible electromagnetic spectrum. Due to the smaller wavelength of the blue laser light, more data could be stored on an optical disc of the same size as a CD or DVD, leading to advancements in information storage technology[1, 7].

In the telecommunications industry, lasers are extremely useful for long distance communication due to the minimal divergence of the laser light compared to light from LEDs. The importance of the temperature dependency of laser efficiency is highlighted here, as a diode laser used for long periods of time to send high data rates would need to be very resistant to the temperature buildup from operation. Thus an understanding of the thermal stability and characteristic temperatures of diode lasers is needed and finding a laser that has a low threshold current at high temperatures is beneficial to telecommunication technologies [12-14].

Laser medicine is a field that has benefited from the cost effectiveness of diode lasers. The small size of the device allows for them to be used in sensitive medical procedures that require a high degree of accuracy. Diode lasers of many different output wavelengths have uses in the medical field. For example, those in the ultraviolet range can be used for sterilization of surgical materials [15]. Many fields of medicine, including cosmetics and dermatology use diode lasers [15].

## 3. Methodology and Apparatus

The experiment was conducted using a GaAs based laser of 670nm, a Peltier cooler, and a large area silicon photodiode as the photodetector, connected to a voltmeter. The Peltier cooler was used to transfer heat to the heat sink and change the temperature of the diode laser. Both the temperature and forward current through the diode laser were set and monitored using the control unit provided.

The laser and detector were both attached to a triangular rail and adjusted to be at the same height. The laser was adjusted so that the output beam fell on the detector. A voltmeter was attached to the photodetector to read the output in mV, which would later be converted to mW for analysis. The experiment was divided into three parts.

### *3.1 Experimental Measurements of the Laser Power Output at Constant Temperature*

For the first part of the experiment, the temperature was set at approximately 20°C and the drive current was varied. The output voltage and corresponding drive current was recorded with the photodetector switched to the x1 sensitivity setting. The current was started at 0.0 mA and went to a maximum of no more than 43.0 mA. The data was plotted in Excel to create an L-I characteristic, as seen in Figure 3. The associated uncertainty was also plotted. From analysis of the data plot, the threshold current was determined and recorded. For data points above the threshold current, a line of best fit was plotted. The equation of this line was determined, and the slop of this line was recorded as the slope efficiency of the diode laser.

### *3.2 Experimental Measurements of Laser Power Output at Varying Temperature*

For the second part of the experiment, the same process from the first part was followed at seven different temperatures between 5°C and 40°C. As with the first part of the experiment, the output voltage and corresponding drive current was recorded to a maximum current of no more than 43.0 mA. Seven L-I characteristics were produced and plotted on the same graph to show the influence of the temperature variation, as can be seen in Figure 4. For each plot, the associated uncertainty was also plotted. For each temperature, the plots were analyzed and threshold current and slope efficiencies were determined and recorded. From Eq. 1., Eq. 2 was derived and the characteristic temperature was empirically calculated.

$$T_o \propto \frac{T}{\ln\left(I_{th}\right)} \tag{2}$$

### *3.3 Experimental Measurements of Beam Spatial Cross-Sectional Power Distribution*

For the third part of the experiment, the aperture was attached to the front of the photodetector. The diode laser was adjusted to be at the same height as the photodetector and moved to be 2.5 ± 0.2 cm from the photodetector. A white sheet of paper was used to view the laser beam and how it diverges. It was noted that the output beam was approximately 45° to the vertical. The sensitivity of the photodetector was switched to the x10 setting.

The temperature was set at approximately 20° and the current at 40.0 mA. The photodetector position was recorded and then displaced in the x-axis at a constant height. The detector output voltage was recorded at 0.5 ± 0.2 mm increments along the x-axis. Once the entire profile of the beam in the x-axis at that height was scanned, the detector was centered on the laser beam again at the original recorded position. The position of the photodetector along the y-axis was then displaced at a constant position on the x-axis. Once again, the detector output voltage was recorded at 0.5 ± 0.2 mm increments along the y-axis. After the entire beam had been scanned, the recorded data was plotted and beam profiles in the x-axis and y-axis were produced, as can be seen in Figure 5. For each plot, the associated uncertainty was also plotted. From the Full Width Half Maximum (FWHM), the beam divergence in the perpendicular and parallel to the junction, $\theta_{\perp}$ and $\theta_{\parallel}$ respectively, were calculated.

## 4. Results

### *4.1 Laser Power Output as a Function of Forward Current at Constant Temperature*

For the first part of the experiment the plot of the L-I characteristic is provided in Figure 3. The associated uncertainty from the detector at a sensitivity setting of x1 of ± 5% is also provided for mW measurements. From the plot, the threshold current $I_{th}$ was determined to be 24.50 mA by analyzing the point at which the diode laser reached lasing conditions. The slope efficiency was determined from the plotted line of best fit for data points above the threshold current as 0.2925 mW/mA. This means the laser is operating at approximately 29.25% efficiency at 20°C.

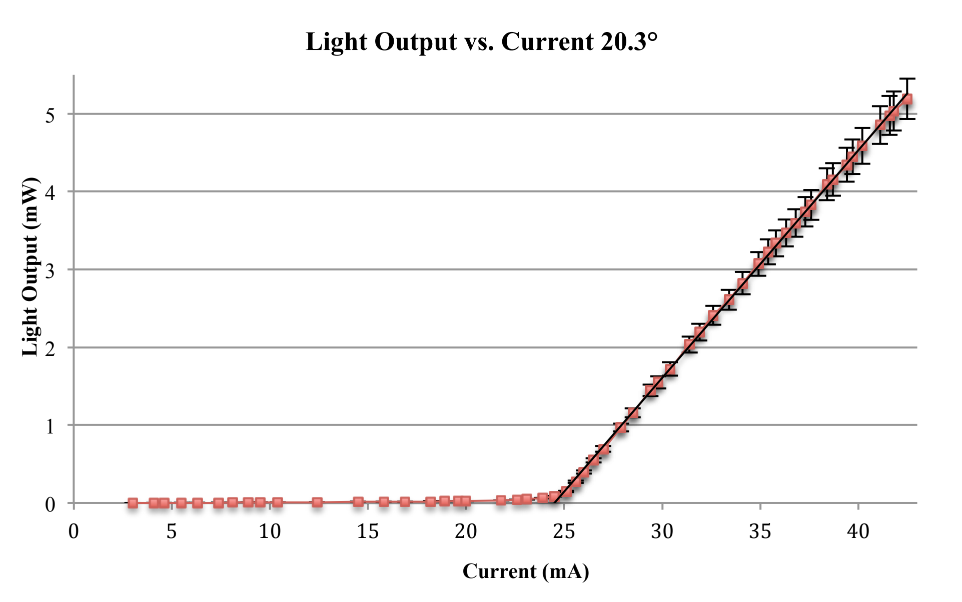



Fig. 3. L-I characteristic for diode laser at 20.3°C and varying drive current.

### *4.2 Temperature Dependence of the Threshold Current*

For the second part of the experiment, the data collected was used to plot seven L-I characteristics at different temperatures, which is provided in the graph in Figure 4. The associated uncertainty from the detector at a sensitivity setting of x1 of ± 5% is also provided for mW measurements. The threshold currents and slope efficiencies were determined from the plots as previously stated and are provided in Table 1. Furthermore, the characteristic temperature $T_o$ was estimated, based on the experimental relation in Eq. 2, for each temperature. For further data analysis, the characteristic was calculated in K, rather than the temperature units used by the Peltier cooler, °C.

**Table 1. Threshold Current, Characteristic Temperature, and Slope Efficiencies for various diode laser temperatures.**

| $T$ (°C) | 7.1 | 10.8 | 15.5 | 20.3 | 25.2 | 29.9 | 34.8 | 39.9 |
|---|---|---|---|---|---|---|---|---|
| $T$ (K) | 280.25 | 283.95 | 288.65 | 293.45 | 298.35 | 303.05 | 307.95 | 313.05 |
| $I_{th}$ (mA) | 22.705 | 23.216 | 23.721 | 24.50 | 24.814 | 25.533 | 26.126 | 27.087 |
| $T_o$ (K) | 89.75 | 90.29 | 91.16 | 91.74 | 92.90 | 93.54 | 94.38 | 94.89 |
| Slope Efficiency | 31.21% | 30.78% | 29.89% | 29.25% | 27.82 % | 27.11% | 25.96% | 25.49% |

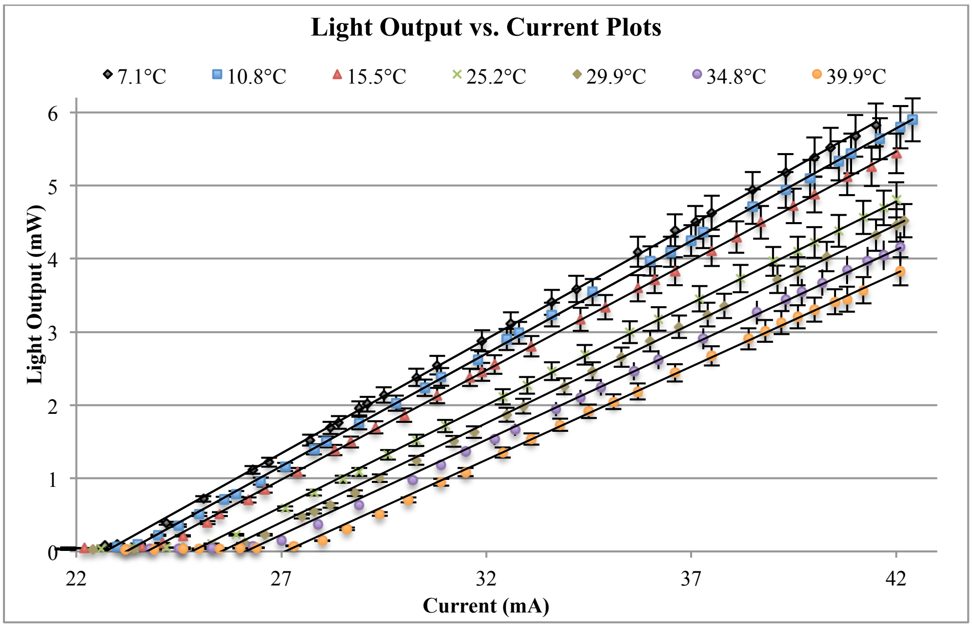
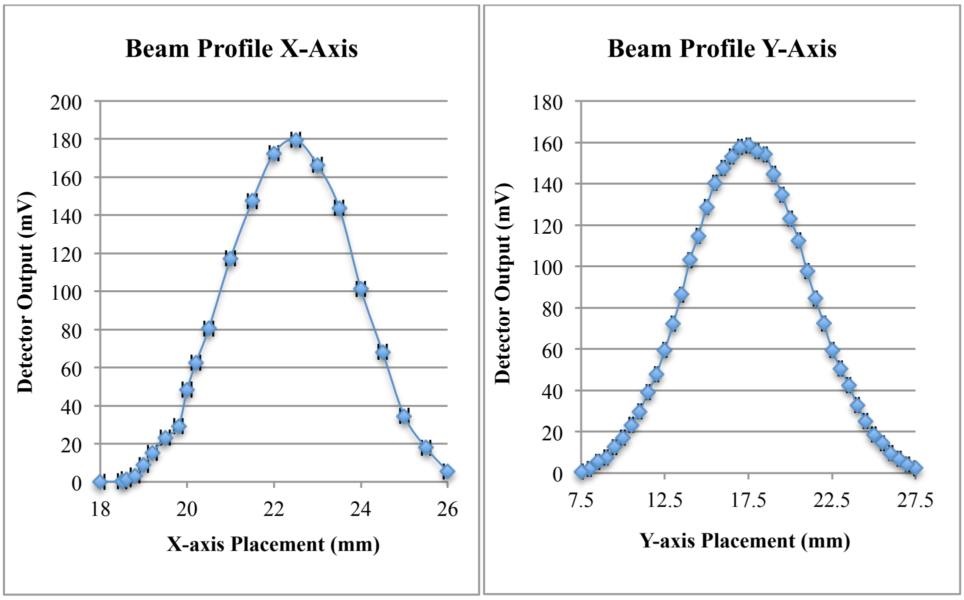



Fig. 4. L-I characteristics for diode laser at varying temperatures between 5°C and 40°C and varying drive current below 43.0 mA.

*4.3 Analysis of Beam Profile and Beam Divergence Angle*

For the third part of the experiment, Figure 5 shows the beam profile in the x-axis and y-axis. The associated uncertainty in the displacement of the photodetector of ± 0.2 mm is also provided. No associated uncertainty is provided for the detector output as the laboratory manual did not provide the uncertainty at a sensitivity setting of x10. The beam divergence in the perpendicular and parallel was calculated from the Full Width Half Maximum (FWHM), as $\theta_{\perp}$= 21.8° ± 1.6° and $\theta_{\parallel}$= 9.1° ± 0.7° at a distance of 2.5 ± 0.2 cm.




(a) (b)

Fig. 5. Beam profile: (a) along x-axis at constant y-height; (b) along y-axis at constant x-axis displacement.

## 5. Discussion

The experiment was completed and yielded good results. Over fifty measurements were recorded for the first part of experiment, with following parts having fewer measurements taken at low currents, which were deemed to not influence significant calculations (currents below approximately 20 mA). The results for the threshold current $I_{th}$, provided in Table 1, were consistent with the expected results [16]. It was observed that the threshold current varied with temperature, increasing as the temperature of the diode laser increased. Typical values for threshold currents of InGaAsP based diode lasers at room temperature range between 31-34 mA[17]. The diode laser used for this experiment is GaAs based with a GaInP active layer and AlGaInP p-type and n-type doped cladding layers, thus the resulting threshold currents can be said to be comparable with known results.

The empirically calculated values for the characteristic temperature $T_o$ were within the expected range of values. However, the values varied slightly with temperature, which was not expected. This variation was only by 5% between the measurements taken at 7.1°C and 39.9°C. Typical values for $T_o$ for GaAs/AlGaAs based diode lasers are between 60K to 150K, and consistent with the calculated results [17, 18]. The value of $T_o$ is highly dependent on the active layer used for the diode laser [17]. Specifically, larger values of the threshold current can be expected for lasers that use semiconductors with wider band gaps, and higher energy gaps, such as GaN as previously mentioned [8, 11, 19].

It should be noted that the calculated $T_o$ was only a proportional empirical relation with a final value needing multiplication by a constant based on the dimensions of the diode material. Actual values for the characteristic temperature use the current density through the device. However, additional research has shown that the relation used for calculating the characteristic temperature only holds for a small range of temperatures and current densities, with other equations used when determining the characteristics of diode lasers at very low temperatures [20]. Higher characteristic temperature values correspond to lower threshold current values. This provides a laser that is more thermally stable. Characteristic temperature is a measurement of thermal sensitivity, with good lasers having high values of $T_o$. Such diode lasers with large characteristic temperatures would be useful in fibre optics and other telecommunication systems [21, 22].

For the final part of the experiment, it was observed that the laser beam was diverging and formed an ellipse that was not directly aligned with the x-y axis. The angle of the laser beam was approximately 45° to the vertical, with respect to the elliptical beam shape being vertical. The diffraction of laser light through a small aperture is expected to form diffuse circular discs, Airy's disc, followed by faint concentric circles [23, 24]. The calculated values for the divergence of $\theta_{\perp} = 21.8° \pm 1.6°$ and $\theta_{\parallel} = 9.1° \pm 0.7°$ were within the expected limitation. Typical angle values for the perpendicular axis is 30°, up to 40°, and parallel axis of 10° up to 12° [17-19]. The calculated values are lower than those of the expected values. This is due to the alignment of the beam and the diode laser. The method used for data collection did not scan the entire width of the beam profile. To properly determine the angular divergence, the full length and width of the beam must be measured by either changing the angle of the beam or simultaneously changing the x and y displacement of the sensor rather than keeping one constant. However, considering the limitation, the calculated divergence angles are acceptable.

The plots of the beam profile use the detector output readings in mV rather than light power in mW. This is because the x10 sensitivity setting of the photodetector was required for readings and the lab manual did not include information on the uncertainty of the detector sensitivity at the x10 setting. As the resulting values for the divergence angles are agreeable with known values, the uncertainty of the sensitivity of the detector at the x10 setting may be considered insignificant enough to have not caused any discrepancies with the final results.

To further expand this experiment, taking a full scan of the beam profile would have shown more accurate results to compare with the known divergence angles. From a full beam scan, an accurate full 2D cross-sectional map of the power distribution of the beam could have been plotted.

## 6. Conclusion

The experiment was conducted to explore the characteristics of a diode laser. The temperature dependence of the threshold current $I_{th}$ was investigated and L-I characteristic plots for various temperatures were produced and analyzed. The characteristic temperature $T_o$ was estimated using the empirical relation given. The optical properties of the output beam profile were investigated and the divergence angles of the laser beam are calculated. All results were within the experimental uncertainty of expected values and consistent with other research literature.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