Laser Characterisation

PY4113 Lab Report

University College Cork
School of Physics

Author: Jordan Darran Emmett Walsh (120387836)

Lab Partner: Rory Tomas Fox (120445052)

Location: Kane Building 202, University College Cork

Date: 01/11/23

Contents

Laser Characterisation

Introduction

This report details one of five experiments completed as part of enrollment in PY4113, the objective of which is to characterise a semiconductor laser diode.

The report begins with a brief motivation and discussion of fundamental concepts relevant to laser diodes. The remainder of the report is structured typically, with sections for methodology, results (including error analysis where appropriate), discussion, and conclusion.

1.1 Motivation

Lasers and laser diodes in the modern day need little introduction. Throughout the field physics and many other commercial industries the semiconductor laser is dominant in it's applicability. CD players, laser printers, telecommunications systems, LIDAR, and equipment such as welders and CNC cutters are among many commercial applications of the semiconductor laser.

In the field of physics, the semiconductor laser (and adjacent) continues to be an active area of research. Research has been focused on increasing peak output power at various wavelengths [1], creating devices with hard to achieve emission wavelengths [2], fabrication techniques [3] [4], and improving quantum efficiency [5] among many other topics. Adjacent research involves monolithically/heterogenously integrating lasers and other semiconductor devices such as Superluminescent Light Emitting Diodes (SLEDs) for commercial application in virtual reality displays, gas sensing, and high resolution projectors [6]. Proposed and custom fabricated devices/designs are characterised to evaluate device performance, while those that have been commercialised and individually packaged are required to be characterised to verify correct operation before shipping to the consumer.

1.2 Fundamentals

Material and Device Structure

Typically III-V materials such as GaAs, InGaAs, InP (and so on) are employed in the material structure of multi-layer semiconductor lasers. Two primary categories of semiconductor laser diodes are edge-emitting and top-emitting devices, and their distinct characteristics arise from the fabrication techniques employed. Semiconductor devices are created by depositing multiple layers of semiconductor alloys on a crystalline substrate using epitaxial growth techniques such physical vapor deposition (PVD) or chemical vapor deposition (CVD) [7], resulting in semiconductor wafers. These wafers are later refined using lithographic methods to delineate the desired devices.

Basic Laser Operation

At a fundamental level a laser can be described as an optical resonator containing a gain medium [8]. Energy is introduced into the lasing material which is stored as atomic/molecular excitation. By externally pumping energy into the system it's internal energy is redistributed, a population inversion will take place in which more atoms will exist in higher energy states than in lower. At any time, an atom can spontaneously return to it's initial state, emitting a photon (spontaneous emission). An incident photon can also cause an excited atom to transition back to the lower energy state, emitting a photon (stimulated emission). Laser light that has already been emitted circulates between mirrors on either end of the laser cavity, with a fraction of the light escaping through one, and the reflected further stimulating the gain material. Given enough energy input, the result is an intense beam of highly monochromatic radiation [7] [8].

In a semiconductor laser, a p-n junction is forward biased; electrons are injected into the p-side of the junction and holes are formed/injected on the n-side. The recombination of holes and electrons within the junction region results in recombination radiation (photon emission) with energy according to the material band-gap [7]. With a significant enough current density across the junction a population inversion will occur and lasing action commences once the optical gain exceeds loss in the junction layer (lasing threshold current is reached) [8].

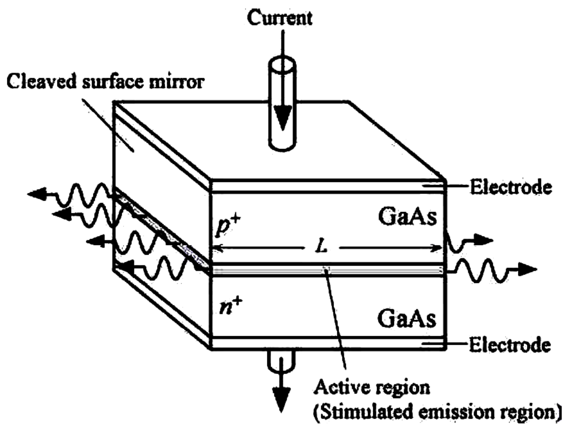


Figure 1.1: [9] Schematic illustration of a GaAs homojuntion laser diode. The cleaved surfaces act as reflecting mirrors.

Relevant Characteristics

The carrier rate equation (in the active region) is

$$\frac{dN}{dt} = \frac{\eta_i I}{qV} - \frac{N}{\tau} - v_g g N_p \tag{1.1}$$

where η_i is internal quantum efficiency, I is current, V is active region volume, N and $N_p h$ are the carrier and photon densities, g is the gain per unit length, v_g is the group velocity, and τ is the carrier lifetime [7].

The relationship between optical power and current is linear above lasing threshold and the output power is orders of magnitude greater. At this point the system described previously is effectively in a steady state and the carrier density $N(I) = N_{th} \ \forall \ I > I_{th}$. The threshold modal gain is defined as

$$\Gamma g_{th} = \langle \alpha_i \rangle + \alpha_m \tag{1.2}$$

where α_m is mirror loss, $\langle \alpha_i \rangle$ is the internal modal loss and Γ is the modal confinement factor [7]. In [9] Kasap determines from the carrier rate equations that

$$I_{th} = \frac{N_{th} eLWd}{\tau_r} \tag{1.3}$$

where τ_r is the average time for spontaneous radiative recombination, L, W, and d are the device active region length, width, and thickness respectively ($LWd = V$), N_{th} is the related threshold electron concentration, and e is electron charge ($q = e$). Eq 1.3 shows the lasing threshold is directly proportional to the volume of the active region.

Substitution of Eq 1.3 into 1.1 and assuming steady state ($I > I_{th}$), it follows that

$$\frac{dN}{dt} = \frac{\eta_i(I - I_{th})}{qV} - v_g g N_p = 0$$
$$\implies N_p = \frac{\eta_i(I - I_{th})}{q v_g g_{th} V}$$

One can construct the optical power output by recognising that $N_p h\nu V_p = E_{os}$ is the energy loss from the mirrors (V_p is cavity/resonator volume) and the rate at which it occurs is $v_g \alpha_m$ [7]. Using $\Gamma = V/V_p$, the resulting power is

$$\begin{aligned} P_0 &= v_g \alpha_m N_p h\nu V_p \\ &= \eta_i \left(\frac{\alpha_m}{\langle \alpha_i \rangle + \alpha_m} \right) \frac{h\nu}{q}(I - I_{th}) \\ &= \eta_d \frac{h\nu}{q}(I - I_{th}). \qquad (I > I_{th}) \end{aligned}$$

The quantity η_d is the differential quantum efficiency. It represents *"the number of photons out per electrons in"*[7] and can be determined experimentally by measuring the slope $\Delta P_0/\Delta I$ **[W/A]** and multiplying correspondingly by $q/h\nu$ **[C/J]** to empirically get a ratio of photons per electron.

$$\eta_d = \frac{q}{h\nu}\frac{dP_0}{dt} \tag{1.4}$$

Experimental Methods

This section details the methods and utilised apparatus to demonstrate the discussed characteristics of a semiconductor laser diode.

Apparatus

The laser diode used throughout is ADL-65055TL AlGaInP Visible Laser Diode (Laser Components). A THORLABS TED200C Temperature Controller was used to manage and control the operating temperature of the device. Also utilised was a Model 505 Laser Diode Driver, THORLABS LDM56/M mount for lasers, a THORLABS DET10A/M Si Biased Detector for measuring optical power, a multimeter, and a THORLABS DCC1545M CMOS camera to image the operating mode(s) of the laser.

Laser Safety

The minimum safe operating distance of the diode laser can be calculated using the 'Nominal Ocular Hazard Distance' (NOHD) formula [10]:

$$NOHD = 2\sqrt{\frac{P}{MPE\pi\theta_1\theta_2}}$$

where MPE is Maximum Permissible Exposure, θ is beam divergence and P is optical power. For general lab use we will assume a blink-reflex accidental exposure time of 0.25s. According to [11], the MPE of a 650nm laser is

$$\begin{aligned} MPE &= 18t^{0.75} Jm^{-2} \\ &= 18(0.25)^{0.75} Jm^{-2} \\ &= 6.3639 Jm^{-2} \\ &\equiv 25.45 Wm^{-2} \end{aligned}$$

According to [12], the minimum perpendicular and parallel divergence angles of the laser diode are

$$\begin{aligned} \theta_{\|} &= \theta_1 = 6° \equiv 0.1047 rad \\ \theta_{\perp} &= \theta_2 = 25° \equiv 0.4363 rad \end{aligned}$$

We consider the minimum divergences as to maximise the potential optical power density. $P = 7mW$ is the absolute maximum power the ADL-65055TL is capable of [12]. Therefore, we can conclude

$$NOHD = 2\sqrt{\frac{7mW}{25.45[Wm^{-2}]\pi(0.1047)(0.4363)}} = 8.8cm$$

It was ensured that a distance of 8.8cm was maintained between the laser and our eyes at all times.

2.1 Laser Threshold Current and Differential Quantum Efficiency

Setup/Procedure

The experiment was setup as shown in Fig 2.2. The procedure was followed verbatim to [13], where by the temperature controller was first turned on and set to 20°. The power supply for the equipment in Fig 2.2 was turned on and the current set to zero on the laser power supply. A LabView program designed to record the output power versus current (LI) curves was utlised. The program was run for laser operating temperatures between 10°C and 40°C.

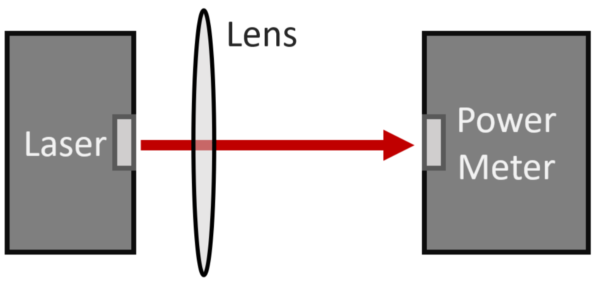


Figure 2.2: Experimental setup for optical power measurement (LI) and determination of laser threshold current (simplified schematic). The laser is mounted on a system (LDM56) with a heatsink and thermo-electric (Peltier) based cooling setup which is controlled by the Temperature Controller. As the laser is turned on, its output beam is focused onto a silicon detector (DET10A) using a plano-convex lens and translation stage.

Analysis

The silicon detector acts a power meter, The laser output power is calculated using the detector responsivity $R(\lambda)$ and the current I_0 delivered by the photodiode. The value of this current is determined by passing photodiode output through a low impedance load, 50Ω [13].

$$P_{in} = \frac{1}{R(\lambda)}\frac{I_0}{2} = \frac{1}{R(\lambda)}\frac{V_0}{(2)(50\Omega)} \tag{2.5}$$

The responsivity of the detector at 650nm is approximately $R(650nm) \approx 0.4$ [13] [14]. We can determine the slope of the resulting data and thus the differential quantum efficiency using Eq 1.4 as discussed previously and recognising that $\frac{hc}{\lambda}$ is the material band gap;

$$\begin{aligned}\eta_d &= \frac{q}{h\nu}\frac{dP_0}{dt}\\ &\equiv \frac{e\lambda}{hc}\frac{\Delta P_0}{\Delta t}\end{aligned}$$

2.2 Semiconductor Laser Transverse Patterns

Setup/Procedure

The experiment was setup as shown in Fig 2.3. The Thorlabs CMOS camera with its software is used to image the output of the laser facet. The focusing lens in front of the laser is positioned at a distance approximately equal to its focal length. At an operating temperature of 20°C, the current was set to a value slightly larger than its threshold current operation. It was ensured that the incident power at a fine focus did not over-saturate the CMOS sensor. Multiple images were saved using the camera software.

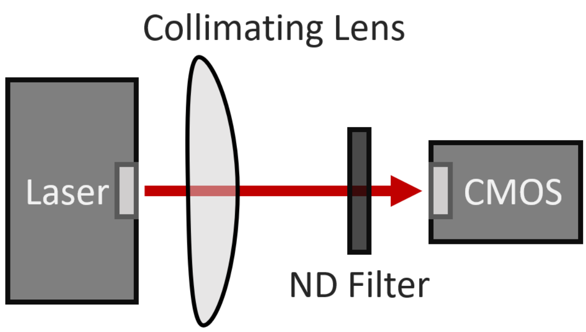


Figure 2.3: Experimental setup used to examine the laser facet. Lens in front of the laser is positioned at a distance approximately equal to its focal length. The laser facet is reimaged on the CMOS detector matrix with some magnification given by the specific lens used. ND = Neutral Density, CMOS = Complementary Metal-Oxide Semiconductor

Analysis

The image of laser facet (mode) at some value above threshold was exported in jpeg format. The expected transverse profile is expected to be Gaussian [13] in the horizontal and vertical, as such the function

$$y(x) = y_0 + Ae^{-\frac{(x-x_c)^2}{2w^2}}$$

was fit to the grey scale data at the midpoint of the determined mode for both horizontal and vertical data in Origin using the 'Convert to grey + data' function. From this the width of the beam can be determined - and as such the physical beam size as the sensor dimensions is known.

Results

The following sub-sections compile and analyse the relevant data obtained by the procedures and methods outlined.

3.1 Laser Threshold Current and Differential Quantum Efficiency

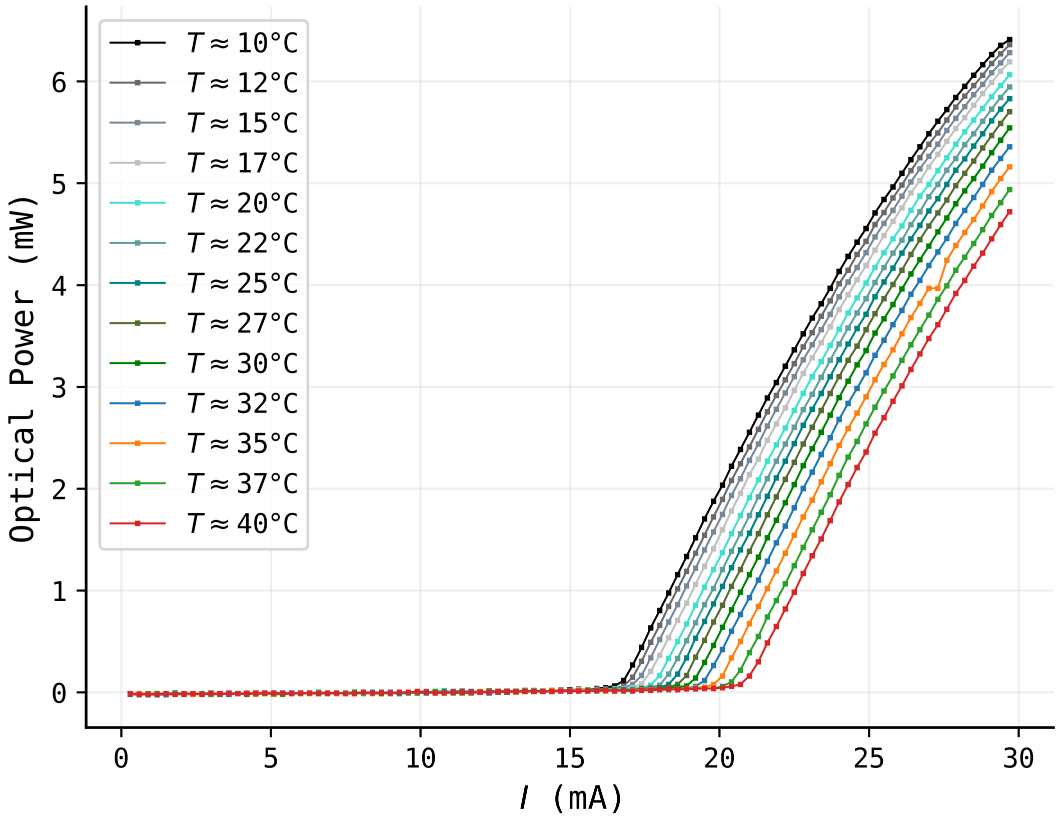


Figure 3.4: LI curves of ADL-65055TL at varying controlled operating temperatures. As the laser is turned on, its output beam is focused onto a silicon detector (DET10A) using a plano-convex lens, the voltage from the photodiode/detector has been transformed using $P_{in} = \frac{1}{R(\lambda)} \frac{V_0}{(2)(50\Omega)}$ [13] to obtain measurements in mW. The LI curves are typical as per the discussion in section 1.2. The temperature of operation as set by the temperature controller has a significant effect on the lasing threshold. This is investigated and discussed further in Fig 3.5.

Temperature Dependence of I_{th}

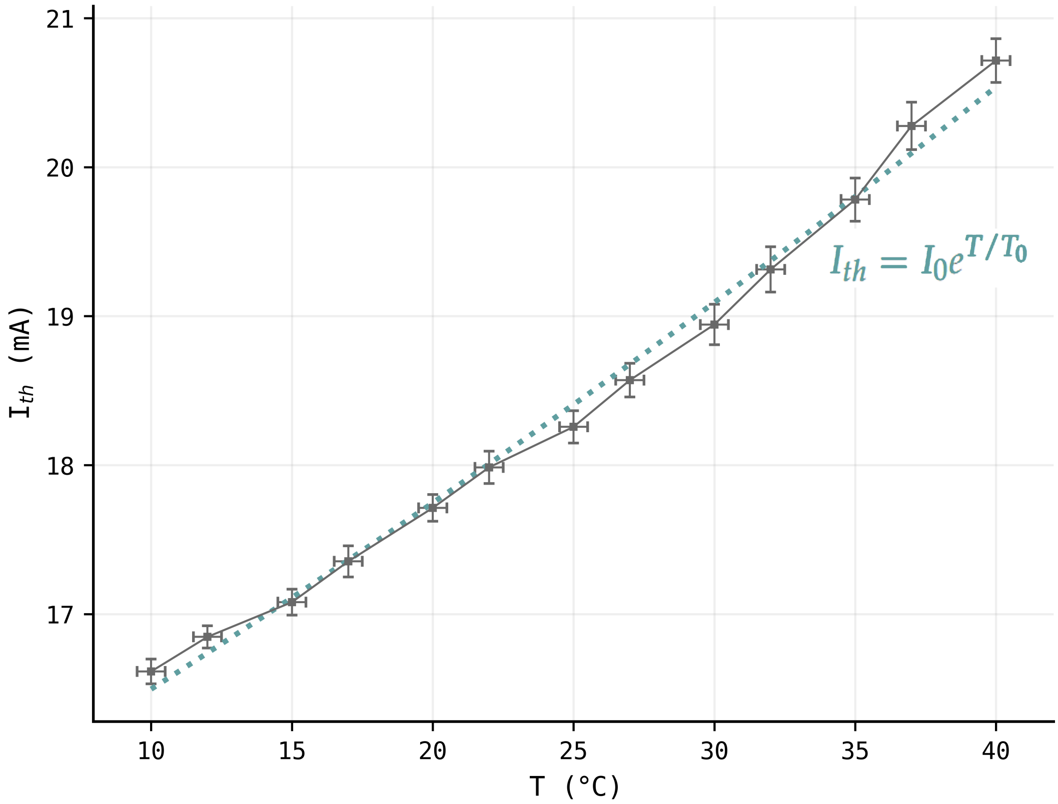


Figure 3.5: Threshold currents I_{th} as determined from LI curves of ADL-65055TL at varying controlled operating temperatures as determined in Fig 3.4. The temperature of operation as set by the temperature controller has a significant effect on the lasing threshold, the relationship appears to be approximately linear, but in actuality the relationship is governed by Eq 3.6 with determined fit parameters ($I_0 = 15.334[mA]$ $\frac{1}{T_0} = 0.0073[K^{-1}]$).

A linear fit to the data in Fig 3.5 gave a proportionality constant of 0.1634 mA/K, which is in this case an effective but incorrect rule. [15] cites two main contributors to have an effect on the crystal band structure of the laser: *"thermal lattice expansion, associated with the dependence of the carrier energy levels on the unit cell volume, and electron-phonon interaction"* with reference to [16], [17]. Eq 1.3 (See section 1.2) showed that $I_{th} \propto V$ the volume of active region. It would be naive to assume this effect is linear, in fact [7] suggests from observation that the effect can be modelled by

$$I_{th} = I_0 e^{T/T_0} \tag{3.6}$$

where T_0 is some characteristic temperature. The fit shown in Fig 3.5 resulted in parameters

$$I_0 = 15.334[mA] \qquad \frac{1}{T_0} = 0.0073[K^{-1}]$$

which implies a characteristic temperature of

$$T_0 = 136.98K \tag{3.7}$$

This result (Eq 3.7) seems physical as typical values for the characteristic temperature of a semiconductor laser diode are between 60 to 150K [18].

Differential Quantum Efficiency

Using a Python script A.1, the differential quantum efficiency was found by extrapolating slope features for $I_{th} > I$ for data shown in Fig 3.4. The resulting data has $\frac{d\eta_d(T)}{dT} \ll \Delta\eta_d(t)$ and as a result it is best visualised when tabulated. See Tab 3.1.

T (°C)	η_d(T)
10 ±0.5	0.3051 ±0.0254
12 ±0.5	0.3037 ±0.0226
15 ±0.5	0.3018 ±0.0262
17 ±0.5	0.3029 ±0.0317
20 ±0.5	0.3027 ±0.0271
22 ±0.5	0.3007 ±0.0326
25 ±0.5	0.2996 ±0.0324
27 ±0.5	0.2995 ±0.0337
30 ±0.5	0.2985 ±0.0405
32 ±0.5	0.2965 ±0.0451
35 ±0.5	0.2972 ±0.0431
37 ±0.5	0.2961 ±0.0473
40 ±0.5	0.2944 ±0.0431

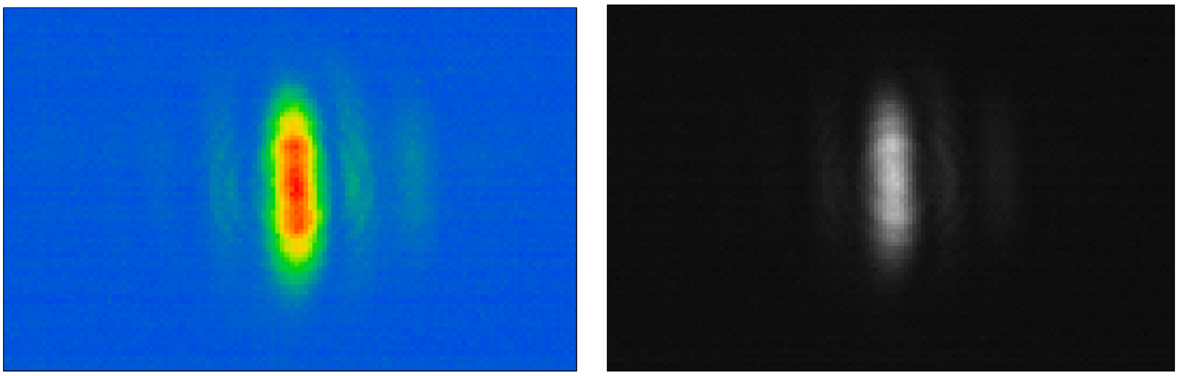
Table 3.1: Differential Quantum Efficiency η_d as a function of T. Using a Python script A.1, the differential quantum efficiency was found by extrapolating slope features for $I_t h > I$ for data shown in Fig 3.4. There is a visible trend of reducing efficiency as T increases.

From Tab 3.1 there is a visible trend of reducing efficiency as T increases. However, even though a trend can be identified it is clear that $\frac{d\eta_d(T)}{dT} \ll 1 \;\forall\; T \in [10°C, 40°C]$ (DQE is effectively the same for this diode in the determined region). As such it reasonable to take an average of the determined values with an uncertainty $\Delta\eta_d$ corresponding to the standard deviation of the determined η_d's in Tab 3.1 (this was also done in the Python script A.1). The determined differential quantum efficiency is

$$\boxed{\eta_d(10°C < T < 40°C) = 0.2998 \pm 0.0031}$$

The Python scripts utilised throughout this section, with relevant output, figures, and justification/explanation of error analysis, are available to view in Appendix A.

3.2 Semiconductor Laser Transverse Patterns



(a) pseudo-rainbow CMOS mapping.

(b) Grey-scale CMOS mapping.

Figure 3.6: Captured images of the laser facet / mode operating at 25°C. An interference pattern is visible along the horizontal, potentially due to diffraction at a wave guide boundary / facet, however the manual mentions interference patterns in the x-direction allegedly due to the optical filter used to reduce the laser power. There is also a localised circular interference pattern which is due to the filter (these were static when adjusting the translation stage - the interference pattern along the horizontal was not). This will be discussed further later.

Horizontal Mode Profile

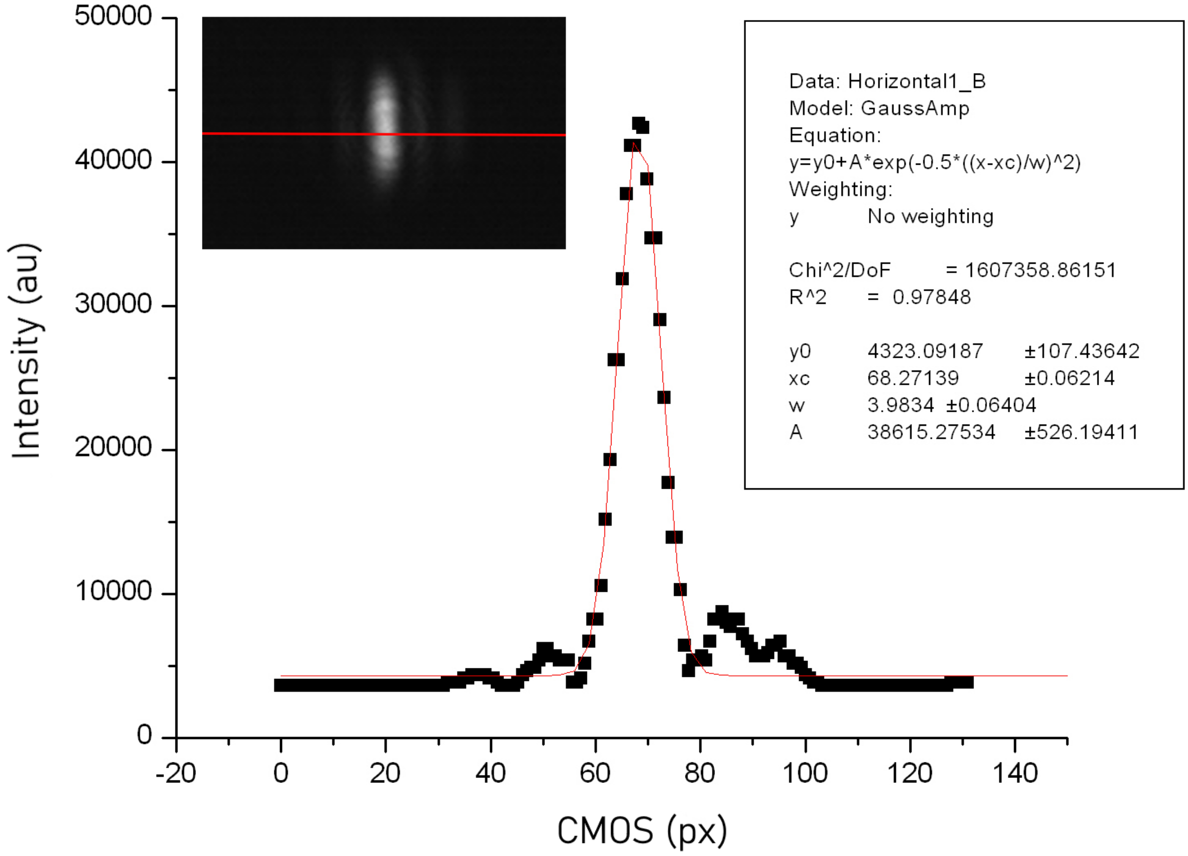


Figure 3.7: Horizontal mode profile of Fig 3.6 **(b)**. Determined Gaussian Width $w = 3.9834 \pm 0.064$. This better visualises the argument of diffraction pattern mentioned previous, which evidently has the form of a $sinc(x)$ function (characteristic of single slit diffraction [19]).

Vertical Mode Profile

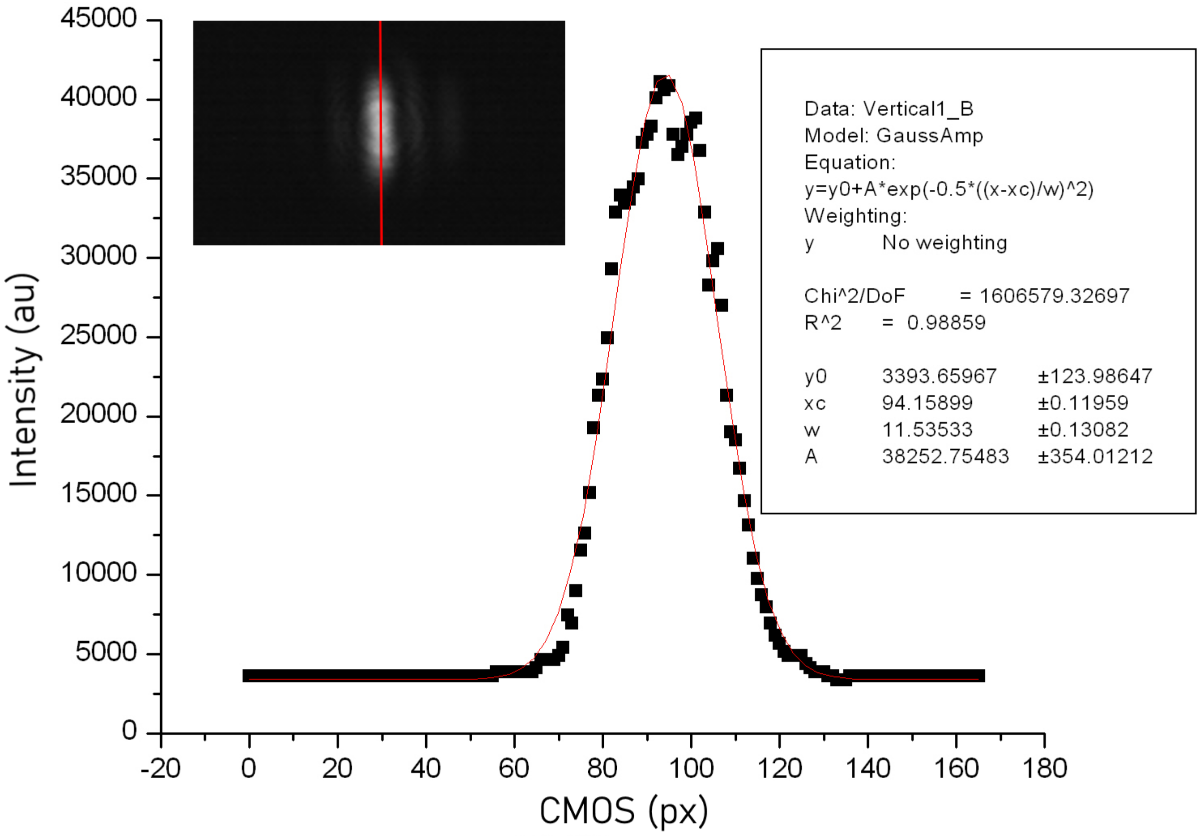


Figure 3.8: Vertical mode profile of Fig 3.6 **(b)**. Determined Gaussian Width $w = 11.5353 \pm 0.1308$.

w_H **(px)**	w_V **(px)**
3.9834 ±0.064	11.5353 ±0.1308

Table 3.2: Determined Gaussian FWHM from horizontal and vertical fitted profiles in Fig 3.7, 3.8.

The individual pixel size of the DCC1545M CMOS camera corresponds to [20]

$$1px \equiv 5.2\mu m \tag{3.8}$$

Assuming that there is no magnification (this was **not** provided, but mentioned and referenced in [13]) the resulting beam dimensions are

w_H **(µm)**	w_V **(µm)**
20.714 ±0.333	59.9836 ±0.6802

Table 3.3: Determined beam dimensions based on facet image, fitted Gaussian parameters and CMOS sensor size.

Discussion

From Fig 3.4, the laser appears to be in working order. A temperature dependence trend can be observed and is further visualised in Fig 3.5. Fitting an exponential relation according to 3.6 [7] found a characteristic temperature of $T_0 = 136.98K$ for the laser. This result (Eq 3.7) seems physical as typical values for the characteristic temperature of a semiconductor laser diode are between 60 to 150K [18].

[15] cites two main contributors to have an effect on the crystal band structure of semiconductor lasers: *"thermal lattice expansion, associated with the dependence of the carrier energy levels on the unit cell volume, and electron-phonon interaction"* with reference to [16], [17]. This can be seen from the data in Fig 3.6, whereby a combination of the discussion in [15] (temperature causing deformations of the laser cavity), and the derived relation in Eq 1.3, the aforementioned volume deformation directly impacts the threshold current.

Since η_d is inversly proportional to the material band gap (as demonstrated in section 1.2), one would expect the differential efficiency to drop with temperature analogous to the above discussion. This was precisely the case, as demonstarted in Tab 3.1.

We determined that $\eta_d(10°C < T < 40°C) = 0.2998 \pm 0.0031$. [12] states that the 'differential efficiency' in [mW/mA] is typically $\eta = 0.7$. If we negate our applied factor $(q/h\nu)$ to return to units of [mW/mA] we get an efficiency of ≈ 0.6 [mW/mA], in line with the spec sheet.

The result for the beam size in Tab 3.3 are questionable due to an ambiguous setup. Wave guide dimensions in semi-conductor lasers are typically on the order of 10^0µm. Of course, this doesn't necessarily mean that the beam is confined strictly to a wave guide core. The large determined beam dimension may be due to the absence of a magnifying factor. The magnification of the lens setup was **not** provided, but mentioned and referenced in [13].

The interference pattern in Fig 3.6, 3.7 is highly comparable to that of a $sinc(x)$ function, the characteristic intensity distribution of single slit diffraction [19]. The main contributor to this observation is the fact that the minimum points of intensity are **not** centered between maxima, and that the adjacent peaks from centre are much less intense than the centre. The observed distribution is symmetrical and the peaks are space uniformly˜17px apart. This interference pattern was not static, and could be observed at any point on the sensor, unlike the mentioned localised circular interference patterns which were static and clearly a characteristic of the ND filter.

Let's say hypothetically that there is no magnification and the interference observed is a result of diffraction. We know that the distance from lens to facet is 4mm [13]. In PY3101 (Optics) we numerically solved $\frac{dsinc(\beta)}{d\beta} = 0$ (where $\beta = \frac{\pi W}{\lambda} sin(\theta)$, W is diffracting aperture size, and θ is an incident angle from diffracting aperture) to find the positions of maximum intensity projected on a wall. The first maximum was located at $\beta \approx 4.4934$. We know from Fig 3.7 that this corresponds to a distance of 17px from the centre. In this case one could say

$$\begin{aligned} \theta &= tan^{-1}\frac{17 \times 5.2\text{µ}m}{4mm} = 0.022 \\ \beta &= \frac{\pi W}{\lambda} sin(\theta) \\ 4.4934 &\approx \frac{\pi W}{650nm} sin(0.022) \\ \implies W &\approx \frac{(4.4934)(640nm)}{\pi(0.022)} = 42\text{µ}m \end{aligned}$$

Where W is now representative of some diffracting aperture such as a waveguide, or the cavity of the laser, though it would be more likely to be due to something integrated within the TO-can at the 10^1µm scale.

Conclusion

A laser diode is characterised. LI curves of the diode at varying controlled operating temperatures are determined and analysed. The temperature of operation as set by the temperature controller has a significant effect on lasing threshold. The relation $I_{th} = I_0 e^{T/T_0}$ is used to determine a characteristic temperature for the diode, the value of which is in line with expectations according to common source. The differential quantum efficiency η_d is extrapolated from experimental data at various operating temperatures and is found to trend towards inefficiency as T increases. Determined differential efficiency, η, matches the expected to a reasonable degree according to the laser diode specification sheet. A CMOS camera is used to image the laser facet at 25°C. Beam dimensions are determined to be at a 10^1µm scale with some skepticism. A convincing single-slit diffraction pattern is observed and a hypothetical argument is made for a diffracting aperture which may correspond to a physical device parameter.

References

[1] L. Hua, B. Zhuang, Y. Zhang, J. Tian, P. Zhang, Y. Song, *Optimization of the output performance of optically pumped semiconductor disk lasers*, Optics & Laser Technology, Volume 150, 2022, 107971, ISSN 0030-3992,

[2] Y. Zhang, R. Wang, Y. Zhou, S. Cao, D. Lu, H. Xu, W. Han, J. Liu, *Diode-pumped Dy3+, Tb3+:LuLiF4 continuous-wave and passively Q-switched yellow lasers*, Optics Communications, Volume 510, 2022, 127917, ISSN 0030-4018.

[3] Hurtado, A., Jevtics, D., Guilhabert, B., Gao, Q., Tan, H.H., Jagadish, C. and Dawson, M.D. (2018), *Transfer printing of semiconductor nanowire lasers.* IET Optoelectron., 12: 30-35. https://doi.org/10.1049/iet-opt.2017.0105

[4] Piotr J. Cegielski, Anna Lena Giesecke, Stefanie Neutzner, Caroline Porschatis, Marina Gandini, Daniel Schall, Carlo A. R. Perini, Jens Bolten, Stephan Suckow, Satender Kataria, Bartos Chmielak, Thorsten Wahlbrink, Annamaria Petrozza, Max C. Lemme, *Monolithically Integrated Perovskite Semiconductor Lasers on Silicon Photonic Chips by Scalable Top-Down Fabrication* Nano Letters 2018 18 (11), 6915-6923 DOI: 10.1021/acs.nanolett.8b02811

[5] Ryvkin, B. S., and E. A. Avrutin. *Improvement of differential quantum efficiency and power output by waveguide asymmetry in separate-confinement-structure diode lasers.* IEE Proceedings-Optoelectronics 151.4 (2004): 232-236.

[6] R. Cahill, P. P. Maaskant, M. Akhter, B. Corbett, *High power surface emitting InGaN superluminescent light-emitting diodes.* Appl. Phys. Lett. 21 October 2019; 115 (17): 171102. https://doi.org/10.1063/1.5118953

[7] Larry A. Coldren, Scott W. Corzine, Milan L. Mašanović, *Diode Lasers and Photonic Integrated Circuits*, John Wiley & Sons, DOI:10.1002/9781118148167, ISBN:9780470484128

[8] G. R. Fowles, *Introduction to Modern Optics,* 2nd Edition, Dover Publications, Inc., New York, 1989

[9] S. O. Kasap *Optoelectronics and Photonics: Principles and Practices*, Prentice Hall, 2001

[10] University College Cork Laser Safety Guidelines and supplementary course notes (2022)

[11] University College Cork Laser Safety Tables (v5), *"Annexes to course on; Lasers and Laser Safety"*

[12] ADL-65055TL Specification Sheet, *Arima Lasers*, *Laser Components*

[13] PY4113 Laser Characterisation Guidelines, School of Physics, University College Cork

[14] DET10A Si Detector, Operating Manual, THORLABS

[15] S. Vlasova, A. Vlasov, K. Alloyarov, T. Volkova *Investigation of temperature dependence of radiation from semiconductor lasers and light emitting diodes*, **S Vlasova et al 2020 IOP Conf. Ser.: Earth Environ. Sci. 539 012137**

[16] Zubkova S et al 2003 *The temperature dependence of the band structure of polytypes 3C, 2H, 4H, and 6H silicon carbide*, **Fizika i tehnika poluprovodnikov 37 257**

[17] Vainshtein I et al 1999 *The applicability of the empirical Varshni relation for the temperature dependence of the band gap*, **Fizika tverdogo tela 41 994**

[18] T. Hertsens, *An Overview of Laser Diode Characteristics, Measuring Diode Laser Characteristics*, **ILX Lightwave Corporation/Newport Corporation** [Pg 1]

[19] Q. Luo, Z. Wang and J. Han"*A Padé approximant approach to two kinds of transcendental equations with applications in physics*", Eur. J. Phys. 36 (2015) 035030 (14pp) [FIGURE 1]

[20] DCx Camera Functional Description and SDK Manual, **THORLABS**

Appendix A

Source code

A.1 Determination of I_{th} and Differential Quantum Efficiency Extrapolation

Output of script is 2 tables, tab delimited. The first table has columns of:

$$\text{T} \mid I_{th} \mid \Delta I_{th} \mid \Delta T \mid \eta \text{ (no applied factor)}$$

I_{th} is determined from where the returned polynomial has a value of 0. ΔI_{th} is determined from a covariance matrix as follows (ae^{xb} is function for A.2),

fitting $y = ae^{xb}$

Returned by polyfit() for a polynomial of degree 1:

$\bar{a}, \bar{b}, M_{cov}$

where $M_{cov} = \begin{bmatrix} \sigma_{aa} & \sigma_{ab} \\ \sigma_{ba} & \sigma_{bb} \end{bmatrix}$

We want $b = \bar{b} \pm \sigma_b$

→ Degree 1 variance ${\sigma_b}^2 = \begin{bmatrix} 0 \\ 1 \end{bmatrix}^T \begin{bmatrix} \sigma_{aa} & \sigma_{ab} \\ \sigma_{ba} & \sigma_{bb} \end{bmatrix} \begin{bmatrix} 0 \\ 1 \end{bmatrix} = \sigma_{bb}$

→ $\sigma_b = \sqrt{\sigma_{bb}}$

The second table contains relevant η_d data tab delimited to be exported.

[9]:
```
from glob import glob
import numpy as np
import matplotlib.pyplot as plt
import os
from pylab import *
import sys
import tkinter
from tkinter import filedialog
```

```
index = 0
peaks = []
data = []
legend = []
h = 6.62607015e-34 #planck
c = 2.99792458e8 #speed of light
e_l = 1.60217663e-19 #electron
k = 1.380649e-23 #boltzmann
J_eV = 1/(6.242e18) #Joules / eV
i = 0

#FORMAT:
#   X | Y | Y_MAX | Y_MIN

PLOT_LIMIT = []
Y_LIMIT = [] # enforced only for log plots [lower, upper] - leave blank␣
 ↪for auto
FIT_RANGE = [17, 22]
ERROR_BARS = False
colours = [ 'black','dimgrey','lightslategrey' ,'silver','turquoise',␣
 ↪'cadetblue', 'teal','darkolivegreen','green']

def plot_graph(x, y): #create a single plot
    if(ERROR_BARS == True):
        plt.errorbar(x, y, yerr=y_err, linewidth = 0.75, color =␣
 ↪'dimgrey', capsize = 3, marker = 's', markersize = 3,␣
 ↪markerfacecolor='dimgrey')
    else:
        if(i>=len(colours)):
            plt.plot(x, y, linewidth = 0.75, marker = 's', markersize =␣
 ↪1, markerfacecolor='dimgrey')
        else:
            plt.plot(x, y, linewidth = 0.75, marker = 's', color =␣
 ↪colours[i], markersize = 1, markerfacecolor='dimgrey')
    legend.append(r"$T\approx$"+"{}".format(str(float(file[56:
 ↪58]))+r"$\degree{}$C"))
    plt.grid(True, alpha=0.2)

# FILE_PATH -----------------------------------------------------

path = 'Z:\A_PY4113\Laser Characterisation\LabVIEW Data - Copy'

# ---------------------------------------------------------------

os.chdir(path)
All_files = glob('*.dat')
```

```
print(All_files)
plt.figure(facecolor='white')
fig, ax = plt.subplots()
i = 0

I = []
T = []
n_d = []
n_d_err = []
np.array(I)
np.array(T)
np.array(n_d)
np.array(n_d_err)

for file in All_files:
    file_path =f"{path}/{file}"
    file = os.path.splitext(file_path)[0]
    #print(file_path)
    rc('axes', linewidth=1)
    plt.rcParams["font.weight"] = "normal"
    plt.rcParams["axes.labelweight"] = "normal"
    plt.rcParams["font.family"] = "monospace"

    f = open(file_path)
    labels = f.readlines()[:1]
    close(file_path)

    f = open(file_path)
    lines = f.readlines()[1:]
    close(file_path)

    label_x = labels[0].split()[0]
    label_y = labels[0].split()[1]
    x = [float(line.split()[0]) for line in lines]
    y = [float(line.split()[1]) for line in lines]



    # Y_DATA MANIPULATION --------------------------------------

    y = np.array(y)
    y = (1/(0.4))*y*(10*10)/100#y is volts
    x = np.array(x)

    try:
        indices = np.where((x >= FIT_RANGE[0]+i*0.4) & (x <=␣
 ↪FIT_RANGE[1]+i*0.4)) #extrapolate range for fitting
```

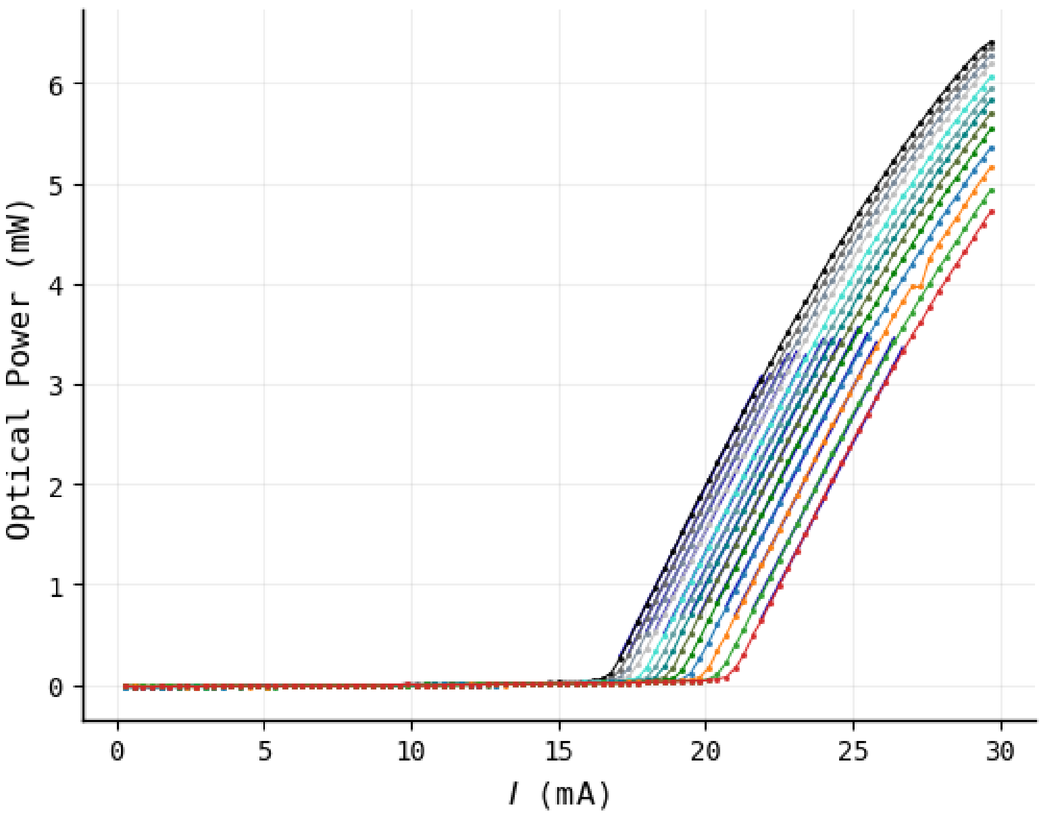
```
        if indices[0].size < 1:
            raise Exception("Failed to find indices in range provided")
    except Exception as err:
        print("ERROR [{}]".format(err))

    x_fit = x[indices]
    y_fit = y[indices]
    deg = 1
    p, cov = np.polyfit(x_fit, y_fit, deg, cov=True)
    a = p[deg]
    b = p[0]
    poly_error = sqrt(diag(cov)[1])

    x_fitted = np.linspace(np.min(x_fit), np.max(x_fit), 100)
    y_fitted = a+b*x_fitted

    I_th=-a/b
    #print("I_th = " + str(I_th))
    I.append(I_th)
    T.append(float(file[56:58]))
    n_d.append(b)
    n_d_err.append(sqrt(diag(cov)[1]))

    plt.plot(x_fitted, y_fitted, linewidth = 1, color = '#0c00b4ff')
    print("{}\t{}\t{}\t0.5\t{}".format(float(file[56:58]), float(I_th),␣
↪sqrt(diag(cov)[1])/b, b))

    #-----------------------------------------------------------


    if(ERROR_BARS == True):
        y_err_max = [float(line.split()[2]) for line in lines]
        y_err_min = [float(line.split()[3]) for line in lines]
        y_err_min = np.subtract(y, y_err_min)
        y_err_max = np.subtract(y_err_max, y)
        y_err = [y_err_min, y_err_max]
        print(y_err)

    plot_graph(x, y)
    i+=1

labels = np.array(labels)

#OVERRIDE LABELS
label_x = u'$I$ (mA)'
label_y = u'Optical Power (mW)'
plt.title(f"")
```

```
plt.xlabel(label_x, fontsize=12)
plt.ylabel(label_y,  fontsize=12)
plt.xticks(fontsize = 10)
plt.yticks(fontsize = 10)

#legend = ['405nm Laser Incicent', '532nm Laser Incident', 'White␣
 ↪Light']
#plt.legend(legend)

if(bool(Y_LIMIT) == True):
    plt.ylim(Y_LIMIT)
if(bool(PLOT_LIMIT) == True):
    plt.xlim(PLOT_LIMIT)

right_side = ax.spines["right"]
top_side = ax.spines["top"]
right_side.set_visible(False)
top_side.set_visible(False)

plt.savefig(f'{file}_figure_all.png', dpi = 1000, bbox_inches='tight')
plt.show()

print("n = ")
#print(650e-9*e_l*n_d/(h*c))
#print(" +- ")
#print(650e-9*e_l*n_d_err/(h*c))
n_d=650e-9*e_l*np.array(n_d)/(h*c)
n_d_err=650e-9*e_l*np.array(n_d_err)/(h*c)

i=0
print("T\tDT\tn\tn_err")
for i in range(len(n_d)):
    print("{}\t0.5\t{:.4f}\t{:.4f}".format(T[i], n_d[i], n_d_err[i]))
```

```
['T1056.dat', 'T1278.dat', 'T15.dat', 'T172.dat', 'T20.dat', 'T227.dat',
'T25.dat', 'T275.dat', 'T30.dat', 'T325.dat', 'T35.dat', 'T375.dat',␣
 ↪'T40.dat']
10.0    16.614693805930866      0.08326239145481205     0.5
0.5820057189542486
12.0    16.8469285563157        0.07433765996730071     0.5
0.5792075163398708
15.0    17.079948914431675      0.08686714977341647     0.5
0.5757352941176478
17.0    17.35354263894781       0.10457186303478681     0.5
0.5776960784313718
20.0    17.71263928685135       0.08936969600409554     0.5
0.5773897058823552
22.0    17.9847430464048        0.1082617305419179      0.5
```

```
0.5735089869281053
25.0     18.256638907752254      0.10817988394998097     0.5
0.5714665032679748
27.0     18.570264955125698      0.11240573608581603     0.5
0.5712214052287586
30.0     18.943502905933848      0.1358323115666559      0.5
0.5693218954248358
32.0     19.31370120255677       0.15209741722402373     0.5
0.5655841503267973
35.0     19.781972115142132      0.1451649702999859      0.5
0.5669321895424838
37.0     20.276715003797033      0.15957213757831898     0.5
0.5648080065359466
40.0     20.715449519930182      0.1464808243483368      0.5
0.5616013071895429
```

```
<Figure size 640x480 with 0 Axes>
```




```
n =
T        DT       n        n_err
10.0     0.5      0.3051   0.0254
12.0     0.5      0.3037   0.0226
15.0     0.5      0.3018   0.0262
17.0     0.5      0.3029   0.0317
```

```
20.0     0.5     0.3027  0.0271
22.0     0.5     0.3007  0.0326
25.0     0.5     0.2996  0.0324
27.0     0.5     0.2995  0.0337
30.0     0.5     0.2985  0.0405
32.0     0.5     0.2965  0.0451
35.0     0.5     0.2972  0.0431
37.0     0.5     0.2961  0.0473
40.0     0.5     0.2944  0.0431
```

[ ]:

```

```

A.2 Analysis and fitting of $I_{th}(T)$

This script determines T_0. Relevant output of script is the plotted figure and printed value of $b = \frac{1}{T_0}$.

[36]:

```
from glob import glob
import numpy as np
import matplotlib.pyplot as plt
import os
from pylab import *
import sys
import tkinter
from tkinter import filedialog

index = 0
peaks = []
data = []
h = 6.62607015e-34 #planck
c = 2.99792458e8 #speed of light
e = 1.60217663e-19 #electron
k = 1.380649e-23 #boltzmann
J_eV = 1/(6.242e18) #Joules / eV
i = 0

#FORMAT:
#   X | Y | X_DEV | Y_DEV

PLOT_LIMIT = []#400,800]
Y_LIMIT = [] # leave blank for auto
ERROR_BARS = True

def plot_graph(x, y): #create a single plot
    labels = []
    plt.figure()
    fig, ax = plt.subplots()
```

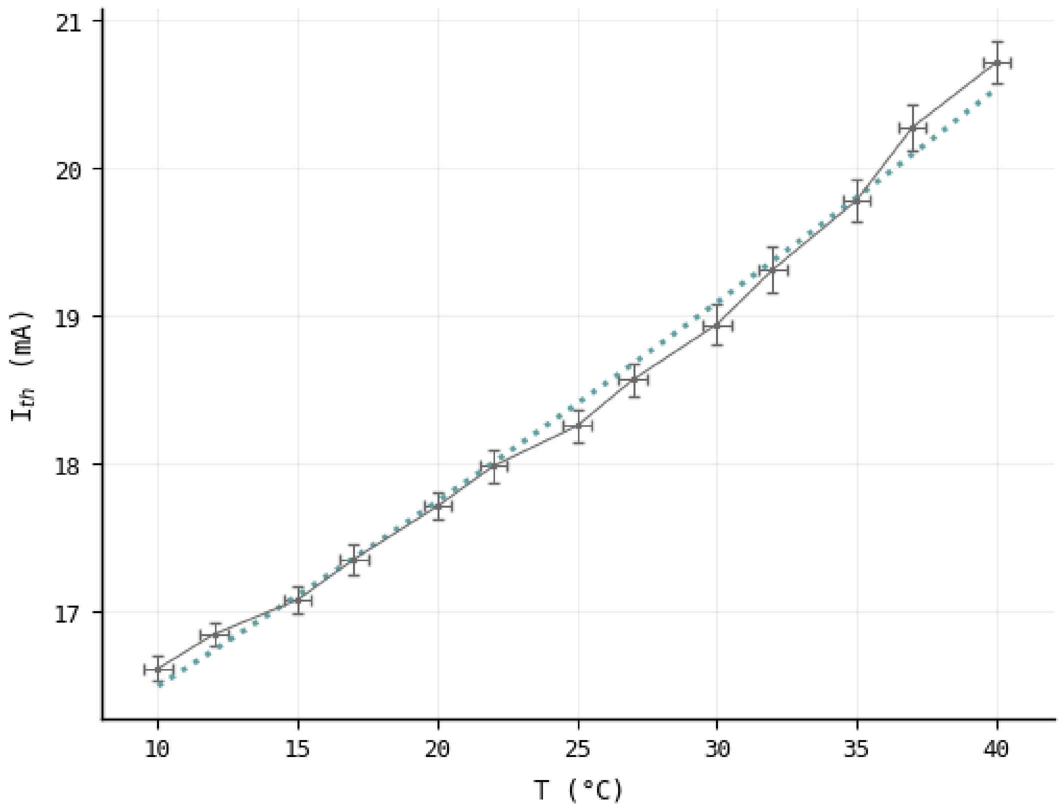
```
    plt.title(f"")
    plt.xlabel(label_x, fontsize=10)
    plt.ylabel(label_y,  fontsize=10)
    plt.xticks(fontsize = 9)
    plt.yticks(fontsize = 9)
    if(bool(Y_LIMIT) == True):
        plt.ylim(Y_LIMIT)
    if(bool(PLOT_LIMIT) == True):
        plt.xlim(PLOT_LIMIT)

    right_side = ax.spines["right"]
    top_side = ax.spines["top"]
    right_side.set_visible(False)
    top_side.set_visible(False)
    if(ERROR_BARS == True):
        plt.errorbar(x, y, xerr=x_err, yerr=y_err, linewidth = 0.75,␣
↪color = 'dimgrey', marker = 's', capsize = 2, markersize = 2,␣
↪markerfacecolor='dimgrey')
    else:
        plt.plot(x, y, linewidth = 0.75, color = 'dimgrey', marker =␣
↪'s', markersize = 1, markerfacecolor='dimgrey')

    plt.plot(x_fitted, y_fitted, linewidth = 2, color = 'cadetblue',␣
↪linestyle='dotted')

    plt.grid(True, alpha=0.2)
    labels = np.array(labels)
    plt.savefig(f'{file}_figure.png', dpi = 1000, bbox_inches='tight')
    plt.show()

file_path = filedialog.askopenfilename()
file = os.path.splitext(file_path)[0]
print(file_path)
rc('axes', linewidth=1)
plt.rcParams["font.weight"] = "normal"
plt.rcParams["axes.labelweight"] = "normal"
plt.rcParams["font.family"] = "monospace"

f = open(file_path)
labels = f.readlines()[:1]
close(file_path)

f = open(file_path)
lines = f.readlines()[1:]
close(file_path)

label_x = labels[0].split()[0]
```

```
label_y = labels[0].split()[1]

#OVERRIDE LABELS
label_y = u'I$_{th}$ (mA)'
label_x = u'T ($\degree{}$C)'

x = [float(line.split()[0]) for line in lines]
y = [float(line.split()[1]) for line in lines]
y = np.array(y)

# --------------------------------

n = [float(line.split()[4]) for line in lines]
n = np.array(n)

# deg = 1
# p, cov = np.polyfit(x, y, deg, cov=True)
# a = p[deg]
# b = p[0]
# x_fitted = np.linspace(np.min(x), np.max(x), 100)
# y_fitted = a+b*x_fitted
x_fit = x
y_fit = np.log(y)
deg = 1
p, cov = np.polyfit(x_fit, y_fit, deg, full=False, cov=True)
a = np.exp(p[deg])
b = p[0]
poly_error = sqrt(diag(cov)[1])
print(p)
print(cov)
print(poly_error)

x_fitted = np.linspace(np.min(x_fit), np.max(x_fit), 100)
y_fitted = a*np.exp(b*x_fitted)

print("a = " + str(a))
print("b = " + str(b))

print("n = ")
print(np.average(n))
print(" +- ")
print(np.std(n))

# --------------------------------

if(ERROR_BARS == True):
    y_err_max = [float(line.split()[2]) for line in lines]
```

```
    y_err_min = y_err_max
    x_err_max = [float(line.split()[3]) for line in lines]
    x_err_min = x_err_max
    #y_err_min = [float(line.split()[3]) for line in lines]
    #y_err_min = np.subtract(y, y_err_min)
    #y_err_max = np.subtract(y_err_max, y)
    y_err = [y_err_min, y_err_max]
    x_err = [x_err_min, x_err_max]
    # print("y_err = ")
    # print(y_err)

plot_graph(x, y)
```

```
Z:/A_PY4113/Laser Characterisation/IT.txt
[0.00730552 2.73008249]
[[ 3.42130029e-08 -8.47429764e-07]
 [-8.47429764e-07  2.39859468e-05]]
0.004897544977731765
a = 15.334151892070203
b = 0.007305521012120825
n =
0.5720368275515337
 +-
0.005977748865526748
```

```
<Figure size 640x480 with 0 Axes>
```



```
[ ]:
```