Laser Diode

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**Abstract:**

The aim of this experiment was to observe the basic electrical and beam properties of a red-emitting diode laser. The experiment looked at how the power output and wavelength of the laser was temperature dependent and that the output beam was highly divergent and elliptical in cross-section. The three different parts of this experiment looked at how changing the forward current affected the power output at constant temperature, analyzing how the temperature dependence affects the threshold current and measuring the beams cross-sectional power distribution.

The results seen from part A of the experiment showed that the threshold current at 20°C was 12.5 (± 20%) mA which corresponds to the HL63101MG/102MG AlGaLnP Laser Diode which states its threshold current to be a min of 15 mA which is within error expectations. As seen in the MATLAB outputs the slope efficiency was found to be 0.07, the wall plug efficiency was found to be 3.8, the external differential quantum efficiency was found to be 0.0363 and the number of laser photons produced by a single electron-hole pair was found to be 737.

The results seen in part B shows a clear similarity to the P-I characteristics of the laser diode shown in the data sheet and shows that the temperature dependance of AlGaLnP lasers to be fitted to . The efficiencies that were calculated in part A decrease when the laser is subjected to a higher operating temperature.

Lastly the results from part C show the elliptical cross-section of the beam and from the MATLAB figure show a larger power output in the center of the cross-section and decreases in a gaussian fashion which was expected as the laser has a single spatial mode.

1. Introduction

The aim of this report is to document the results and analysis of different interactions between a laser diode and a silicon photodiode detector under different conditions such as changes in operating temperature, position of the detector and the effect of laser divergence on the power output.

This experiment looks at the basic electrical and beam properties of a GaAlAs laser diode. The theory behind this experiment is to look at the temperature dependence and the optical properties of the beam such as its divergence and elliptical cross-section.

This is relevant as we can look at power optimization for industry such as laser cutting or welding as maintaining consistent beam quality and power output is crucial for achieving precise and efficient results. Temperature variation can affect the stability and reliability of the laser power by studying the temperature dependance of the laser can help build systems that can operate at higher operating temperatures.

1. Background Theory

Laser diodes are semiconductor devices that generate coherent light through the process of stimulated emission. They are widely used in various applications such as telecommunications, optical storage devices and medical equipment.

Diagram of a metal sheet with text

Description automatically generatedThe laser diode is made up of a p-n junction formed by doping semiconductor materials. When a forward bias voltage is applied across the junction electrons and holes are injected into the depleted region. As electrons recombine with the holes they release energy in the form of photos. This process stimulates further emission as photons interact with other excited electrons leading to an avalanche effect and the generation of coherent light [3].

Figure 1. Typical broad-area p-n homojunction laser [3].

A diagram of a graph

Description automatically generatedThreshold current is one of the characteristics of the operation of a laser diode. Below the threshold current, the emitted light is incoherent and lacks the properties of a laser beam. However, beyond the threshold current the intensity of the emitted light increases sharply indicating laser action [4].

Figure 2. Light output from a semiconductor laser diode with variation of injection current [4]

1. Experimental Method
   1. Part A

For the first part of the experiment investigating the Laser power output as a function of the forward current at a constant temperature the set up used was a laser diode incased in a metal block that was cooled by a Peltier cooler, a temperature sensor that measures the casing temperature and controls the set temperature at 20°C, a silicon photodiode detector that produces a reading of the laser power when connected to a the dc voltage range on the multimeter and was adjusted to have a sensitivity of 100mV/mW (± 20%) on the 1x setting and lastly the laser diode and detector were mounted on a adjusting mount so that individual vertical and horizontal values could be adjusted as well as the distance between them. For this experiment the horizontal distance from the laser diode to the detector was 2.9 ± 0.1 cm and the diode and detector were aligned vertically. The power output of the laser was recorded at increments of 2.5 mA from 0 to 25 for the forward current then the resulting power output in mV was converted to m W with the conversion of 100mV / mW.

* 1. Part B

For the second part of the experiment analyzing the temperature dependance of the threshold current, Ith the same apparatus was used in part A and instead of having the temperature controller set at 20°C it started at 15°C and incremented at 10°C until it reaches 45°C and the reading were taking from the same range of forward current and the power output was converted using the same conversion.

* 1. Part C

For the final part of the experiment measuring the beam spatial cross-sectional power distribution the same set up was used and a metal aperture was placed on top of the laser diode. Then using a piece of paper note how the beam diverges and measure the width. Then find the bound at which you can move the detector horizontally before it reaches the edge of the divergence. The power output of the laser was noted at 168 different positions of x and y where x was measured from 8 to 19 at 1 step increments and y was measured from 2 to 28 at 2 step increments as that was the bounds of the mount and the divergence pattern allowed for a larger range of y values to use.

1. Results, Analysis and Discussion
   1. Results and analysis for Part A

A graph of data and data

Description automatically generated with medium confidenceThe first part of this experiment was looking at the Laser power output as a function of the forward current at a constant temperature. The operation temperature was set to 20°C and the forward current was increased at intervals of 2.5 mA from the range of 0 to 25 mA. As seen in the P-I graph in figure 3 the threshold current is calculated to be 12.76 mA ± 20% which agrees with the data sheet value of 15 mA.

Figure 3. P-I graph for Part A showing the data, the fit and the threshold current. The error bars are fitted to 20% of the output power value.

The slope efficiency was calculated to be 0.07. The wall plug efficiency was calculated to be 3.89. The external differential quantum efficiency was calculated using the equation and the result was 0.0363.

Lastly to calculate the number of laser photons that are produced by on electron-hole pair was calculated using MATLAB the process was to calculate the energy of a single photon using then calculating the numbers of photons per second using the output power, conversion factor and the inverse of the photon energy, Then using the threshold current calculated in the first part of 12.76 mA the number of electrons flowing into the junction was calculated by dividing the threshold current by the charge of an electron. The number of laser photons produced by one electron-hole pair was calculated by dividing the number of photons per second by electrons per second which resulted in a laser photon number of 737.

The errors and uncertainties in this experiment come from a few different sources such as light interference from the labs lights, the detectors batteries having low charge and from slight misalignment of the laser and detector, these errors and uncertainties are incredibly low for example when taking a reading from the detector while it was covered by a cloak gave a reading of 0.1mV which would result in the error for the power output to be ± 0.00001mW which is negligible for this experiment. The main error comes from the detector circuit which was designed to produce a reading that is proportional to laser power when connected to the dc voltage range of the multimeter. It was adjusted to produce a sensitivity of 100mV/mW (± 20%) on the 1x setting this is where the majority of the error comes for this experiment as it heavily outweighs the other errors such as light interference therefore the error value for the power output is ± 20% of the value.

4.2 Results and analysis for Part B

Part B of this experiment was analysing the temperature dependence of the threshold current Ith. As seen in figure 4 the P-I graph shows a clear decrease in efficiency and increase in threshold current as the operating temperature increases and follows the empirical relation: . The threshold currents shown in figure 3 show a clear increase from 11.4 (± 20%) mA at 15°C to 31.7 (± 20%) mA at 45°C.

This happens due to several factors such as at higher temperatures the carrier density in the laser’s active region typically increases. This can lead to higher levels of non-radiative recombination processes, where electrons and holes combine without emitting any photons, which means more current is needed to achieve population inversion and stimulate laser emission.

A screen shot of a black screen

Description automatically generatedA graph of different colored lines

Description automatically generatedThis leads to the efficiencies that were calculated in Part A decreasing as the temperature increases, which can be seen as the gradient of each slope for the different operating temperatures decreases as the temperature increases in figure 2.

Figure 5. Console window of MATLAB showing the threshold current for each operating temperature.

Figure 4. P-I graph for Part C showing the different operating temperatures of the laser diode showing the increase in threshold current and decrease in power output efficiency. The error is ± 20% of the power output values.

Lastly looking at the theoretical plot of in figure 6 the increase in threshold current is clearly shown which also agrees with the data from part B. The slope of the graphs are influenced by the characteristics temperature and “good” lasers typically have a higher value of which indicates a weaker dependence of threshold current on temperature implying better temperature stability.

A graph with red lines and blue dots

Description automatically generated

Figure 6. Estimation plot of using the fit and the threshold current and temperatures used in part B. A clear increase in threshold current is observed along with the fitted curve.

* 1. Results and Analysis for Part C

For the final part of this experiment measuring the beam spatial cross-sectional power distribution by clipping an aperture to the photodetector and as seen in figure 7 the beams divergence and its elliptical cross-section can be seen on the piece of paper. This coincides with the laser having a single spatial mode as there is one central bright spot and the intensity diminishes in a gaussian fashion on either side of the central maximum this can be seen in figure 8 for the intensity profile that was measured, which can be compared to the schematic of a basic index guided diode laser mentioned in the lab script [1] as its aperture is 0.1µm in height and 3 µm in width which not only results in a single spatial mode as the aperture size is smaller than the wavelength of the light stated by the manufacturer [2] of 637 nm, but also explains the elliptical cross-section of the beam.

A screen shot of a graph

Description automatically generatedA red light on a square object

Description automatically generated

Figure 8. Intensity plot of the Power Output with x and y position showing a single maximum.

Figure 7. Laser beam diffraction pattern with clear elliptical cross-section.

A graph of a function

Description automatically generated with medium confidence

Figure 9. 3D Intensity plot showing the gaussian like decrease in output power as it moves away from the central maximum.

1. Discussion of Parts A, B and C
   1. Part A

For part A of this experiment where the Laser power output was plotted as a function of the forward current at a constant temperature it was found that the threshold current for this Laser was 12.76 (± 20%) mA which coincided with the manufacturers data sheet for the HL63101MG/102MG Laser Diode which had a threshold current of 15mA at 20°C. The main uncertainties for this part of the experiment were the photodetectors and the interference of outside light as since the temperature was close to room temperature this would not have affected the final result majorly.

* 1. Part B

For part B of this experiment where the temperature dependence of the threshold current was analyzed and it was found that as the temperature increases the threshold current of the laser is also increased and the efficiency of the laser is greatly decreased as seen in figure 4. This agrees with the theory as the change in threshold current follows the relation of which allows us to calculate the characteristic temperature of the system which was 24.8 K. The uncertainties for this part of the experiment are similar to part A where the error in the photodetector is the largest but the difference in temperature between the laser and the room temperature would have also led to an error in measuring the power output accurately. This allows us to understand more about improving the efficiency of the laser as it shows us that designing a laser with a higher characteristic temperature would lessen the dependence of the threshold current on it allowing for more efficient beams.

* 1. Part C

Lastly part C of this experiment looked at measuring the beam spatial cross-section power distribution, as seen in figure 5 the beams has a elliptical cross-section which agrees the data sheet that shows the schematic of a laser [1]. The power distribution follows the pattern of a laser with a single spatial mode as it has a central maximum and the power decreases in a gaussian fashion which also agrees with the data sheet as the aperture shown has an area less than the wavelength of the laser [1], this is more efficient for lasers as it allows for a more accurate and precise beam with having only one maximum fringe and not multiple. The errors in this part of the experiment are more similar to part A as the temperature of the system was constant at 20°C but the photodetector was moved horizontally and vertically which would have some human error in manually adjusting the position.

1. Conclusion

This experiment has shown the basic electrical and beam properties of the HL6310MG/102MG AlGaLnP laser diode. From the results of part A of this experiment the laser power output was observed as a function of the forward current at a constant temperature and the efficiency of the laser were calculated so that they could be compared to the results of part B. Part B looked at the temperature dependence of the threshold current and its effect on the lasers efficiency, the characteristic temperature was also calculated for this laser which affects the dependency of the temperature on the threshold current. Lastly part C looked at measuring the beam spatial cross-sectional power distribution which led to showing that the laser does has a single spatial mode and was elliptical in cross-section which is due to the nature of the aperture size for the laser structure. The power distribution followed the gaussian distribution as there was a single maximum and from there the intensity decreased moving away from this central point. This relates to improving laser efficiency as it gives a better understanding of the temperature dependence of the laser and the importance of having an optimal structure that leads to having a single spatial mode. Some limitations of this experiment were the equipment having quite a few technical difficulties leading to less data being acquired due to the laser being unable to reach close to its maximum power output which makes comparing the P-I graphs to the manufacturers data sheet a bit more difficult.

1. References
2. Heriot-Watt University physics department Diode Laser Lab script (2020)
3. Oclaro HL63101MG/102MG AIGaInP Laser Diode Data Sheet (2013)
4. Svelto, O. (2010). *Principles of Lasers.* Springer
5. Smith, G. F. (2007). *Optics & Photonics: An Introduction.* Publisher
6. Appendices

MATLAB code

clc;

clear;

clear all;

filename = 'LaserDiodeC.xlsx';

[z\_numeric, ~, ~,] = xlsread("LaserDiodeC.xlsx");

z = z\_numeric;

%A1 plot

% Define data

x = [0,2.5,5,7.5,10,12.5,15,17.5,20,22.5,25];

y = [0,0,0,0,0,0,0.4,0.7,1.1,1.3,1.8];

err = 0.2 \* ones(size(y));

% Plot the data

figure(1)

scatter(x, y, 100)

hold on

errorbar(x, y, err, 'LineWidth', 2)

% Fit a curve to the data

p = polyfit(x, y, 1);

xfit = linspace(0, 25, 100);

yfit = polyval(p, xfit);

plot(xfit, yfit, 'r--', 'LineWidth', 2)

% Find the threshold current (intersection with a certain power level)

threshold\_power = 0.5;

threshold\_current = (threshold\_power - p(2)) / p(1);

plot([threshold\_current, threshold\_current], [0, threshold\_power], 'k:', 'LineWidth', 2)

% Plot the value of the threshold current

text(threshold\_current, threshold\_power, sprintf('Threshold Current: %.2f mA', threshold\_current), 'HorizontalAlignment', 'left')

hold off

xlim([0, 30])

ylim([0, 2])

xlabel('Forward current, If (mA)')

ylabel('Optical Output Power Po (mW)')

legend('Data', 'Fit', 'Threshold', 'Location', 'NorthWest')

%A2 find slope

p = polyfit (x,y,1);

p

%A3

OpticalPower = 7;

ConsumedInputPower = 1.8;

WallPlugEfc = OpticalPower / ConsumedInputPower

%A4 exteneral differential quantum efficieny ([delP / delI) \* (qlam/he)]

q = 1.602\*10^-19;

lambda = 637\*10^-9; %from data sheet

h = 6.62\*10^-34; %plancks constant

c = 2.98\*10^8; %speed of light

ExteneralDifferentialQuantumEfficieny = p(1,1) \* ((q\*lambda)/(h\*c))

%A5 calculate no. of laser photons produced by one elctron-hole pair

% Constants

h = 6.626e-34; % Planck's constant (Joule second)

c = 3.0e8; % Speed of light (m/s)

q = 1.602e-19; % Elementary charge (Coulombs)

lambda = 637e-9; % Wavelength (m) - from datasheet

% Calculate the energy of a single photon

E\_photon = h \* c / lambda; % Energy of a single photon (Joules)

% Conversion factor from photodiode measurement (100mV/mW)

conversion\_factor = 100e-3; % (V/mW)

% Power measured by the photodiode

power\_measured = 1.8; % mW

% Calculate the number of photons per second

photons\_per\_second = power\_measured / conversion\_factor \* (1 / E\_photon);

% Current flowing into the junction

threshold\_current = 12.53e-3;

% Calculate the number of electrons per second flowing into the junction

electrons\_per\_second = threshold\_current / q; % Number of electrons per second

% Calculate the number of laser photons produced by one electron-hole pair

photon\_per\_electron\_hole\_pair = photons\_per\_second / electrons\_per\_second;

disp(['Number of laser photons produced by one electron-hole pair: ', num2str(photon\_per\_electron\_hole\_pair)]);

%B1

% Define data for different temperatures

y1 = [0,0,0,0,0,0.2,0.6,0.9,1.3,1.6,1.9];

y2 = [0,0,0,0,0,0,0.3,0.6,0.9,1.3,1.6];

y3 = [0,0,0,0,0,0,0,0,0.2,0.6,1.2];

y4 = [0,0,0,0,0,0,0,0,0,0.4,0.8];

% Plotting

figure(2)

hold on

scatter(x, y1, 'r')

scatter(x, y2, 'b')

scatter(x, y3, 'g')

scatter(x, y4, 'magenta')

plot(x, y1, 'r', x, y2, 'b--', x, y3, 'g:', x, y4, 'magenta-.')

errorbar(x, y1, err, 'linewidth', 1)

errorbar(x, y2, err, 'linewidth', 1)

errorbar(x, y3, err, 'linewidth', 1)

errorbar(x, y4, err, 'linewidth', 1)

hold off

xlim([0, 30])

ylim([0, 2.5])

grid on

xlabel('Forward current, If (mA)')

ylabel('Optical Output Power Po (mW)')

legend('15°C', '25°C', '35°C', '45°C')

legend("Position", [0.23738,0.69857,0.15256,0.16142])

% Calculate and print threshold currents for each temperature

threshold\_temps = zeros(1, 4); % Array to store threshold currents for each temperature

for i = 1:4

% Fit a linear curve to the data

p = polyfit(x, eval(['y', num2str(i)]), 1);

% Find the threshold current (intersection with a certain power level)

threshold\_power = 0.5;

threshold\_current = (threshold\_power - p(2)) / p(1);

threshold\_temps(i) = threshold\_current;

% Print threshold current for each temperature

disp(['Threshold Current at ', num2str((i - 1) \* 10 + 15), '°C: ', num2str(threshold\_current), ' mA']);

end

%B2

% data

T = [15, 25, 30, 35, 40]; % Temperature (in Kelvin)

I\_th = [1.2, 1.5, 2.0, 2.5, 3.0]; % Current threshold (in amps)

% Plot the data

figure;

plot(T, I\_th, 'bo', 'MarkerSize', 8);

xlabel('Temperature (K)');

ylabel('Current Threshold (A)');

title('Current Threshold vs. Temperature');

% Fit the data to the equation I\_th = I\_0 \* exp(T/T0)

f = fittype('I\_0 \* exp(T/T0)', 'independent', 'T', 'dependent', 'I\_th');

opts = fitoptions(f);

opts.StartPoint = [1, 100]; % Initial guess for fitting parameters [I\_0, T\_0]

opts.Lower = [0, 0]; % Lower bounds for fitting parameters [I\_0, T\_0]

opts.Upper = [Inf, Inf]; % Upper bounds for fitting parameters [I\_0, T\_0]

[fitted\_curve, gof] = fit(T', I\_th', f, opts);

% Plot the fitted curve

hold on;

plot(fitted\_curve, 'r');

legend('Theoretical Data', 'Fitted Curve', 'Location', 'northwest');

hold off

% Extract the characteristic temperature T0

T0 = fitted\_curve.T0;

% Display T0

fprintf('Characteristic Temperature (T0): %.2f K\n', T0);

%C

figure (3)

x1 = [8,9,10,11,12,13,14,15,16,17,18,19];

y5 = [2,4,6,8,10,12,14,16,18,20,22,24,26,28];

surf(x1,y5,z)

colorbar();

grid off

xlabel('x position (mm)')

ylabel('y position (mm)')

zlabel('Outut Power (mW)')