

Student name:	Yongqing Jiang	CRSID:	yj375	Module number:	3B6
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		Very good	Good	Needs improvmt
C O N T E N T	Completeness, quantity of content: Has the report covered all aspects of the lab? Has the analysis been carried out thoroughly?			
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1 Introduction

This lab activity investigates laser characteristics, including light-current characteristics and output spectrum. The goal is to understand the behavior of lasers under different conditions and analyze their performance based on the measured data.

2 Part I: Measurement of Light-Current Characteristics

The apparatus used for this measurement includes a laser diode, a driver circuit, a photodiode for measuring output power, and a transimpedance amplifier to quantify output power by voltage output. The raw data collected from the experiment will be analyzed to determine some key parameters of the laser, and the circuits used in the experiment. The raw data will be available in appendix.

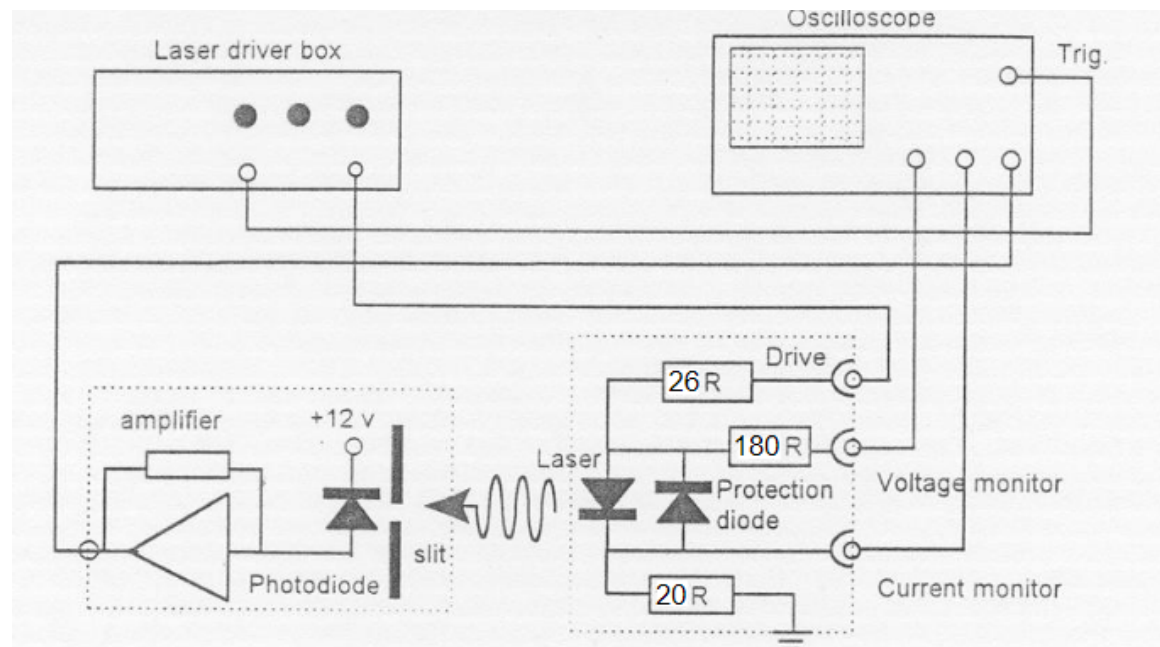


Figure 1: Circuit Diagram

2.1 Laser Theory

According to laser theory, photon emission becomes stimulated when the gain exceeds the losses in the laser cavity. This could be observed in the light-current (L-I) characteristics of a laser, where the output power increases significantly once the threshold current is reached. The expectation of the L-I curve is that it will show a linear increase in output power after the threshold current, with a steep slope indicating efficient lasing action.

As given in the lab handout, this threshold current is between 40 and 55 mA, while the actual threshold current observed from the raw data is around 75 mA. This could be reasonable, because the

operation of laser diode is very temperature sensitive. The threshold current can increase significantly with temperature.

2.2 Data Analysis

As shown in Figure 2, the plot of the raw data of L-I curve shows a clear threshold behavior. Below the threshold current, the light output is negligible. This is because the gain is not sufficient to overcome the losses in the cavity. the laser is not lasing, and only spontaneous emission occurs. Above the threshold current, the output power increases rapidly, indicating that the laser is lasing and the gain exceeds the losses. The large slope of the L-I curve above the threshold can provide insights into the efficiency of the laser, with a steeper slope indicating higher efficiency in converting electrons to photons.

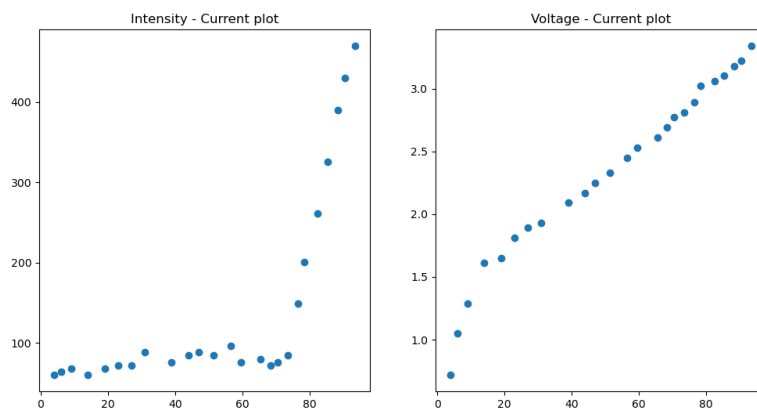


Figure 2: Plot and linear fit of raw data

While the other plot shows relation of voltage across the laser diode and the current through the laser diode. The V-I relation can be derived from the equivalent circuit of the laser diode, as shown in Figure 3.

There is a non-negligible stray series resistance in the laser diode, which contributes to the linear increase in voltage across the laser diode as the current increases.

The relation could be expressed as:

$$V = V_{th} + I \cdot R_s$$

Where V and I are the voltage across the laser diode and the current through the laser diode, respectively. V_{th} is the threshold voltage, and R_s is the stray series resistance.

By the linear fit of the V-I curve, we can determine the threshold voltage and the stray series

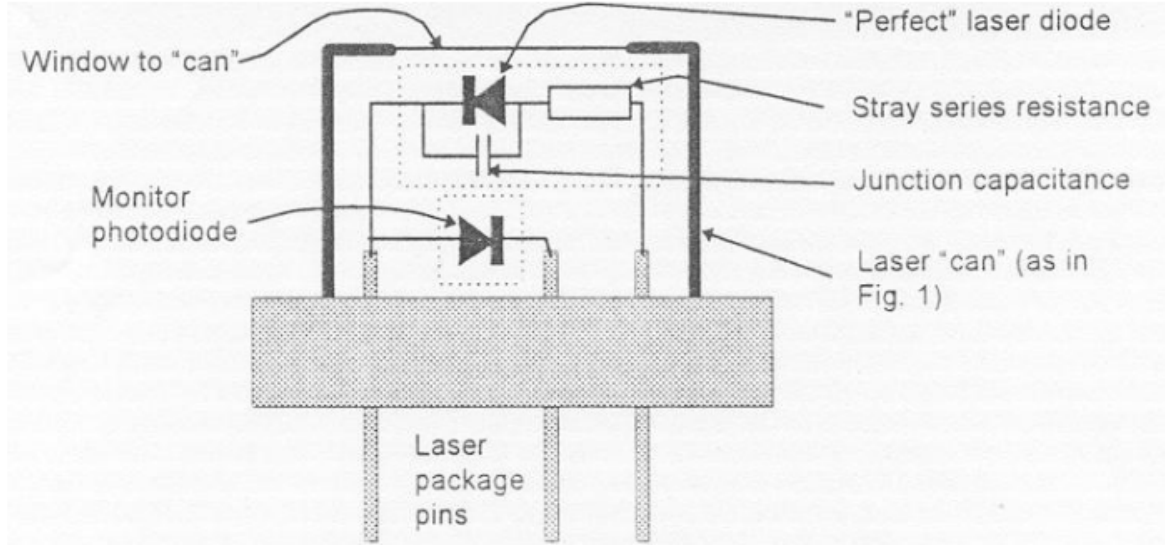


Figure 3: Equivalent Circuit of Laser Diode

resistance. $V_{th} \approx 1.28V$, and $R_s \approx 21.145\Omega$, whose error analysis will be carried out later.

From the circuit diagram given, the stray series resistance is 26Ω , which is close to the value obtained from the linear fit, with an error of 17.3%. This error could be attributed to the measurement errors, and the non-ideal behavior of the laser diode.

With the threshold value of perfect diode, we could estimate the lasing wavelength of the laser diode λ_0 by the following equation:

$$\lambda_0 = \frac{hc}{eV_{th}}$$

The value of wavelength is 968.39nm, which is within infrared range. This calculation agrees to the observation during the lab. There was no visible light emitted from the laser diode.

2.3 Error Analysis

To carry out error analysis on gradient of intercept of a linear fit, a built-in module in python, `scipy.odr`, is utilized. The measurement is modelled to have a 3% system error and corresponding random error caused by human reading. The total error is assumed to be geometric mean of the two error sources.

The linear fit with error bar is shown in Figure 4.

The stray resistance is $1000 \times \text{gradient}$, with value of 21.145Ω , and an error of $\pm 0.3861\Omega$. It is obvious that the real value of the stray resistance is not within the error range of this linear fit. There might be other non-ideal imperfections that affected the measurement. For example, it could be effect of temperature or extra parasitic effect in the circuit.

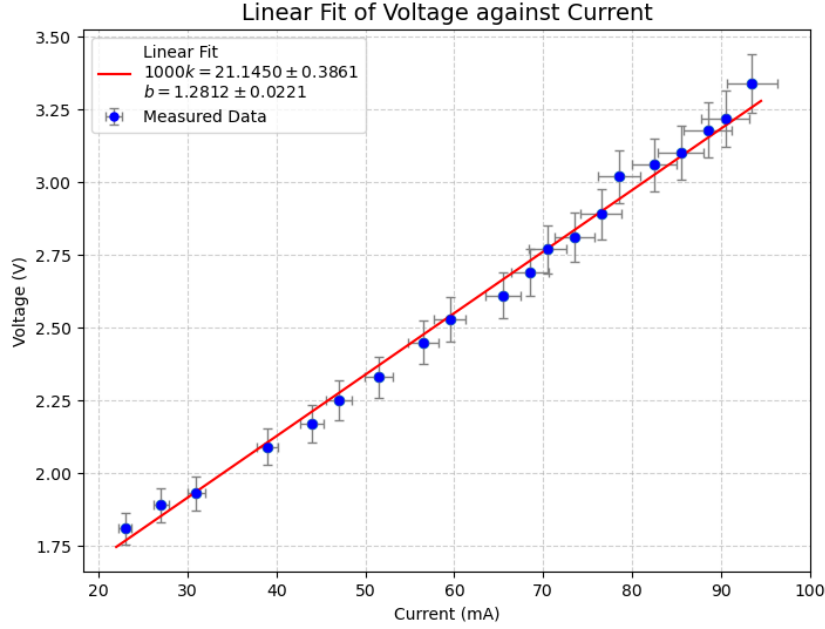


Figure 4: V-I linear fit with error analysis

The intercept corresponds to the threshold voltage of the laser diode. It has a value of 1.2812V with error of ± 0.0221 V, or a percentage error of $\pm 1.72\%$. This error would propagate to the calculation of wavelength of light emitted.

The wavelength is calculated by $\lambda_0 = \frac{hc}{eV_{th}}$, in which h , c , e are all constants. The only source of error comes from V_{th} , which gives a percentage error of $\pm 1.72\%$. This is an absolute error of ± 16.66 nm.

Thus, the stray resistance is measured to be $21.145 \pm 0.3861\Omega$. The wavelength of light emitted is measured to be 968.39 ± 16.66 nm.

3 Part II: Measurement of laser output spectrum

In this part, the output spectrum of the laser diode is measured using an optical spectrum analyzer. Data is collected for both stimulated and under-stimulated conditions, and the results are analyzed to understand the spectral characteristics of the laser output.

3.1 Effective Refraction Index of the Semiconductor Material

Within the cavity of the laser, the light forms a standing wave, with a wavelength $\lambda_g = \frac{\lambda}{n}$. Where λ is the wavelength of the light in vacuum, and n is the effective refraction index of the semiconductor

material. This wavelength should satisfy the resonance condition of the cavity, which is given by:

$$m \frac{\lambda_g}{2} = L$$

Where m is an integer representing the mode number, and L is the length of the cavity. By rearranging the equation, we can express the wavelength in vacuum as:

$$\lambda = \frac{2nL}{m} \rightarrow f = \frac{mc}{2nL}$$

The change in frequency is:

$$\delta f = \frac{c}{2nL}$$

From $f = \frac{c}{\lambda}$, $\delta f = \frac{c}{\lambda^2} \delta \lambda$, we can derive the change in wavelength as:

$$\delta \lambda = \frac{\lambda^2}{2nL}$$

Thus, the effective refraction index can be calculated as:

$$n = \frac{\lambda^2}{2L\Delta\lambda}$$

3.2 Measurement of Laser Output Spectrum

The observed output spectrum of the laser diode shows multiple peaks, which correspond to different longitudinal modes of the laser cavity. Figure 7 and Figure 8 in the appendix show the output spectrum under stimulated and under-stimulated conditions, respectively. The collected data is shown in Figure 5.

Current (mA)	center wavelength (um)	3dB width (um)	ripple width (nm)
17.63	1.5565	0.0049	1.205
13.02	1.5547	0.0254	1.205

Figure 5: Spectrum Data

3.3 Discussion and Analysis

By comparing the two sets of data, it is clear that the only discrepancy is the 3dB width of the spectrum. The 3dB width of the spectrum under stimulated condition is narrower than that under under-stimulated condition. This is expected because the stimulated photon emission leads to a more concentrated spectrum, while spontaneous emission results in a broader spectrum due to the random

nature of photon emission.

The center wavelengths of the two spectra are very close, which indicates that the lasing wavelength range is consistent regardless of the stimulation condition.

At last, the ripple width corresponds to $\Delta\lambda$ in the equation for effective refraction index. As the two measurements use the same laser diode, the ripple widths are expected to be the same.

The effective refraction index could be calculated as:

$$n = \frac{\lambda_{center}^2}{2L\Delta\lambda} = 3.351$$

by taking $L = 300\mu m$. This value of refractive index is within the typical range of semiconductor.

3.4 Error Analysis

The calculation of refractive index has two sources of error: $\Delta\lambda$ and λ_{center}^2 . Thus, the error of refractive index should include both sources:

$$U_n = \sqrt{\left(\frac{\partial n}{\partial \Delta\lambda} U_{\Delta\lambda}\right)^2 + \left(\frac{\partial n}{\partial \lambda_{center}^2} U_{\lambda_{center}^2}\right)^2}$$

in which U_x is the absolute error of measurement on x .

For each reading of wavelength from the spectrum analyzer, there is a random error of $U_0 = 0.00005\mu m = 0.05nm$.

By measuring $\Delta\lambda$, two readings were taken to measure width of 15 ripples. The error is diluted by a factor of 15: $U_{\Delta\lambda} = \frac{2U_0}{15} = 6.67pm$.

The percentage error of λ_{center}^2 should be twice the percentage error of λ_{center} . $\%U_{\lambda_{center}} = \frac{0.05nm}{1.5565\mu m} = 3.2ppm$. The absolute error of λ_{center}^2 is then $(1.5565\mu m)^2 \times 2 \times 3.2ppm = 1.55 \times 10^{-17}m$.

The partial differentials are found by:

$$\frac{\partial n}{\partial \Delta\lambda} = -\frac{\lambda_{center}^2}{2L(\Delta\lambda)^2} = -2.78 \times 10^9 m, \quad \frac{\partial n}{\partial \lambda_{center}^2} = \frac{1}{2L\Delta\lambda} = 1.38 \times 10^{12} m$$

The total error of refractive index is:

$$U_n = \sqrt{(2.78 \times 10^9 \times 6.67 \times 10^{-12})^2 + (1.38 \times 10^{12} \times 1.55 \times 10^{-17})^2} = 0.0185$$

Thus, the measured value of refractive index is 3.351 ± 0.0185 .

4 Conclusion

In this experiment, the electro-optical characteristics of a laser diode were successfully characterized. The Light-Current (L-I) analysis confirmed the transition from spontaneous to stimulated emission. Through linear regression of the V-I characteristics, the threshold voltage and the stray series resistance are determined. Based on the threshold voltage, the bandgap emission wavelength was estimated, confirming operation in the infrared region.

Spectral analysis demonstrated a distinct narrowing of the 3dB bandwidth under stimulated conditions compared to spontaneous emission. By analyzing the longitudinal mode spacing, the effective refractive index of the semiconductor material was calculated.

Overall, the experimental results align well with theoretical expectations for semiconductor laser diodes, accounting for temperature sensitivity and parasitic circuit effects.

5 Appendix

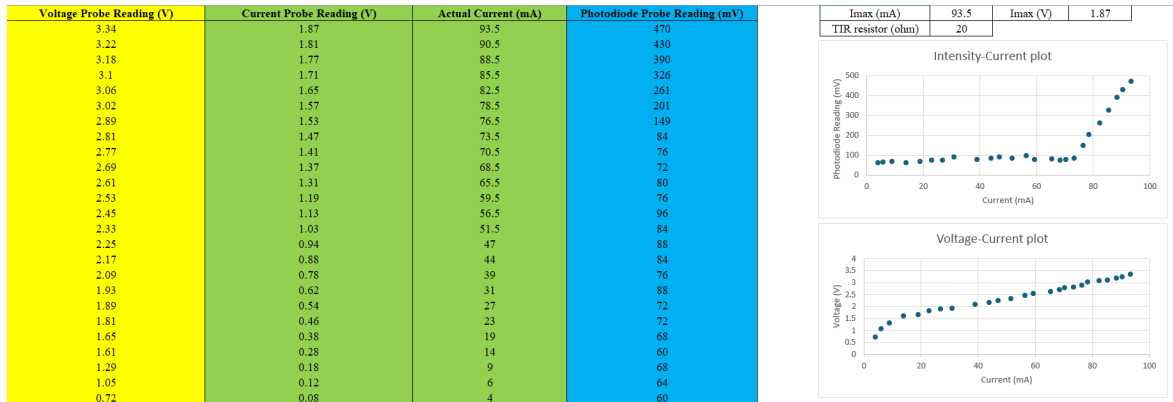
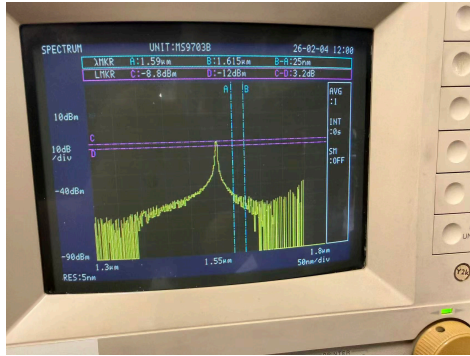
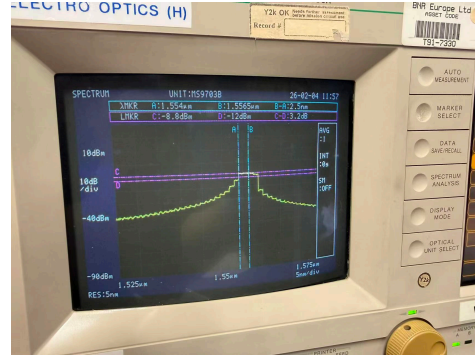


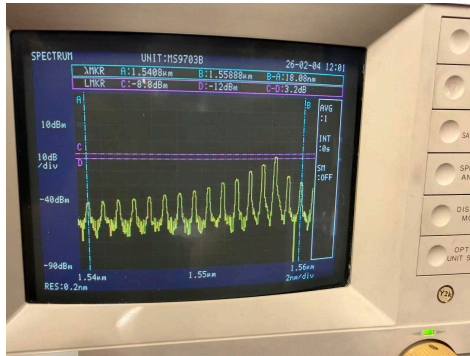
Figure 6: Raw Data



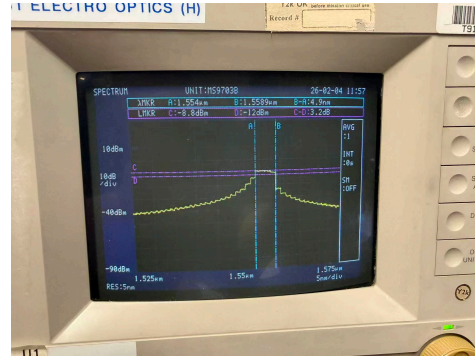
(a)



(b)

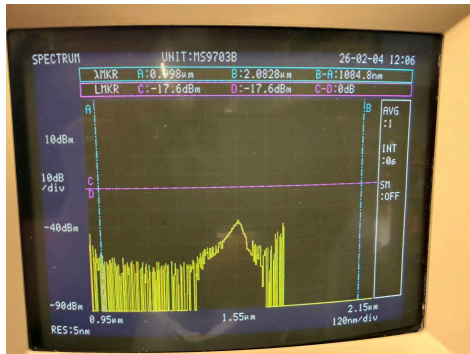


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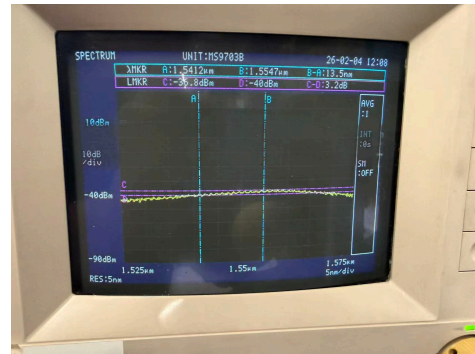


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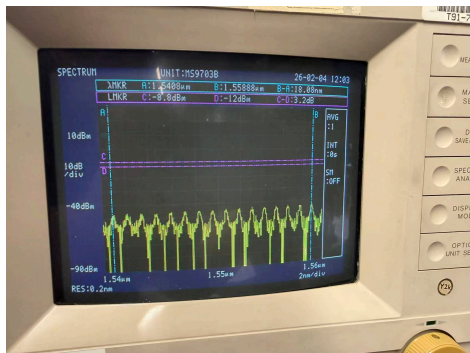
Figure 7: Stimulated Output Spectrum of the Laser Diode



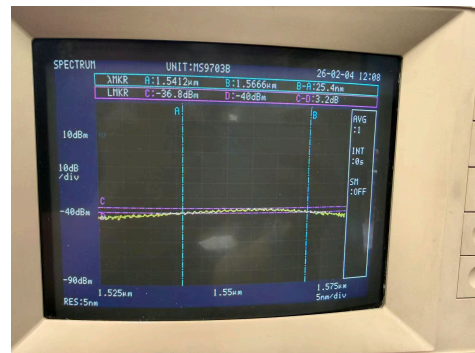
(a)



(b)



(c)



(d)

Figure 8: Under Stimulated Output Spectrum of the Laser Diode