External Cavity Diode Lasers:
Controlling Laser Output via Optical Feedback

A thesis submitted in partial fulfillment of the requirement for the degree of **Bachelor of Science** with Honors in **Physics**
from the College of William and Mary in Virginia,

by

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April 2003

Abstract

Semiconductor diode lasers are widely used in modern technology because of their compactness, low cost, and durability. However, diode lasers have two major drawbacks. Light emitted by a diode laser is not monodirectional and typically has a large bandwidth. While collimating the output of a diode laser is a relatively simple problem to solve with lenses, narrowing the bandwidth of the output requires construction of an external cavity. In this project we have created an external cavity diode laser (ECDL), which selects a single wavelength from the entire output spectrum of the diode laser and drives the laser at this wavelength. Thus, by using optical feedback from a diffraction grating, we are able to narrow the total bandwith emitted by the diode laser. We have characterized the tuning of this laser and show how the laser can be used to conduct research and also teach students the fundamentals of laser physics and semiconductor applications.

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Acknowledgements

First of all, I would like to thank my advisor, Prof. Anne Reilly of William and Mary, for guiding me through my first long term research project in physics. Prof. Reilly was a constant source of help for me and I thank her for giving me her time and patience. I would also like to thank some other members of the William and Mary community; Kirk Jacobs in the machine shop for allowing me to use the shop tools and for his expertise in creating several of our components; Keoki Seu for his help and advice in the lab; Prof. Gina Hoatson for reminding me of important deadlines that I was not supposed to miss; and Prof. Todd Averett and Prof. Robert Lewis for agreeing to be on my defense committee. I would also like to thank Prof. Kane and Prof. Kossler and their students; Carson Davis, Drew Donnelly, Jack Simonson, Kyle Wisian, and Jim Younkin, for working my project into their advance laboratory class for physics and giving me excellent feedback, which helped me prepare for my defense. Finally, I would like to thank the College of William and Mary for providing me with the space and materials I needed to conduct this thesis project.

1.0 Introduction

Because of their small size, low cost, and durability, semiconductor diode lasers are common in such devices as CD players, laser pointers, and telecommunication machinery. Recent discoveries of ways to refine the output of diode lasers, which is naturally very divergent and has a large bandwidth, have allowed these lasers to be used even in research applications such as atomic spectroscopy, where a precise tunable light source is required[1]. One of the outcomes of these discoveries is more cost effective laboratory equipment. A tunable diode laser system costs on the order of one thousand dollars while a tunable dye laser system can costs tens of thousands of dollars. Consequently, diode laser systems can be used to open up new areas of research for small laboratories and also make tunable lasers accessible to educators and students.

While collimating the output of a diode laser is a relatively simple problem with lenses, narrowing the bandwidth of the output involves more complicated physics. In this thesis work we have constructed an external cavity diode laser, which selects a single wavelength from the entire output spectrum of the diode laser using a diffraction grating and drives the laser at this wavelength. Using this form of optical feedback we demonstrate control over the laser wavelength. In this work we have studied the laser output parameters, wavelength and power, as a function of the laser input and cavity parameters, current and grating angle.

2.0 Physics Background

2.1 General Principles of Lasers

This thesis work relies heavily on exploiting the properties of semiconductor diode lasers. Before we can begin to discuss these properties, it is necessary to understand the basics of lasers in general. The term laser is an acronym for Light Amplification by Stimulated Emission of Radiation. Unlike light from standard sources such as light bulbs, laser light is coherent. In a perfectly coherent beam of light all of the photons composing the beam propagate is the same direction, are all of the same wavelength, and have same phase. In order to construct a laser system one must have three basic components: an active medium, an excitation source and a laser cavity. The excitation source and the active medium must be chosen so that the source creates a population inversion of electrons in the medium. As in most materials, the electrons of the active medium of any given laser tend to stay at or near their ground state energy levels in the absence of excitation. Excitation can be accomplished either by introducing thermal or electronic energy (hear or a current), or using light of a certain wavelength to excite electrons into higher orbitals, thereby putting the atoms in higher energy states. This process of exciting electrons up to higher energy states is often referred to as *pumping*. Once an electron is excited up to a higher energy level, it has a tendency to jump back down to its previous lower energy state. If the rate a which electrons are pumped into the higher energy levels is faster than the natural time it takes for the electrons to degenerate to their ground states a *population inversion* is created in the active medium. Simply stated, a population inversion occurs when more electrons are being excited to higher energy states of a medium than the system can remove from these higher energy levels via natural decay.

When the electron in the higher energy state decays down to its lower energy state it emits some form of energy to preserve the principle of energy conservation. Quantum mechanics tells us that this energy takes the form of another photon, and moreover that this energy of this photon must equal the energy difference between atomic energy states:

$$E_2 - E_1 = h\nu \qquad (1)$$

where E_2 and E_1 are the excited and the unexcited energy levels of the electron, respectively, h is Plank's constant, and ν is the frequency of the photon. Thus, the frequency, and therefore the wavelength, of the emitted photon are entirely predictable if one knows the initial and final energy states of the electron.

The direction of the propagating photon, however, is not predictable. How then does this process lead to coherent light sources that are characteristic of laser light? To answer this we must differentiate between *spontaneous* and *stimulated emission* of photons. Spontaneous emission of photons involves electrons randomly decaying from higher energy levels to lower energy levels. This process does not produce coherent light. In stimulated emission, an incoming photon initiates the decay or transition of an electron from an excited level to a lower level, causing it to emit a photon which is a replica of itself. This stimulated emission is a product of the quantum mechanical nature of the active medium. The region between the ground state of the electrons and the allowed higher energy states is quantum mechanically forbidden to the electron. To describe transitions between these states we use probability models. Thus given the existence of an incoming photon, an electron in the ground state has a certain probability of moving across the forbidden quantum mechanical barrier into the higher level energy state. The probability of transition is independent of the direction of the motion across this barrier. Therefore, an electron that is already in the higher state has the same probability of moving into the ground state given an incoming photon as an electron in the ground state has of moving into the higher energy state. For a complete explanation of this phenomenon we refer to Griffiths' *Introduction to Quantum Mechanics* [2]. For this discussion, all that one needs to know about the process of stimulated emission is that the photon given off by this induced decay to the ground state is of the same frequency and direction of the photon that induced the change. The initial photon is never absorbed by the electron. Consequently, the number of photons moving in the same direction with a given frequency doubles after the induced energy level jump.

The coherent light of a laser is achieved by coupling our active medium with a laser cavity. The cavity selects some of the photons emitted spontaneously to repropagate through the medium. The only photons allowed to repropagate through the medium are those having a wavelength that satisfies the equation:

$$\lambda_n = 2L/n \qquad (2)$$

where L is the length of the laser cavity, n is the harmonic mode of the wave. Thus, the cavity allows only photons whose wavelength can form a standing wave in the cavity, which limits the wavelength, phase, and direction of the photons allowed to repropagate through the medium. These photons induce other photons of the same propagating direction, phase and wavelength via stimulated emission, and in a brief time all the photons propagating through the cavity are coherent. To get this coherent light out of the cavity and make use of it, one only needs to make one of the reflective end of the cavity semi-reflective, thus allowing some of the coherent light to escape. The rate at which photons are randomly absorbed or exit through the semi-reflective ends of the cavity is called *loss*. The rate at which the photons give rise to other photons via stimulated emission is call *gain*. To have a functioning laser our gain versus loss ratio must be greater than one.

Lasers consist of multiple energy level systems with *metastable* states where population inversions can be maintained (see Figure 1). This energy level is given the name metastable because the electrons in this state have a significantly long lifetime before dropping down to the ground state. The longer decay time results from the fact that the transition from the metastable state to the ground state is quantum mechanically forbidden.

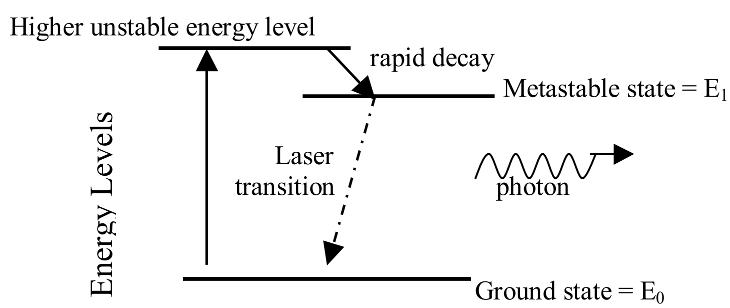

Figure 1 : This diagram shows the typical path of an electron of a chromium atom that is excited in a ruby laser. After an initial pulse of light from the flash bulb an electron is excited from the ground state to a higher energy level. From there it quickly jumps back down to the metastable state. Eventually, the electron decays from the metastable energy level to the ground state, either by stimulated or spontaneous emission, and in doing so releases energy in the form of a photon, whose frequency is $(E_1 - E_0)/h$.

Typical decay times of allowed transitions take about a microsecond or less. Transitions across forbidden energy regions may take one thousand to one million times longer depending on the size of the energy gap[3].

Perhaps the best example of a simple laser which shows how all the above requirements come together is the ruby laser. The ruby laser was the world's first laser created in 1960 by Theodore Maiman, a researcher at Bell Labs [4]. Maiman's ruby laser was simple and elegant, consisting of a cylindrical ruby rod with smooth silvered ends, surrounded by a coiled flash lamp tube (see Figure 2).

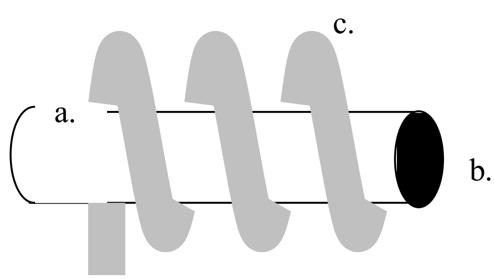

Figure 2 : Schematic of the ruby laser where (a) is the ruby rod, (b) shows the silvered ends, and (c) is the coiled flash tube.

In this example, the ruby rod serves as the active medium of the laser. The flash bulb provides the electromagnetic radiation needed to stimulate the medium. Meanwhile the silvered ends of the ruby rod define the boundaries of the lasing cavity. When the laser is turned on the flash bulb bombards the ruby rod with short pulses of electromagnetic radiation. The high energy photons emitted by the bulb excite the chromium atoms in the ruby crystal to higher energy states. At the highest of these levels, the electrons are unstable, and so they quickly decay via allowed transitions down to a metastable energy level (see Figure 2). As the flash lamp continues to pulse, more and more electrons get "stuck" in metastable energy level due to the slower decay rate, and a population inversion is created. When electrons finally do make the jump from the metastable state down to the ground state, they give off a photon of a precise frequency as discussed before. These photons are reflected through the active medium by the silvered ends of the ruby. Some escape the cavity and produce the laser's beam of light. Others induce other photons via stimulated emission before eventually escaping or being absorbed by an atom in the crystal.

After the success of the first ruby laser, research in the field of lasers took off at an amazing rate. Today we have lasers that produce coherent beams of a wide range of wavelengths using a variety of mediums. The work of this thesis, however, deals specifically with semiconductor diode lasers. In order to understand how these devices function, it is necessary to understand the basics of semiconductor physics.

2.2 Semiconductor Physics

The unique distribution of electrons in atoms is what makes some materials good conductors, other materials poor conductors, and still other materials semiconductors. Each electron in an atom has a net energy value that comes from the sum of its kinetic and potential energies. We know from quantum mechanics that each electron's energy is not random. Rather, there are defined regions of allowed and unallowed energy states about the nucleus that constrain the "choice" of energies for a given electron. Moreover, from the Pauli Exclusion Principle we know that not more than two electrons, each with opposite spins, can occupy a given state the same time. When atoms are brought together to form a solid, the individual energy states split and spread out to form energy bands, in order to preserve the exclusion principle. Thus, we are left with the band model of possible distributions of electrons throughout the energy levels in materials, shown in Figure 3.

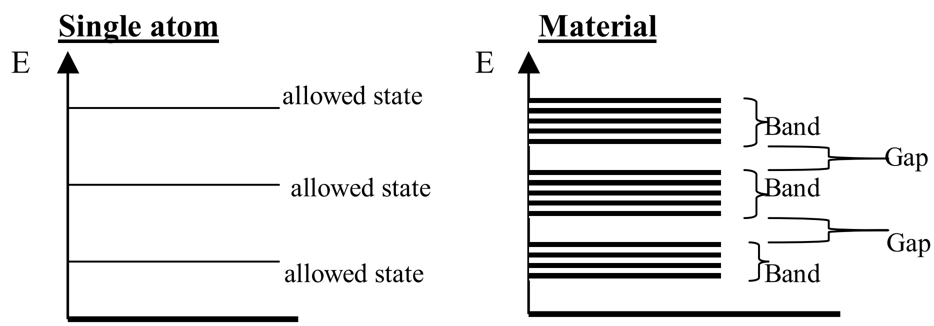

Figure 3 : How the band-structure in materials form from individual atomic levels. The lines of the single atom diagram represent the allowed orbitals of an electron. The cluster of lines in the material energy diagram represent the allowed regions for electrons of in a solid known as energy band. These bands form from the splitting of energy states when multiple atoms are brought near each other. Energy regions for which the solution to Schrodinger's equation indicate zero or negative probabilities of electrons existing there are called gaps.

The previous diagram shows how there are energy gaps that occur between regions of allowed energy regions. These energy gaps are what determine whether a material is a metal, insulator, or semiconductor. To distinguish between a poor conductor and a good conductor, or an insulator and a metal, one may examine the distribution of electrons of an atom of each material at absolute zero. At 0˚K all the electrons of an atom occupy the lowest possible energy levels available. The *valence band* is defined as the highest energy level that contains an electron at absolute zero. A *conduction band* is defined as any band of allowed energy states that is either partially or entirely unfilled by electrons at 0°K. Armed with these definitions we can define a metal as a material whose conduction bands and valence band overlap;

no energy gap between the two states. An insulator, on the other hand, is a material whose valance band entirely fills the energy band that contains it, thereby leaving a large energy gap between the valence band and the nearest conduction band, which is empty (See Figure 4).

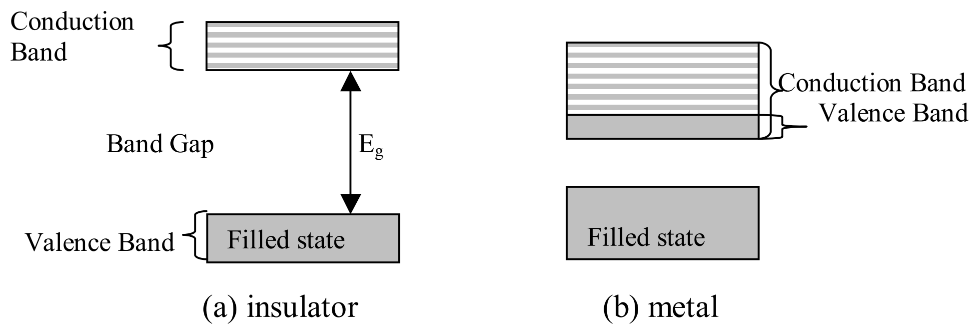

Figure 4 : Band-structure of an (a) insulator and (b) metal. For and insulator, the space between the conduction band and the valence band is known as the band gap and is associated with a quantifiable energy difference between the two states, here denoted as E_g. For metals the valence band and the conduction band overlap, hence there is no initial energy an electron must gain in order to move from the valence band to the conduction band in a metal(b).

Increasing the temperature of both metals and insulators gives the electrons of the atoms extra energy. For metals this extra energy allows some valence electrons to move into the conduction band when T > 0˚K. However, for insulators even at room temperature, $E_g >> kT$, where k is Boltzmann's constant and kT has units of energy. Therefore, the thermal energy added to the system by raising the temperature up from absolute zero is not enough to promote electrons into the conduction band.

As one would guess by the name, the energy diagram of a semiconductor falls somewhere between that of metal and that of an insulator. Like an insulator, at T = 0˚K the valence band and the first conduction band of the semiconductor do not overlap. However, the band gap that separates these levels is significantly smaller than the band gap of an insulator. Thus, by transferring a minimal about of energy to an electron one can eject an electron from the valence band of a semiconductor across the band gap and into the conduction band (See Figure 5), leaving a hole behind.

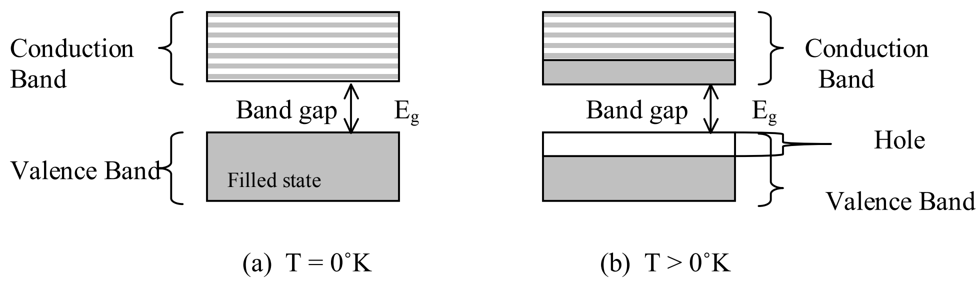

Figure 5 : At absolute zero the distribution of electrons in a semiconductor resembles that of an insulator (see figure 4a) with the only exception being a smaller band gap between the conduction and valence bands(a). Figure 5b shows how as temperature increases electrons from the valence band can gain enough energy to cross over the band gap and enter the conduction band. The space that is left by the missing electron in the valence band is known as a "hole".

2.3 Semiconductor Diode Lasers

A diode laser's large bandwidth is a consequence of the way a diode laser is made. To make a diode laser, one takes two semiconductor crystal structures and adds impurities into the lattice. This process is called *doping*. One semiconductor crystal structure is doped with atoms that leave electron "holes" in the covalent bonds that make up the crystal. Consequently this material, while having a neutral net charge, appears positive at close distances due to its "desire" for extra electrons to fill the holes of the lattice structure. This type of semiconductor is called a p-type semiconductor. Its counterpart, an n-type semiconductor, is a semiconductor crystal structure that has been doped with atoms having more electrons in the valence shell than the atoms of the crystal which they replace. These impurities give the semiconductor a negative appearance at close distances due to its willingness to give up the extra electrons not used in the covalent bonding of the crystal lattice. When a p-type and an n-type semiconductor are joined together the result is called a p-n junction. Applying a voltage across this junction creates a diode. If a voltage is applied in the right direction current flows through the pn-junction and as it does electrons in high energy states in the n-type lattice find holes as they move across the p-n junction. When an electron finds a hole, it decays down to a lower energy state, releasing a photon. The energy released as an electron drops down into a hole depends on the size of the energy gap an electron crosses to combine with a hole. This gap distance depends on three things: the type of semiconductors used to make the diode, the thermal energy inside the diode, and the way in which the p and n-type semiconductors are joined together. The faces of the semiconductor crystals are made reflective by either coatings or the cut of the crystal. The reflective ends create the laser cavity, the final component of our laser[5]. Since the size of a standard diode laser cavity is about 1mm in length, one can see (using Equation 2) that the difference between allowed wavelengths in the laser cavity are very small. For example, if λ_n = 700nm and L = 1mm, then Equation 2 gives the next allowed wavelength $\lambda_{n+1} \approx$ 699.8nm, making $\Delta\lambda$=0.2nm. This property of the diode laser causes the laser to emit multiple wavelengths of light.

2.4 The External Cavity Diode Laser (ECDL)

Another drawback of working with diode lasers is that, unlike other types of lasers, the light emitted by a diode laser greatly diverges in an oval shape pattern with the highest spread of light at an angle of about 25 degrees. Such a wide beam is practically useless to an experimentalist. Therefore, it is necessary to *collimate* the output of the diode laser, that is, bend the diverging light through a lens (or several lenses) so that all the output goes in one direction. One can achieve this result using a single lens as long as the laser is placed exactly at the *focal point* of the lens one chooses. The focal point of a lens is also the point through which all light parallel to its normal axis will converge. Hence, if we place our diode laser at the focal point of our collimating lens all light from the diode laser that passes through the lens will exit parallel to the normal axis and all light that enters the face of the lens at normal incidence will be focused the diode laser. This property of optics allows us to send optical feedback back into the laser (see Figure 6).

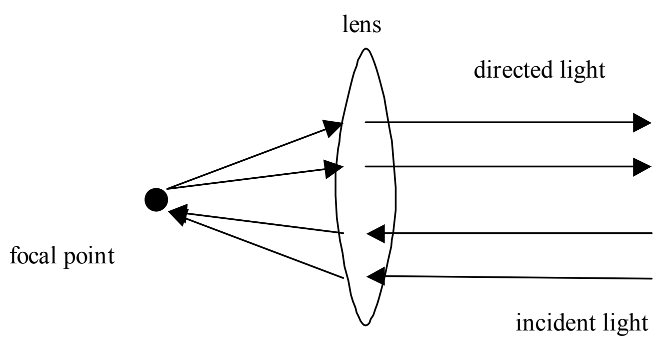

Figure 6 : Light radiating from the focal point is monodirectional after it passes through the lens and how entering the lens in a direction perpendicular to the lens face is directed to the focal point.

As mentioned before, because of its small cavity, diode lasers have a larger bandwidth, which means that the laser emits light over a broader range of wavelengths than other lasers (see Section 2.3). One of the ways to narrow the bandwidth of a diode laser is to use optical feedback to drive the laser at a single allowed lasing frequency. As previously discussed, the collimation lens of the ECDL is one critical part of attaining optical feedback. The second part of our system that allows optical feedback is the *diffraction grating*. A diffraction grating is finely scored reflective material that, due to its geometry, allows only certain wavelengths of light incident at an angle θ to interfere constructively with itself as it is reflected outward. The formula for constructively diffracted orders of light reflected from a diffraction grating is:

$$d \sin\theta = m \lambda \tag{3}$$

where d is the spacing between reflective surfaces, θ is the angle of incidence, λ is the wavelength of the incident light and m is an integer[6]. One consequence of the above equation for is that spectra diffracted off a grating are reproduced at several different angular positions about the grating. The various replications of the spectra are called o*rders of diffraction* and obey the following relationship.

$$(\sin \theta_i \pm \sin \theta_m) = N\, m\, \lambda \tag{4}$$

where θ_m is the angle of the m^{th} order diffracted beam, N is the spatial frequency of the grating (units nm^{-1}), and θ_i, m, λ are incident angle, integer, and wavelength as before[7].

3.0 Experiment

3.1 Description of Materials and Setup

The key components of this external cavity diode laser (ECDL) setup are a current driver, a standard 9mm diode laser of the 780nm range, a collimating lens, a diffraction grating, two kinematic optical mounts, an Ocean Optics S2000 spectrometer, and two digital multimeters used to monitor the input current the and the power of the laser output. In this thesis work, the construction began with the housing for the Thorlabs laser diode current driver (model LD1255). The driver is a small circuit board roughly 8cm x 3.5cm in size and is about 1.0cm thick when all the electrical components are mounted onto it. Consequently, the housing for the driver is only of modest size, 15cm x 5cm x 7cm. The benefits to using this particular driver include the ability to vary the input current both internally and externally by electronic control, and the ability to monitor the input current and output power simultaneously. The next critical piece of the setup is the laser housing. The housing consists of a three prong 9mm diode laser socket placed in a kinematic mirror mount from Thorlabs (product number : KC1-T), which as three independent adjusters on the back to change the angle. By wiring our laser driver to a three-prong socket rather than directly to the diode laser, one can easily replace the diode laser within the system and thus have the ability to diodes of different ranges of wavelengths. The lens used is an aspheric collimating lens of focal length 5mm, and it is mounted to a 35 mm cage plate, CP03 (from Thorlabs). The optical feedback of the system is controlled by a 12.7mm gold diffraction grating from Edmund Optics having a coarseness of 1200 grooves per millimeter. Like the laser diode, the diffraction grating is placed on a mount whose angle can be finely adjusted by three screws on the back. Before securing the diffraction grating on our kinematic mount, the grating is first affixed to a cylindrical piece of Lucite, which at one end has a cross-section cut at a 28˚ angle from the face of the cylinder. This is the Litrow angle for the particular laser we used and it allows the first order of diffracted light to be sent back to the laser. The Litrow angle is determined from the grating equation (eqn 4). Hence, if we define θ_L as the angle of incidence in the case when $\theta_i = -\theta_m$ then our equation for the Litrow angle of the system is

$$2d(\sin(\theta_L)) = m\lambda \tag{5}$$

where *d, m,* and λ are defined as before in the grating equation. As one can see, the equation for the Litrow angle is obtained by substituting θ_i for (- θ_m) in the grating equation. The optical feedback of the external cavity diode laser setup only works if the first order of diffracted light is sent directing back to the diode laser. Therefore, to determine the initial displacement of the grating one does the follow calculations. In this setup, d = 1/(1200 grooves/ mm) ~ 833.33nm, m = 1, and λ = 785nm according to the specifications for the HL7851 provided by Thorlabs. Plugging these constants back into the previous equation we get

$$\begin{aligned} \theta_L &= \sin^{-1}\left(\frac{785}{2\times 833.33}\right) \\ \theta_L &= 28.10^\circ \end{aligned} \tag{6}$$

Since the kinematic mount for the grating can be adjusted ±5˚, the Lucite grating mount was cut at 28˚.

All of the afore-mentioned components of the ECDL, including the laser housing, the collimating lens, and the diffraction grating, are connected by four rods that run through the corners of the square mounts of each component. Therefore, length of the ECDL is adjustable, however, as we have the device setup in the lab, its dimensions are 18cm x 7cm x 7cm. The whole cage is connected to an optical stand by the middle component of the setup, the cage plate of the collimating lens. The laser housing and the diffraction grating are attached to the same mount rather than different mounts so that one can redirect the output beam to any position without disturbing the angle or alignment of the diffraction grating with respect to the laser housing (see Figure 7).

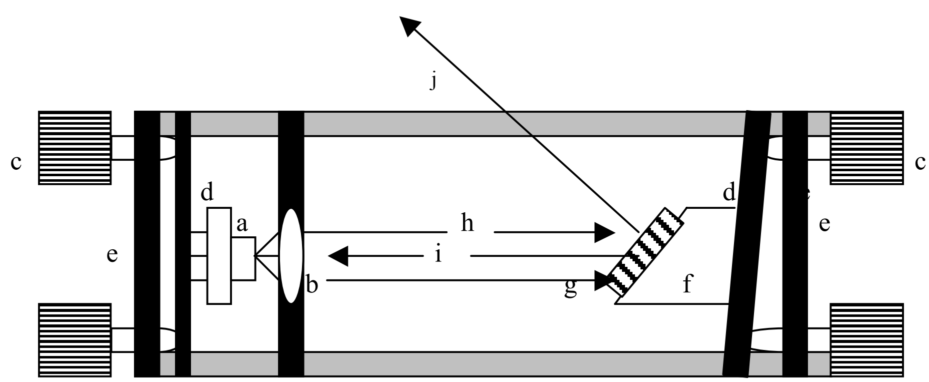

Figure 7 : A schematic of our constructed external cavity diode laser as seen from above with the following components label: (a) the laser diode, (b) the collimating lens, (c) adjustment knobs for (d) our kinematic optical mounts, (e) fixed face plates, (f) angled grating mount cut to blaze angle, (g) the diffraction grating. The diagram also shows (h) the initial light from the diode laser, (i) the first order diffraction beam from grating which is the source of the lasers optical feedback, and (j) first order diffraction beam from grating which is the output we measure.

The Ocean Optics S2000 spectrometer connects to a driver inside our lab PC which came with software for analyzing the spectra we send into the spectrometer. In the lab, there are also two digital multimeters connected to the current driver to monitor current across the diode laser and the output power. The resolution of the spectrometer is 1nm, while the resolution of the digital multimeters is 0.1mA.

3.2 Operating the External Cavity Diode Laser

To operate the ECDL one first selects a diode laser with the appropriate bandwidth. Since some of the laser's output will be retroreflected back into the cavity, it is important to choose a laser diode with highly reflective coating on the back face and a reduced reflectivity coating on the output face. While many low power diode lasers do not have such coatings, diode lasers that produce 30mW or more output power generally have these extra coatings[8]. In this experiment an HL7851 785nm laser diode with an output power rating of 50mW was used. The HL7851 was placed into the three-prong diode socket on the laser mount. Since all laser diodes are extremely sensitive to static electricity and can be shorted out by sudden spikes of current, it is important to turn the internal variable resistor (pot) all the way to its highest resistance setting before the current driver is turned on. Once this is so, one should turn slowly increase the amount of current through the system by slowly turning the pot until the input current is just above the *threshold current*, or the minimum current value at which the diode laser lases. At this point the laser needs to sit for about 1 hour until the system achieves thermal equilibrium (i.e., it has to warm up) since the thermal energy of the semiconductor material significantly affects the energy of the photons that are emitted by the diode laser.

While waiting, the laser output is collimated by adjusting the laser until it is exactly 1 focal length from the collimating lens. In practice the best way to see if the laser is at the focal point of the lens is to remove the back half of the ECDL, which is the diffraction grating and mount, and aim the entire laser housing at a distant wall to see if the spread of the output beam on the wall is the same size as the spread produced by shining the laser on a piece of paper right in front of the setup. It is possible for one to have agreement in the size of the light beam on the wall and that of the beam on the piece of paper and still have the output not collimated. Therefore, one should examine the spread of the laser beam on the piece of paper when the paper is at several different points between the laser diode and the wall. If the size of the spread is constant regardless of the position of the paper, then the laser is collimated. Aside from being collimated, it is also desirable to have the output from the laser level with the horizontal plane. Since the laser is on a kinematic mount, it is easy to make sure the collimated beam is not angled up or down from the horizontal. The laser beam must be horizontal so that the first order diffracted beam will be directed back at the collimating lens rather than above or below it. The tool used to ensure the beam is parallel to the ground is a simple thin metal panel (Thorlabs) that hangs from the top rods of our ECDL cage set and has a pin hole located exactly at the height of the center axis of the cage. By placing the panel on the cage, one can see if the laser light is skewed from the horizontal axis, using the angle adjusters on the back of the laser house, and redirect the beam accordingly.

Once the laser beam is collimated, one can replace the grating and mount are replaced onto the ECDL cage, and the alignment of the laser is rechecked. If the alignment tool is hanging in the center of the cage setup, two red dots will be seen from the back (grating side) of the ECDL. One dot is the light coming through the pinhole from the laser diode on the other side. This light reflects off the grating and creates a second red dot on the panel. What is desired is to have these two dots overlap entirely. If this is not already so, one can move the second dot by using the adjustment knobs on the kinematic grating mount. After all the previous alignments have been made the zero order diffraction coming off the ECDL is directed into the fiver optic input of the spectrometer.

Even with all the fine tuning that has been done to ensure the light is being sent back into the laser diode, at this point it is likely that the diffracted beam is still not being sent directly into the diode laser's small cavity. The way to know one has succeeded in creating a new source of optical feedback for the diode laser is to watch the distribution of wavelengths on the spectrometer while slowly adjusting the knobs on the back of the grating mount.

One of tricks learned to get the alignment close to perfect that helped in this experiment was to put the fiber optic cable through a hole in a stiff piece of paper, such that the entire spread of the beam could be seen on the vertical plane. While observing how the light fell on the plane two somewhat overlapping beams were noticed; one being slightly fainter than the other. The second, fainter beam came from the light that was reflected off the collimating lens that had already been diffracted by the grating. Thus the two distributions came from two light beams that had traveled two different distances. That the light beams did not line up exactly indicated that there still was some error in the alignment. By adjusting the kinematic mounts one can get these beams to overlap.

Once certain the light diffracted off the grating is reentering the lasing cavity of the diode laser, one can use the new extended adjustable cavity to select several different output wavelengths to study or utilize. To select different wavelength within the tunable range of the diode laser, one simply adjusts the horizontal angle of the diffraction grating using a fine adjustment micrometer on the back of the mount. To understand why changing the angle of the diffraction grating changes the wavelength of the retroreflected beam, consider the Litrow angle equation (eqn. 5). We see that when we adjust θ_L we change the allowed wavelength of light that is directed back into the laser diode. Hence, changing the angle of the diffraction grating selects a different wavelength at which we drive the lasing process.

3.3 Measuring Intense Output from the ECDL

Initially, we ran into the problem that the unfiltered light from the ECDL was too intense for our spectrometer to read accurately, making it impossible to determine where the peak of a distribution was located. To overcome this obstacle we had to devise a way to cut down on the intensity of the light that was being sent to the fiber optic receiver without omitting any wavelengths from the spectrum. The solution was to first reflect the output beam off a normal piece of glass before sending the beam to the spectrometer.

4.0 Data and Analysis

4.1 Output Power versus Current

The threshold current for the HL7851 diode laser was found to be around 40mA. The threshold current is found by setting the internal pot of the laser diode to zero and then slowly increasing the driver current using the manual pot. Meanwhile, one watches for light to appear on a flat piece of paper placed in front of the diode laser. Since the human eye is far more sensitive to photons than most electronic equipment, finding the threshold current of the diode laser by eye is perfectly legitimate.

Beyond finding the threshold current it is also useful to know how the laser power increases as a function of current. To measure the power of our output spectrum we used an external laser power meter (Molectron AS500). The power meter was located so that it received the collimated output coming directly from the diode laser. Figure 8 shows the output power versus input current for the HL7851 laser diode, with the diffraction grating removed.

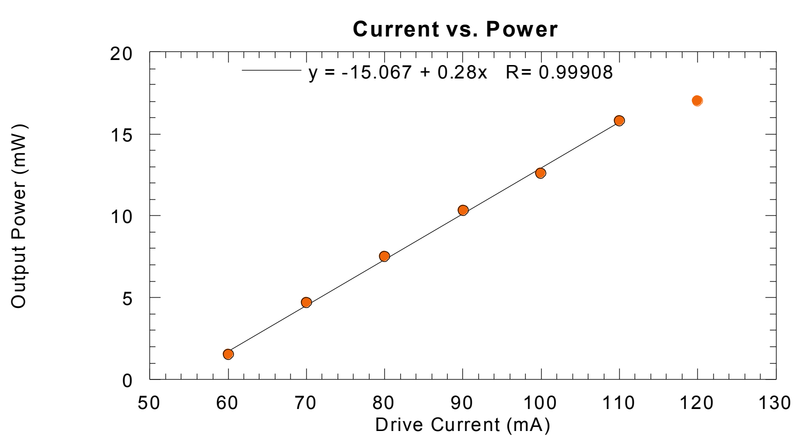

Figure 8: The relationship between output power and input current. From the threshold current up till roughly 110 mA the plot of the output power vs. current follows a linear trend. However, beyond this region this output is not linear.

From our research on semiconductor laser diodes we expected the output power to be linearly dependent on the drive current. However, what we found for the HL7851 was that the output power followed a linear trend with respect to the input current until the current reached 110mA. Beyond this point the system becomes nonlinear in nature. Furthermore, if the drive current exceeds 130mA the output current becomes unstable and will fluctuate within a range of 10mW.

4.2 Tunable Modes of the ECDL

The main objective of this research project was to construct an external cavity diode laser that could select a wide range of output frequencies from a simple diode laser whose output had a broad bandwidth. Figure 9 shows that we were able to accomplish just this.

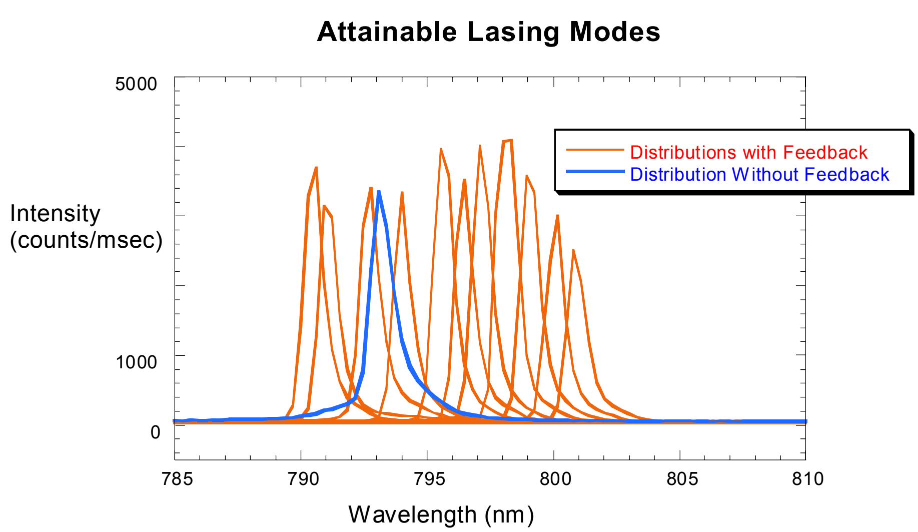

Figure 9: The red lines in this graph show the attainable stable lasing modes of the ECDL with a drive current of 69mA. The blue line shows the distribution of the HL7851 without the optical feedback from the diffraction grating. We found that at this current the ECDL had a stable tuning range of 11nm.

Once we had the first order diffraction from the grating going directly back into the lasing cavity of the diode laser, we were able to get results like those shown in

Figure 9. The individual lasing modes, shown in red, where obtained by varying the normal angle of the diffraction grating to select different wavelengths to be reflected back to the diode laser. This plot shows the superposition of many of the stable lasing modes that the ECDL selected individually. The blue line in the graph shows the original output from the HL7851 diode laser without optical feedback. It is important to note that that original output is broader than any of the spectra with the optical feedback. Also, one should notice how the right tail of the original distribution is fatter than the left tail. Because the original distribution is made up of all the individual modes, one would expect to find more individual attainable lasing modes to the right of the original peak than to the left, based on the heavier right tail on the original distribution. Looking at the red lines on our plot, which range from the lowest stable mode to the highest stable mode, we see that this is precisely what we found. The fact that there is not a more significant difference between the bandwidth of our original distribution and the bandwidth of each mode, as we would expect there would be, can be attributed to the fact that our spectrometer has a resolution power of only 1 nm. Consequently, we suspect that the individual lasing modes actually have a narrower bandwidth than what is indicated in Figure 9.

4.3 Stable Range versus Current

To study how semiconductor diode lasers are affected by increases in the current and the thermal energy across the p-n junction, we next studied how our tunable range of wavelengths was affected by input current. Figure 10 shows how the position of the highest stable mode of a given tunable range changed with an increasing current.

In general, the upper ends of the tunable ranges increase as current increases. However, the relationship between current and peak wavelength is clearly not linear. Notice that there is a large jump in peak wavelengths as we move from a drive current of 75mA to 80mA, but then the peak wavelength barely changes at all until we push the drive up to 110mA. Such a complex relationship between tunable range and drive current suggests that calibrating an ECDL such as this one would be difficult if one wanted to include all possible parameters that could be varied in the system (see Figure 10).

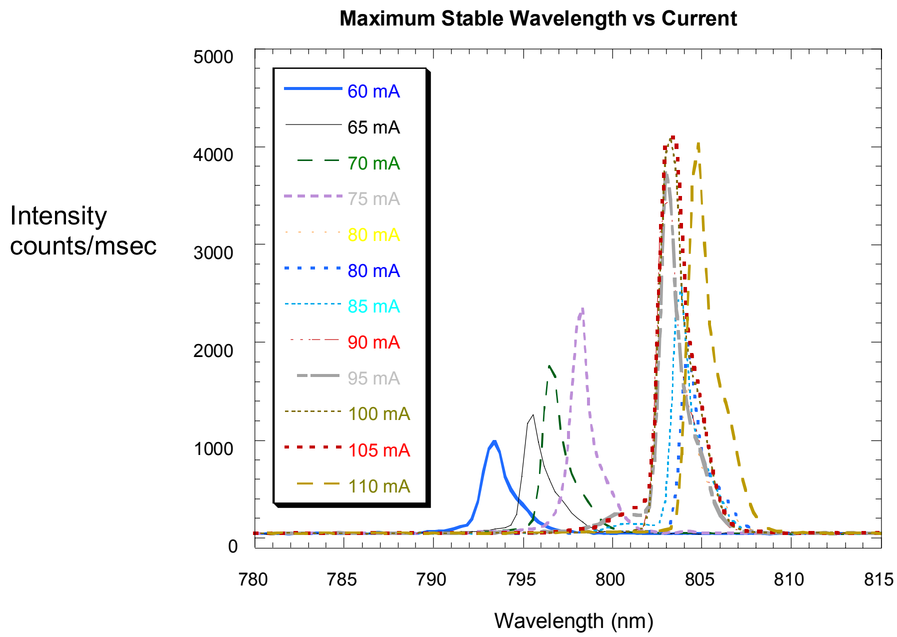

Figure 10: Each peak on this graph represents the highest wavelength in the stable tunable range at a given input current. The different input currents are differentiated by color and pattern and are indicated in the legend to the left. In general, the upper ends of the tunable ranges tend to increase as the current increases.

4.4 Selected Wavelength versus Angular Position

The final aspect of our system that we wished to analyze was the angular dependence of the feedback lasing modes. Using the fine adjustment knob on the back of our diffraction grating mount, we recorded the change of wavelength versus the Litrow angle. Since the wavelength that is sent back to the diode laser travels along the path of the incident beam of light, we expect the relationship between angular displacement and the wavelength of our output to obey the Litrow angle equation (eqn 5). The Litrow angle was changed by moving a micrometer which tilted the grating base plate by a certain distance that we could measure to a level of accuracy of 1μm. The data are shown on Figure 11. We expect, from looking at Equation 5, a linear relationship when plotting the wavelength versus 2sin(θ). Moreover, the expected slope of the graph is d = 833.33(nm), which is the grating spacing constant we calculated earlier.

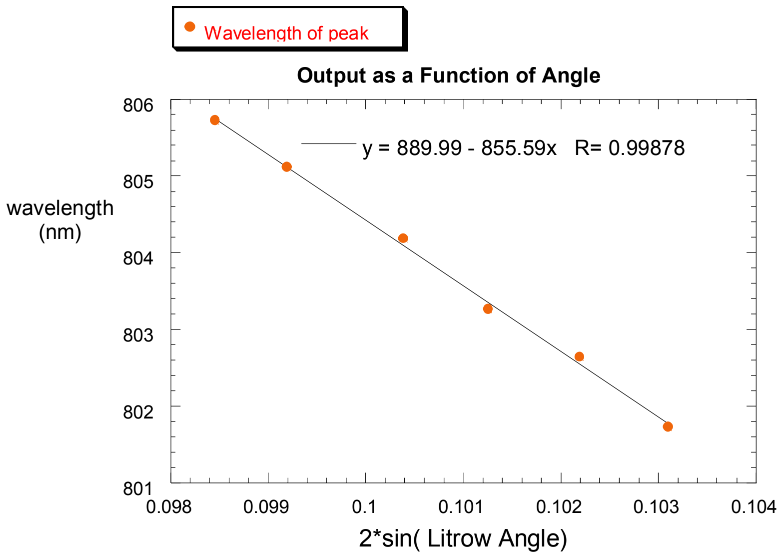

Figure 11: This graph shows the relationship between the selected wavelength and the angle of the diffraction grating. The data above agrees with what is predicted by the Litrow angle equation. The drive current for the laser diode while the data was taken was 130 mA.

Our results, shown on Figure 11, agreed with our expectations. The absolute value of the slope of our best fit line was 855.59 (nm) which is within 2.7% of our expected slope.

5.0 Conclusions and Future Work

5.1 Conclusions

After a semester of failed attempts, we finally constructed an external cavity diode laser that produces a tunable, collimated beam of light. We studied and characterized the output of the tunable, monochromatic light source we had created, and from our observations of the ECDL's output, given variations of certain input parameters, we determined the following properties about out system. First, we noticed that we could select monochromatic lasing modes from an 11nm range of possible lasing modes. Tuning the precise wavelength we wanted was fairly easy with the setup we had. By design, our ECDL has a single knob to control the horizontal change in the normal angle of the grating. We found that, as predicted by the Litrow angle equation, the wavelength selected was linearly dependent on the sine of the Litrow angle.

However, we observed that the laser's response to a change in current was not linear. We suspect the system's complicated response to changes in current stem from internal characteristics of the diode laser. There appeared to be a linear and nonlinear region in the graph of laser output power vs. current, and when the system was driven at higher levels the output power was unstable. These observations suggest than the internal dependence on drive current may more complex than we assumed and may be due to internal saturation of the laser diode.

5.2 Future Study and Use of the System

The next step in improving the lab device we have constructed is to make the device controllable by computer or digital controls. Piezoelectric crystals can be inserted on the back of the diffraction grating mount to adjust the angle of the grating. Such a change in the setup would take minimal effort. Calibrating the input current and the output power, however, will be much more of a challenge. As we noted in our results, further data must be collected to establish the relationship between the drive current and the output light of the ECDL before we can determine and equation that would allow us to understand this behavior.

Until then, the setup as is can still be used for educational purposes in either general public lectures on lasers or for advanced undergraduate labs. This setup is ideal for a teaching a general audience about important concepts in laser physics such as feedback, bandwidth, and coherent light sources. Moreover, since semiconductor lasers are used in many devices today it is important to use setups like this one in general lectures to introduce the members of the audience to this type of laser. For all the above reasons, this setup is well suited for the advanced undergraduate laboratory, and gives the students experience in collimation techniques and working with a variety of optical components.

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