

A Novel Extended-Cavity Diode Laser in Red Wavelengths

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1. INTRODUCTION

1.1 Motivation

Semiconductor diode lasers operate by releasing stimulated emission from recombination of electrons and holes from neighboring semiconductor layers. These lasers have become one of the most widely used sources of laser light, especially in the red wavelegths. They are very cheap, simple to operate, and provide a reasonably large amount of power, from hundreds of microwatts to a few watts. However, because of the nature of the laser cavity in the diode laser chip, they tend to have several properties that are not ideal for atomic physics and spectroscopy. Laser radiation from a naked laser diode tends to be very multimode, poorly collimated, and unstable. There are also several 'holes' in the visible red spectrum, where no commercially available laser diodes operate. The purpose of this project was to create a system in which such a semiconductor diode laser can operate in a stable, single-mode fashion that is easily controllable, and to reach a wavelength not available using commercially available semiconductor lasers.

1.2 Laser Background

A laser's operation is based on stimulated emission. In the case of semiconductor diode lasers, the stimulated emission comes from electrons and holes from neighboring layers of semiconductor material that come together in a middle layer, recombine, and emit light. The density of electron-hole pairs in such diodes is high enough that many more photons are emitted through stimulated emission than are lost through absorption and other processes. Thus laser diodes are said to be very high-gain. Since stimulated emission causes the emitted photons to have the same wavevector and phase as the incident photons, the diode emits coherent laser light.

The laser cavity is the primary mode of control of the wavelength of laser light emitted. Each face of the laser diode acts as a mirror, and constructive interference allows only modes of laser light in resonance with the laser cavity to transmit through the output side of the diode. This cavity, because of its plane, parallel reflectors can be characterized as as a Fabry-Perot cavity[1]. The transmission from this cavity is given by the Airy function.

$$Transmission(\delta) = \frac{1}{1 + F \sin^2(\frac{\delta}{2})}$$

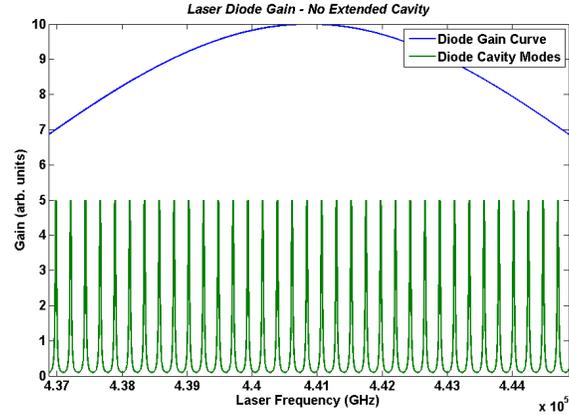


Fig. 1.1: Bare laser diode without an external feedback element. The laser diode's gain curve (blue) is divided into allowed regions by the allowed modes of the laser diode (green). Since the modes are so closely spaced, the laser diode easily switches between them and has trouble achieving single-mode operation. The y-axis here is arbitrary; the width of the diode gain curve and the spacing of the allowed modes of the laser diode were determined using estimates for the laser gain bandwidth and length and reflectivity of the diode[2].

Here, F is the coefficient of finesse of the cavity, given by

$$F = \left(\frac{2r}{1 - r^2} \right)^2$$

where r is the amplitude reflection coefficient of the parallel plates, and δ is the difference in angular frequency between photons that have travelled once through the cavity and photons that have travelled twice through the cavity. One can see that only when δ equals $n\pi$ is there no destructive interference between reflected photons in the cavity. Thus the higher the finesse of the cavity, the more times photons reflect before they leave the cavity, and the more destructive interference of off-resonant photons occurs. This allows the cavity to select a single dominant wavelength at which the laser operates.

The difference in Hz between constructively interfering modes of the cavity, or the free spectral range of the cavity, is given by

$$\Delta\nu = \frac{c}{2nL}$$

where c is the speed of light, n is the index of refraction of the diode medium, and L is the length of the diode. Changing the current to the laser diode changes the index of refraction, changing the frequencies of light allowed to transmit through the laser cavity. Figure 1.1 shows the combination of the overall gain of the laser diode medium and the wavelength selection of the diode cavity. However, since many of the allowed modes have similar amplitude when multiplied by the diode's gain curve, the laser diode tends to

be very unstable and multimode, or jumps between modes frequently. These properties make it very important to introduce a mechanism for controlling the wavelength of the laser diode.

1.3 Extended Cavity Diode Lasers

The main solution to the problem of multimode operation of laser diodes is the construction of an Extended Cavity Diode Laser (ECDL). This is any system in which an external component is added to the laser that feeds back laser light to the laser diode. Since only modes of light that are allowed by both the laser diode itself and the extended cavity can propagate, this allows the user to select the mode of the laser cavity that they want to dominate. Figure 1.4 shows how a single laser mode will be selected using the combination of the diode's overall gain curve, the allowed modes of the diode itself, and the allowed modes of the ECDL cavity. Using this technique, a multimode diode laser can be converted into a stable, single-mode and much more useful ECDL.

The most common ECDLs are Littman-Metcalf and Littrow cavity lasers. In these configurations, a grating placed outside the laser cavity is positioned so that the 0th or 1st order diffracted light is fed back into the laser diode, creating the feedback necessary to achieve single-mode operation. Figure 1.2 shows two examples of such laser designs. Although these lasers are very stable and have good tuning ranges, the gratings can be difficult to work with and are not easily cooled, mostly because of the fact that they are not very compact.

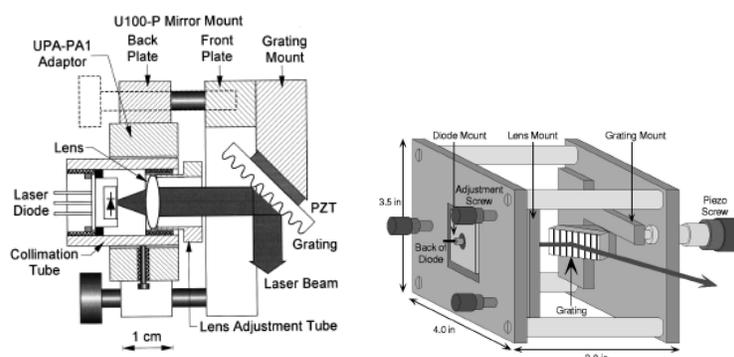


Fig. 1.2: Two examples of simple Littrow extended cavity designs[3][4]. First-order diffracted light from the grating feeds back into the laser diode and causes single-mode operation. Reflected light from the grating is the laser output. The precise positioning of the grating is the main method of wavelength control, since the angle of diffraction is dependent on the wavelength of the light diffracted back.

1.4 Temperature-Tuning of Diode Gain Curves

To reach red wavelengths that do not fall under commercially available diodes' gain curves, we chose to cool our laser diode. It is well known that laser diodes vary their wavelength widely when their temperature is modulated [5]. Laser diodes using temperature as the main method of continuously controlling the laser wavelength have been constructed [6]. An example of such a system is shown in Figure 1.3.

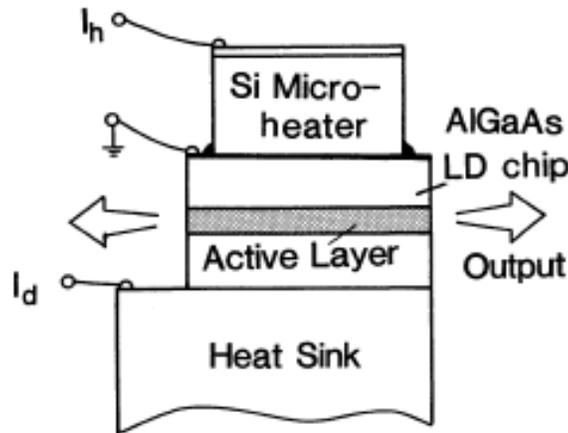


Fig. 1.3: Temperature-modulated semiconductor laser [6]. The temperature is dynamically tuned by the heating element to tune the laser wavelength. Response time is improved by the small size of the laser and the close proximity of the temperature control element to the diode itself.

However, using temperature for active wavelength control is difficult because of the timescales involved in heating and cooling the laser apparatus. We chose instead to use temperature to move the entire laser gain curve, and to dynamically control the laser wavelength using other methods.

1.5 Short Extended Cavity Diode Lasers

A short extended cavity diode laser (SECDL) is one in which the external feedback element is a partial reflector placed extremely close to the output of the laser diode itself, so that the length of the external cavity is on the same order of magnitude as the length of the diode cavity. The output of such a laser is shown in Figure 1.4. We see that the short extended cavity laser uses constructive interference of the allowed modes of the laser diode and the short extended cavity to select a single laser mode. Because of the high gain of the laser diode, all other modes are suppressed and the transmitted light is single-mode.

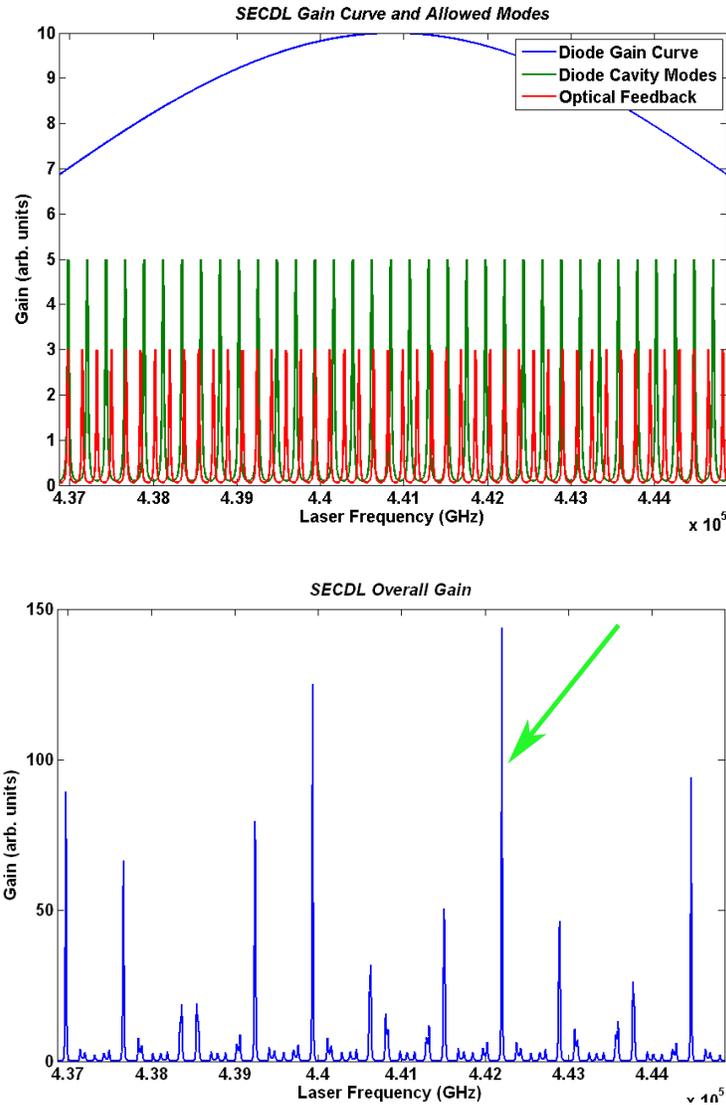


Fig. 1.4: Laser diode with short extended cavity (top). Here, the diode's gain curve (blue) combines with both the laser diode modes (green) and the external cavity modes (red) to allow fewer of the diode modes to transmit. The bottom graph shows the three wavelength selection tools multiplied together. We can see that one mode is clearly more allowed than the rest, and there are no close-by allowed modes. This allows the laser to undergo single-mode operation. Note that the spacing between the laser diode modes and the external cavity modes is very similar; this is an important feature of short extended cavities.

We chose the short extended cavity design because of several advantages that such a system offers. First, because the entire SECDL is compact, it can easily be cooled significantly without changing the alignment of the laser system. It is also easily constructed, because the single-mode operation of a SECDL is not lost when the output coupler is tilted somewhat off-axis[7].

Using short external cavities to control diode laser operation has been explored, mostly in the infrared. Confocal mirrors instead of flat output couplers as the external cavity reflectors have been explored using $1.3\mu\text{m}$ semiconductor lasers[8]. Other systems, such as micromachined external reflectors[9] and using fiber optics as the external feedback element[10] have been realized as well. Figure 1.5 shows such designs.

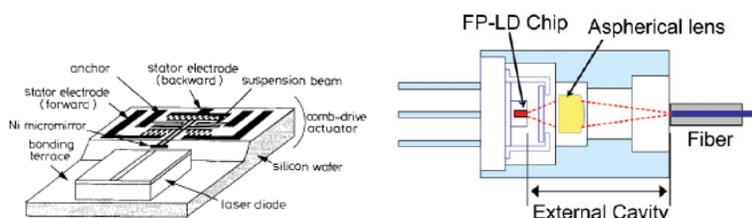


Fig. 1.5: Micromachined SECDL[9] and Fiber-Formed SECDL[10]. The micromachined laser uses a tiny strip of metal as an external feedback element, which can be precisely controlled to tune the laser wavelength. The fiber-formed laser uses the face of the fiber optic that it couples into as its external reflector. Enough light reflects off of the face of the fiber optic to create single-mode operation.

1.6 Temperature Tuning SECDLs in Red Wavelengths

Short external cavity lasers in visible wavelengths have been closely studied, including the dependence of their wavelength on temperature and other aspects of their operation that are similar to the quantities measured in this study[11]. However, the lasers created in these studies are not necessarily designed for integration into a larger atomic physics apparatus. Alternately, lasers designed with the goals of simple design and inclusion in larger experimental apparatus have often been created[3][12]. These have the advantage that their performance is well-known and usually very good. However, they often are not capable of reaching wavelengths not available in commercial laser diodes. This study aims to expand the knowledge of the operation of red wavelength SECDLs to a specific design that has several advantages over previously created designs.

In particular, the concept of using a SECDL as an easily coolable apparatus to take advantage of the fact that the diode's gain curve shifts as its temperature changes is a novel one. Using a simple and novel design, we have created a laser that is able to reach wavelengths not commercially available in laser diodes through cooling to near liquid nitrogen temperatures. It has been

shown to exhibit stable, single-mode operation, good temperature tunability, and a mode hop free tuning range of over 20 GHz.

This design's low cost, simplicity of construction and operation, and large tuning range make it a powerful tool in many atomic physics applications. The fact that it can be cooled in vacuum without modification and thus reach previously unavailable wavelengths makes it even more valuable. Its usefulness in laser cooling and trapping has already been shown, by reaching previously unavailable atomic transitions in Strontium. Such a laser design could be adopted for a variety of functions with very little modification.

2. DESIGN AND CONSTRUCTION

2.1 *Laser Design*

The laser was designed with compactness in mind, so that it could be mounted on a simple thermo-electric cooler for temperature control and installed in a larger apparatus. Figure 2.1 shows a 3D image of the design. Full schematics of all components can be found in the appendix. The laser diode is mounted into the large aluminum outer piece in a slot, and is held in place by a simple aluminum ring which is clamped down with screws and washers. Thus the leads of the laser diode are easily accessible from outside the laser. The optical section of the laser consists of a large brass piece that screws into the outer aluminum block. On it is mounted the cylindrical Piezo-Electric Transducer (PZT), and on top of the PZT the output coupler - in the form of a 50 or 90 percent reflector - is mounted. The aspherical lens, used to collimate the laser light after it passes through the output coupler, is threaded into the brass piece. Thus, the focus of the aspherical lens can be adjusted for optimal collimation at any time from outside the laser apparatus.

The brass piece is prevented from rotating freely with a plastic screw that screws through the outer aluminum body of the laser. Teflon tape helps with smooth rotations of all of the threaded parts. Finally, the entire apparatus is placed on some sort of mount, using plastic screws that pass through the aluminum outer piece, with a thermo-electric cooler (TEC) between the laser and its mount. Thus the entire apparatus is electrically floating, preventing minor fluctuations in the ground from either destroying the laser diode or causing instability in the laser wavelength. It was noticed that proper isolation of all components that attach to the laser and its mount is essential for even acceptable single-mode operation, and several diodes were destroyed because of this mistake. Finally, two small holes for the wires leading to the PZT were drilled through the bottom of the brass piece, leading out of the apparatus.

The entire apparatus takes very little time or precision to construct, and can be easily taken apart, modified, and put back together. In particular, the face of the output coupler was visibly not perpendicular to the axis of the laser light, and the performance of the laser did not seem to suffer. For cold applications, special epoxy must be used to glue the PZT and output coupler components together. However, very little else needs to be done to the entire apparatus for it to properly operate in a vacuum chamber at cold temperatures. One exception is that, to prevent a pocket of air from forming between the brass piece and the PZT, one must drill a hole into the side of the brass piece somewhere along its

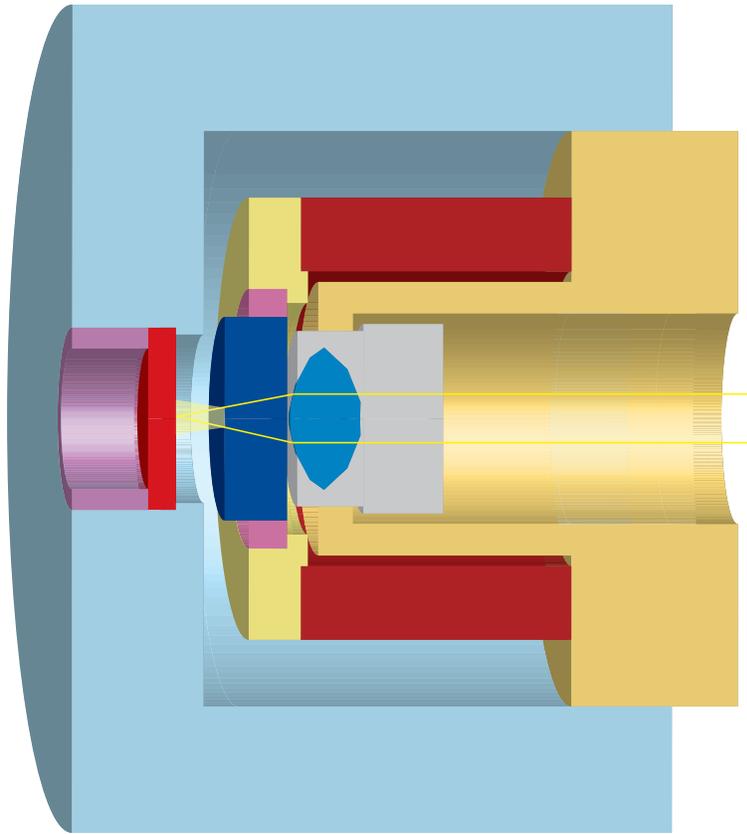


Fig. 2.1: SECDDL Design. Laser light (yellow lines) from the diode (red) is collimated by the aspheric lens (grey). Feedback light reflects off of the the front face of the partial reflector (dark blue). The aspheric lens is mounted with threads, so it can be focused properly. The larger piece holding the aspheric lens and partial reflector is also threaded into the aluminum body. The PZT (dark red) controls the distance from diode to partial reflector.

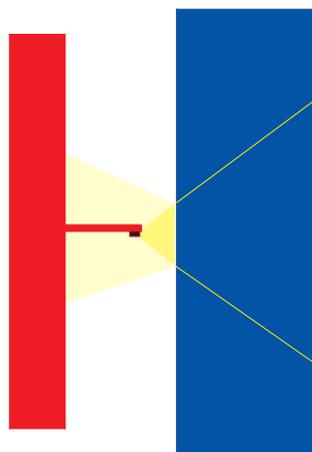


Fig. 2.2: Closeup of feedback. The light coming out of the laser diode chip (black) is very divergent, and the feedback from the partial reflector (blue) easily covers the entire diode. The fact that so much feedback light is lost indicates that a strong (90 percent) partial reflector could be needed to provide enough feedback to achieve single-mode operation. We explored this possibility by characterizing the laser with partial reflectors of two different reflectivities.

length.

It was observed that the laser operation was optimized for the most part when the output coupler was as close to the laser diode chip as possible. The brass threaded piece was usually screwed in until the output coupler actually butted against the diode, and then unscrewed a small amount. To get even closer to the laser diode output, we chose to bevel the laser diode mount down as much as possible without damaging the diode. However, this step is not necessary for stable, single-mode operation and the laser performed admirably without it.

2.2 Laser Characteristics and Advantages

As shown, the laser has three dynamic wavelength control mechanisms. The current supplied to the laser diode, the voltage applied to the PZT, and the temperature of the whole laser assembly (including the diode itself) can all be adjusted to tune the wavelength of the laser. The effectiveness of each of these mechanisms is discussed in later chapters.

There were a few external factors that influenced the operation of the laser. As mentioned before, the laser diode must be completely isolated for it to operate properly. This includes isolating the ground wire to the laser diode itself to the power supply's ground. Also, the wavelength failed to remain stable when-

ever there were significant vibrations in the table that the laser was mounted on. Several rubber pads and a quieter location helped this, but there was always observable jitter in the laser wavelength. It was never determined how much of this was due to vibrations and how much was intrinsic to the laser.

The cost of this laser was significantly less than any commercially available ECDLs. The laser was operated using two laser diodes, most significantly a QPhotonics QLD-735-10S 735 nm laser diode, costing 210 dollars. The aspheric lens was a ThorLabs C330TM-B aspheric lens, costing 89 dollars. The PZT initially used was a large, cylindrical stack PZT from American Piezo costing 1000 dollars, but it was replaced later by three cheaper AE0203D04F PZTs from ThorLabs that cost 72 dollars each. Instead of a stacked PZT ring, a smaller aluminum ring was placed on the threaded brass piece and the ThorLabs PZTs were glued on top of it. This still performed as desired, although the ThorLabs PZTs were not capable of displacing as far as the large cylindrical stack PZT was. All other costs associated with the laser were material and shop fees for constructing the components, and the minor costs of the screws, tape, and epoxy that was used during assembly.

The final laser is extremely easy to construct and use, and its size makes it easy to implement in a larger experimental apparatus. It also costs less to make than other types of lasers that use diffraction gratings, and requires much less precision in construction - the laser comes almost ready to assemble. Its convenience, simplicity, performance, and the fact that it is as easily disassembled as it is assembled makes it a very useful tool in many areas of atomic physics.

3. CHARACTERIZATION TECHNIQUES

As discussed previously, the laser was designed with the intention of using the laser's current, the voltage to the PZT, and the temperature of the system as the main means of tuning the diode's wavelength. We therefore characterized all three of these mechanisms, so that we could find the laser's mode-hop-free tuning range when each of these tuning parameters were employed. We were also interested in the slope of the linear dependence of the wavelength on each of these factors. Finally, with the temperature, we needed to obtain a longer range plot of wavelength vs temperature over several mode hops of the SECDL, so that we could demonstrate the ability to reach wavelengths far from the wavelength of the laser diode at room temperature.

The characterization of the laser was carried out using two major tools, a wavemeter and a Fabry-Perot interferometer. The laser light was collimated and passed through a beam splitter. The reflected light from the splitter was focused slightly into the Fabry-Perot interferometer. The transmitted light was coupled into a fiber optic using a fiber optic mount. The other end of the fiber optic was plugged into the wavemeter, which was used for absolute wavelength readings.

3.1 *Fabry-Perot Interferometer*

The Fabry-Perot interferometer works the same way as described above for the diode laser itself. Two partially reflecting surfaces, this time confocal, form a cavity. The length of the cavity is coarsely tuned using a thread on the blocks holding the two mirrors. The output coupler mirror is mounted onto a large stack PZT, and by adjusting the voltage applied to the PZT we can control with a great deal of precision the length of the cavity. The output from the Fabry-Perot cavity was fed directly into a photodiode.

As we saw before, the cavity transmission goes like the Airy function, where δ is the difference in phase between light that has been reflected once and light that has been reflected more than once. Thus the laser light transmits through the cavity only when the cavity size is such that light in the cavity constructively interferes. Data is then collected by continually ramping some parameter, such as the laser current, so that the laser wavelength tunes continually. If laser light of a single wavelength is coupled into the Fabry-Perot interferometer, as the cavity size reaches a resonance with the laser light, transmitted light will exit the interferometer and a peak will be shown on the oscilloscope. The

free spectral range of the cavity is the minimum difference, in Hz, between two wavelengths of laser light for them to both be in resonance with the cavity. As before, the free spectral range of the cavity is given by

$$\Delta\nu = \frac{c}{2nL}$$

where c is the speed of light, n is the index of refraction of the cavity medium (in this case, air has $n=1$), and L is the length of the cavity. The free spectral range of the cavity can therefore be used to scale the x-axis on data, and determine the tuning range of the laser. The Fabry-Perot cavity used in this experiment had a free spectral range of 500 MHz.

The Fabry-Perot interferometer can also be used to distinguish mode-hop-free tuning from tuning with mode hops. If the wavelength of the laser tunes continuously, then at regular intervals (every 500 MHz) we will see a peak in the transmission from the Fabry-Perot interferometer. If the laser undergoes a mode hop, its wavelength will not be smoothly related to the varied parameter and there will be a break in the graph of Fabry-Perot transmission vs the varied parameter. Thus, if we can fit the output of the Fabry-Perot interferometer to the Airy function, for the region that the data fits well in the Airy function, the laser wavelength tuning is demonstrably mode-hop-free and we can estimate the tuning range by counting the number of transmitted peaks and multiplying by 500 MHz.

3.2 Wavemeter

The light transmitted through the beamsplitter was then coupled into a fiber optic cable, which allowed easy coupling with a wavemeter, a digital device that displays the wavelength or frequency of laser light input into the wavemeter. This has the advantage over the Fabry-Perot interferometer that it gives the absolute wavelength, whereas the Fabry-Perot interferometer can only display the mode shape and relative distance (in Hz) between peaks. The response time of the wavemeter is much slower than that of the interferometer, and it does not demonstrate single-mode operation. However, it can be very useful in conjunction with the Fabry-Perot interferometer. Most notably, the wavemeter was used to measure tuning ranges of several nm , because the Fabry-Perot interferometer can only be used to measure the tuning range of the laser if it continuously tunes over the whole range, so that the entire range can be displayed on an oscilloscope. Specifically, the wavemeter was used in long range temperature tuning measurements.

3.3 Problems Encountered

The main issue that we had to deal with when collecting data on the laser was feedback. As the laser light is coupled into the Fabry-Perot cavity or the fiber optic, some of the light reflected off of the surface of the input optics

reflects back down the laser beam path. Thus, just like in the SECDL, the optic acts as another extended cavity. Because of the very large size of the beam path compared to the size of the SECDL laser cavity, this simply causes the signal to become multimode and very jittery. In fact, feedback effects can be directly observed as the laser is coupled into the cavity with better and better precision. To avoid these effects, we simply chose to misalign the system a slight amount so that the reflected light did not fall back on the diode. We still had a strong enough signal that good data acquisition was possible. We misaligned the system only enough so that the output from the interferometer was clearly single-mode and stable.

The only other problems encountered were vibrations (which the system was very sensitive to) and the short lifetime of laser diodes when not carefully dealt with. The vibrations were dealt with by moving the characterization setup to a different table and placing it on a rubber mat. The diodes tended to die quickly if the system was jostled or there was a problem with the electrical ground. Once in the laser, however, the diode was relatively well protected and it operated admirably.

4. REFLECTIVITY OF OUTPUT COUPLER

One of the major questions addressed in this project was how important the reflectivity of the output coupler is in achieving stable, single-mode operation with good tunability. The original laser design was made with a 90 percent reflector as the output coupler, with the intention of creating a large amount of feedback so that the laser was more likely to achieve single-mode operation. This is because the increased finesse of the extended cavity make the overlap of the Fabry-Perot modes of the diode itself and the extended cavity more sensitive, and thus suppresses all non-dominant modes. One can see that in the Airy function, increased finesse decreases the width of the Fabry-Perot peaks (see figure 1.4). We therefore wanted to know if this large amount of feedback was necessary for stable, single-mode operation and if tuning of the laser diode was dependent on the reflectivity of the output coupler.

Since single mode SECDLs have been constructed using an extended cavity made with something as nonreflective as a microscope slide[12], we suspected that the 90 percent reflector was not necessary. We also were eager to use an output coupler with a smaller amount of reflectivity because reflectivity severely limits the output power of the laser, since the total wattage inside the extended cavity is limited by the laser diode and the amount of transmitted light is equal to $(1 - r)$ times the power inside the laser cavity, where r is the reflectivity of the output coupler.

We therefore performed the same characterization of our laser with a 50 percent reflector as the output coupler of the SECDL, with the goal of seeing if there were any differences in performance between it and the 90 percent reflector laser. The reflectivity curves of both output couplers are given in the appendix.

5. TEMPERATURE TUNING

We were interested in the temperature tuning characteristics of our laser over a long range for reaching new wavelengths, and over a short range to understand the mode hop free tuning range of our laser. The temperature tuning was measured using a wavemeter as described above because of the relatively large range over which we tuned and because of the slow response time of the laser to changing the set temperature of the laser.

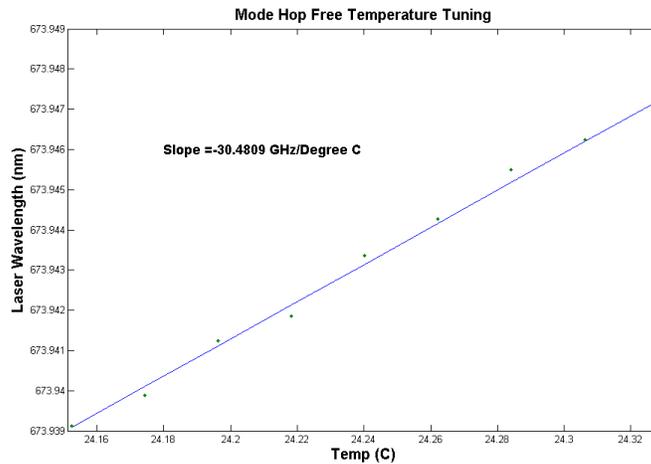


Fig. 5.1: Temperature tuning data for the 90 percent reflector. One full mode-hop-free tuning range was covered near room temperature with a 670 nm laser diode. The response time on the temperature tuning was not fast enough to make continuous tuning of the laser wavelength with temperature a useful tool. The sensitivity of the laser wavelength to temperature is given.

The wavelength of the laser was taken to be stable when the observed output modes in the Fabry-Perot interferometer were stable. The mode-hop-free temperature tuning data was taken by tuning the temperature using the temperature controller until we got just over a mode hop (as observed on the Fabry-Perot interferometer) and then recording the wavelength as we changed the set temperature by small increments. Thus, the wavemeter was used to monitor the wavelength of the laser, and the Fabry-Perot interferometer was used to monitor the laser mode and make sure that the laser did not go over any mode

hops. We were able to achieve mode hop free tuning of around 5 GHz. This is a significant amount, but because of the slow response time of the laser to changes in the set temperature, it is not very useful for dynamic laser control in actual use. Figure 5.1 shows the mode hop free temperature tuning data, taken using a 670 nm laser diode. It is important to note that the wavelength remained very stable, even though in this data no special attempt was made to isolate the laser from the environment other than controlling its temperature with a simple TEC lock circuit. Specifically, the air in the laser cavity was the same temperature as the air in the room, and there was no attempt at protection from wind or other disturbances.

Since our stated goal for temperature tuning was to use large changes in temperature to reach wavelength ranges otherwise unavailable in commercially available laser diodes, we also measured the long-range temperature tuning of the laser. Figure 5.2 shows how the dependence of the laser wavelength on temperature is different for continuous tuning and over several mode hops. This characteristic ladder shape helps confirm the single-mode operation of the laser, as it jumps from mode to mode in a very consistent pattern. This data was taken with a 735 nm laser diode.

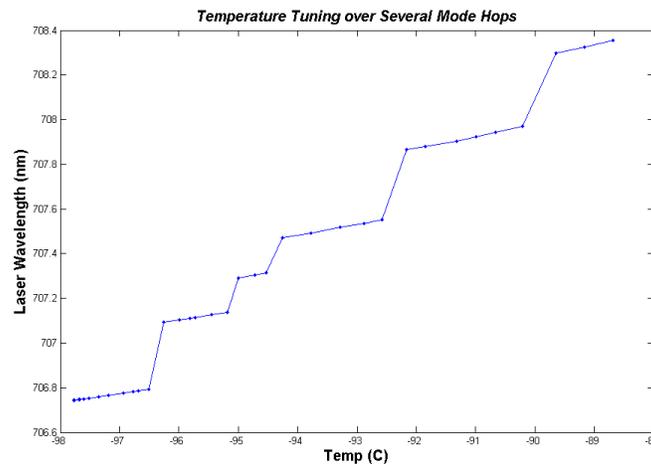


Fig. 5.2: Temperature tuning of a 735 nm diode over several mode hops. The characteristic mode hop free tuning followed by transitions between modes is shown. One can see that the laser wavelength sensitivity to temperature is different in mode hop free tuning than in long range tuning.

We also tuned the temperature of the 735 nm diode all the way from room temperature to near liquid nitrogen temperature to show the long range wavelength dependence on temperature tuning and the ability to reach wavelengths not available in commercial diodes. Figure 5.3 shows the dependence of the wavelength on temperature in our laser for a large range of temperature tuning. Using a least-squares fit, we were able to find a good fit for the wavelength

vs temperature over the entire range of temperature tuning, given by

$$\lambda = 305.7e^{4.41 \cdot 10^{-3}(T-393.9)} + 674.1$$

We can clearly see that the wavelengths achievable by our laser are outside the range of available wavelengths normally available in commercial diode lasers. It is important to note that there are only certain temperature ranges available in this data because the laser temperature was controlled with a simple thermoelectric cooler creating a temperature gradient from either a liquid nitrogen bath or room temperature air.

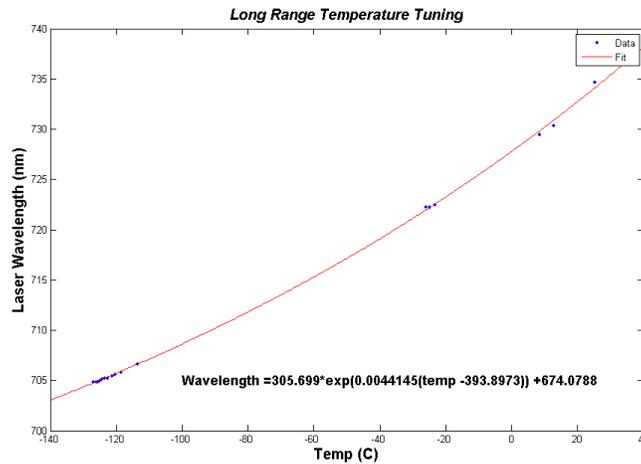


Fig. 5.3: Exponential fit to long range temperature tuning of a 735 nm laser diode. The long range sensitivity of laser wavelength to temperature is shown. The overall tuning range of the laser from room temperature to near liquid nitrogen temperature is very large, and the laser wavelength range clearly reaches wavelengths not available at room temperature from commercially available diodes.

6. WAVELENGTH TUNING WITH CURRENT AND PZT MODULATION

In this section, we will present the two methods of tuning wavelength that have fast response times - tuning the length of the extended cavity with the PZT, and tuning the laser wavelength with the current. We will see that these methods are not equally capable of tuning the laser wavelength. We will also address the impact of using a 50 percent reflector as our output coupler instead of a 90 percent reflector.

6.1 *Tuning with Current*

As the current to the laser diode increases, the power output of the diode changes as well. This modulation also changes the index of refraction of the semiconductor itself, causing the effective path length of the laser diode cavity to change. As we saw before, the allowed modes of the diode laser cavity depend on the relative phase difference between light incident on the output facet of the cavity, which depends on both the wavelength of light and the length of the cavity (see figure 1.1). Thus, as the effective cavity length changes, different wavelengths are allowed to transmit from the diode laser cavity.

We notice that as the effective path length of the diode changes, the effective path length of the extended cavity changes as well, since the extended cavity is defined as extending from the output coupler to the back facet of the laser diode. Thus, both of the Airy functions that combine to allow a specific mode to resonate as in figure 1.4 shift together. The Airy function of the diode cavity is given by

$$Amplitude = \frac{1}{1 + F \sin^2\left(\frac{2\pi n L}{c} \omega\right)}$$

where ω is the frequency of the light, F is the finesse of the cavity, n is the index of refraction of the diode, L is the length of the diode, and c is the speed of light. The corresponding Airy function for the extended cavity is given by

$$Amplitude = \frac{1}{1 + F \sin^2\left(\frac{2\pi}{c} (n_1 L_1 + n_2 L_2) \omega\right)}$$

where here n_1 is the index of refraction of the diode and n_2 is the index of refraction of air ($n_2 = 1$), and L_1 and L_2 are the lengths of the diode and extended cavity, respectively. We can see that the effective length of the extended cavity,

n_2L_2 , is similar to and perhaps even shorter than that of the laser diode, n_1L_1 , because the index of refraction of the laser diode is around 3 and the length of the extended cavity is similar to that of the diode.

Therefore, as the index of refraction of the diode changes, the frequencies at which the diode cavity and the extended cavity will experience maxima will change together, allowing the same mode to dominate for a long range. We should then expect to observe a large tuning range before any mode hops occur when we tune the laser wavelength with current. This continuous tuning of the laser wavelength is very important for reaching desired wavelengths in atomic physics applications.

Data for the tuning range of the laser using current tuning was collected using the Fabry-Perot interferometer. The laser current was ramped using a sawtooth wave, and the resulting output of the Fabry-Perot interferometer as the laser wavelength shifted was recorded. Figures 6.1 and 6.2 show the transmission of the Fabry-Perot interferometer as the laser wavelength was tuned with current. As mentioned before, when the transmission peaks through the interferometer are evenly spaced, we can infer that the laser is undergoing continuous tuning and single-mode operation. This was checked by fitting an Airy function to the data to make sure that the peak spacing was regular. It is very important to remember that this Airy function represents allowed transmission of light through the Fabry-Perot interferometer, and not the allowed modes of the laser itself.

Since the free spectral range of the interferometer is known to be 500 MHz, we can infer the mode hop free tuning range of the laser by counting the number of peaks that coincide with the fitted Airy function. Each peak corresponds to the laser tuning 500 MHz without undergoing a mode hop. Both laser configurations therefore exhibited around 20 GHz of mode hop free tuning. It is believed that an even larger tuning range is available.

It can be seen that the laser with the 50 percent reflector did not operate in any noticeable way that was worse than the 90 percent reflector. However, the data taken with the 90 percent reflector was taken using a diode that was partially damaged, which is why there is an offset of the transmission from 0. This damage to the diode could have also affected its tuning range. Most importantly, we note that this setup is capable of tuning through the majority of the diode's allowed current range without mode hopping, and that both reflectivities provide a wide enough tuning range for most applications.

6.2 Tuning with PZT

This mechanism for tuning the laser wavelength is much simpler than temperature or current tuning of the laser wavelength. As one can see from the laser design, the output coupler is mounted on a PZT, or piezo-electric transducer, which changes its length in a very precise and controlled manner based on the amount of voltage applied across it. Thus, the length of the extended cavity can be tuned by a small amount, changing the effective path length of the extended

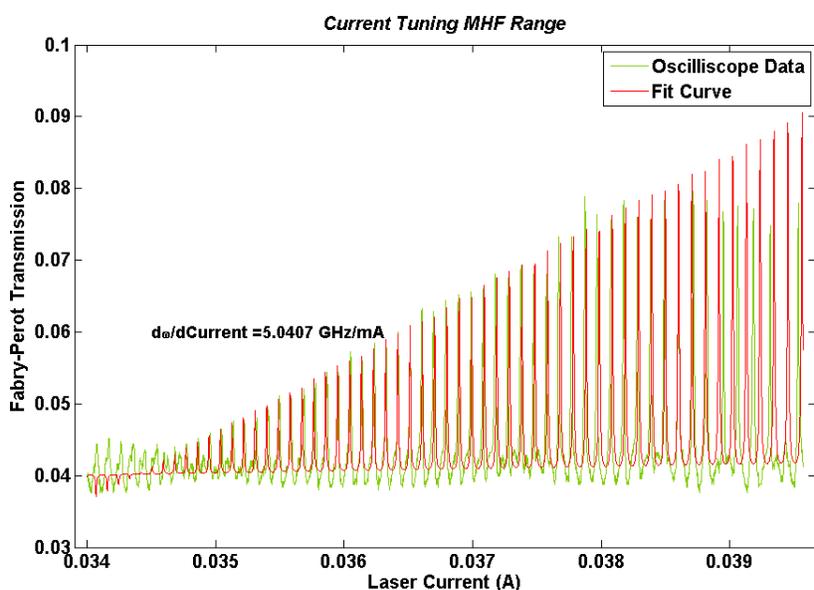


Fig. 6.1: Mode-hop-free tuning of a 670 nm diode with a 90 percent reflector output coupler using current modulation to continuously tune wavelength. Since the free spectral range of the Fabry-Perot interferometer used is 500 MHz, each peak represents 500 MHz of mode-hop-free tuning. The total tuning range verified here is greater than 20 GHz. A mode hop is visible on the right as the fit curve no longer matches the data.

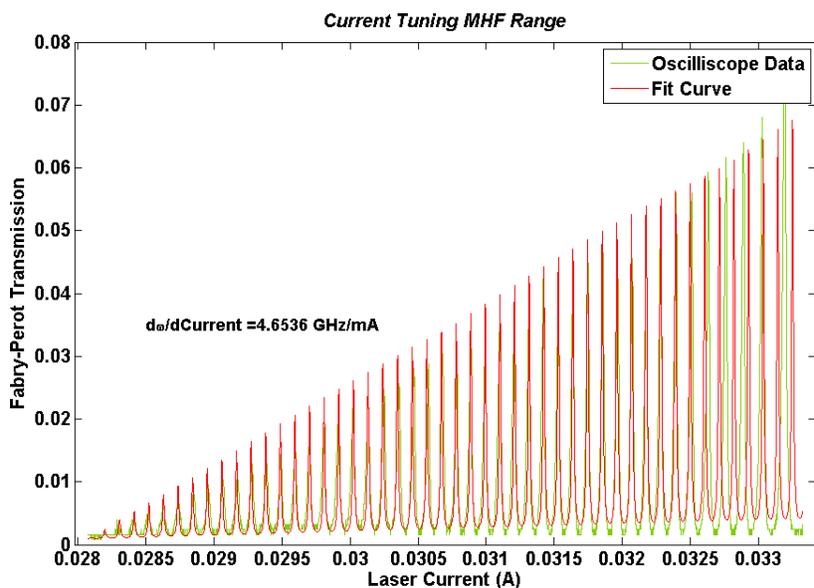


Fig. 6.2: Mode-hop-free tuning of a 670 nm diode with a 50 percent reflector output coupler. Again, the mode-hop-free tuning range is greater than 20 GHz. The lower baseline and stabler output is believed to be the result of using a newer diode. We can see that the decreased reflectivity of the output coupler, while increasing the laser power output, does not limit the laser's tuning range due to decreased feedback.

cavity and shifting the allowed modes in the extended cavity. However, unlike current tuning, only the length of the extended cavity changes as voltage is applied to the PZT. This means that, instead of shifting the dominant mode a long distance before mode hops occur, we can expect the feedback from the extended cavity to select a new mode relatively quickly.

Figures 6.3 and 6.4 show the PZT tuning data. Because of the short and inconsistent tuning range of the PZT, this data was taken in a different manner than the current tuning data. Instead of ramping the voltage to the PZT and observing mode-hop-free tuning as regularly spaced peaks of transmission through the Fabry-Perot interferometer, the length of the Fabry-Perot interferometer was ramped using a PZT of its own. The voltage to the PZT of the laser was left constant, and as the Fabry-Perot interferometer cavity length came in resonance with the laser light from the SECDL, peaks of transmission were observed.

The PZT voltage in the laser was then stepped a controlled amount, and the process was repeated several times. The plots of the data show several of these plots on top of each other, showing how the Fabry-Perot interferometer came in resonance with the laser light at different lengths for each voltage. When the peaks shifted by a constant amount every time the applied voltage was changed, we can assume the laser was undergoing mode-hop free tuning of the wavelength. When the peak locations changed seemingly at random between voltage steps, we can observe mode hops. The red lines indicate mode-hop-free tuning, and the blue circles show mode hops.

Since the free spectral range of the Fabry-Perot cavity is 500 MHz, we can actually use these plots to create a scale for the x-axis. Since several peaks are visible at each voltage level, we can say that the length of separation between peaks is 500 MHz. Thus, when the laser is continuously tuned, we can see what the mode-hop-free tuning range is by seeing how many free spectral ranges the laser tuned over. Because the PZT tuning was very inconsistent, we can only say that the PZT tuning was on the order of 500 MHz. The difference between the 90 percent and 50 percent reflector plots cannot be taken to be concrete evidence of different behaviour between the two laser configurations, because the oscilloscope was operated at different settings between the two plots and because once again the PZT tuning was so inconsistent. However, we can say that the PZT is not a useful tool for significant laser wavelength tuning, as we only got about $\frac{1}{40}$ of the tuning range with the PZT that we did with the current. It was a useful tool in practice, however, because it could be used for mode selection and very short range wavelength tuning. Using a combination of PZT, current, and temperature tuning, the laser was found to be capable of reaching any wavelength in the diode's wavelength range.

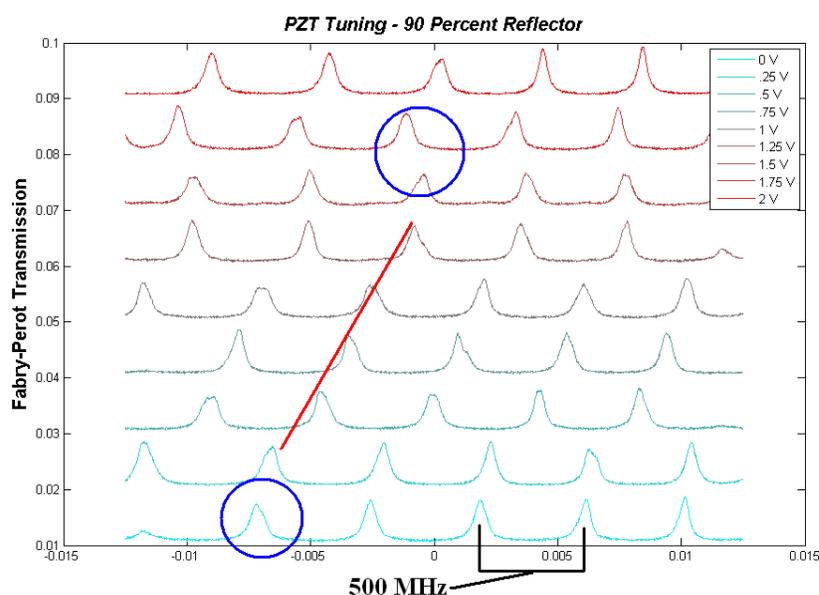


Fig. 6.3: Mode-hop-free PZT tuning of a 670 nm diode with a 90 percent reflector output coupler. For each successive line, one can see that the increase in PZT voltage tuned the laser wavelength somewhat, causing the output of the Fabry-Perot interferometer to shift. However, we can see that the laser was only able to tune about one full width between peaks before the output ceased to shift linearly with increasing PZT voltage, indicating a mode hop. Thus the mode hop free tuning range using the PZT is only on the order of 500 MHz.

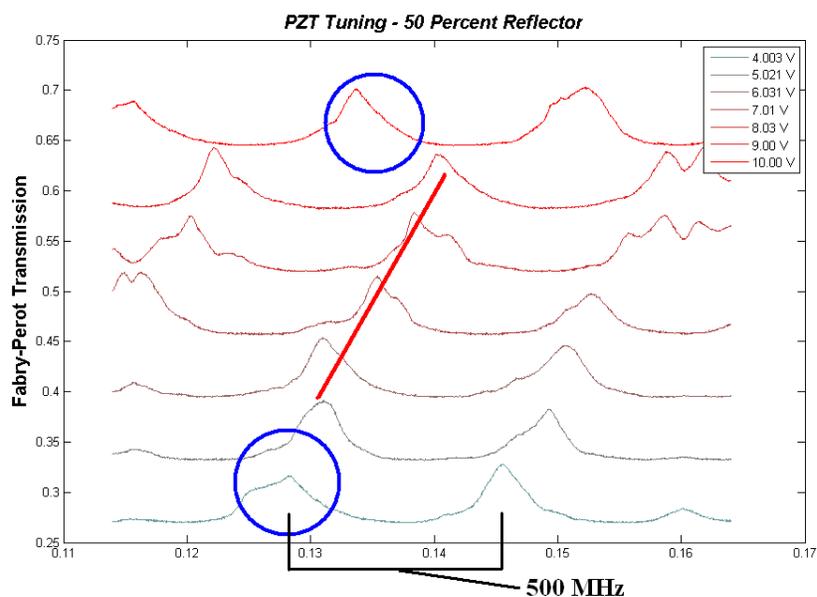


Fig. 6.4: Mode-hop-free PZT tuning of a 670 nm diode with a 50 percent reflector output coupler. We can see that the tuning range of the laser using the lower reflectivity output coupler is still on the order of 500 MHz, making continuous tuning of laser wavelength using the PZT not a very useful tool. The PZT is instead more useful as a mode selector, rather than a continuous tuning tool.

7. THRESHOLD AND POWER

7.1 Laser Threshold

The threshold current of a diode laser is the current at which the density of electrons and holes is high enough that the gain of the laser is greater than 1, or the current at which an emitted photon is more likely to create stimulated emission than to get absorbed. We expect the threshold of the bare diode to be higher than that of the SECDL, because when the output coupler is in place, the extra photons that are reflected into the gain medium help induce stimulated emission, which lowers the threshold current.

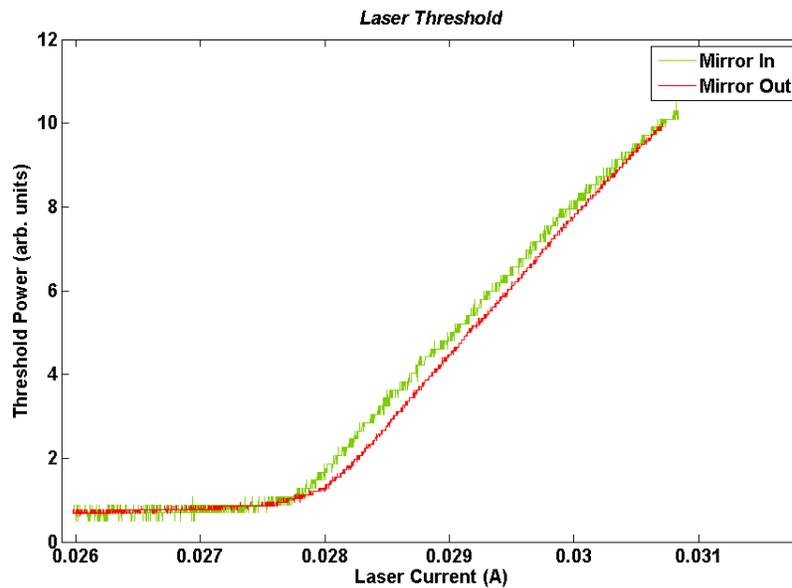


Fig. 7.1: Laser threshold with 50 percent reflector output coupler and with no feedback. One can see that the laser threshold is lowered by the feedback element, as expected. The laser power is normalized to an arbitrary scale to show the threshold location more clearly.

Figure 7.1 shows the thresholds of the bare laser diode and the SECDL with the 50 percent output coupler. The laser current was ramped over the laser

threshold and detected with a photodiode. The output from the photodiode was recorded on an oscilloscope. It is relevant to note that to better depict the laser thresholds, the vertical scale was made to be arbitrary so that each of the power outputs were normalized to the same amount. It is clear that the threshold of the laser with the 50 percent reflector is somewhat lower than that of the bare laser, as expected.

7.2 Laser Power

We also wanted to know the output power of the SECDL. Figure 7.2 shows the laser power as a function of the applied laser current with the 50 percent reflector present. The diode here was rated to 10 mW of total output power. Since the output coupler reflects 50 percent of the light from the laser diode, the amount of power in the extended laser cavity is twice the amount of light output. We therefore never want to exceed 5 mW of output power, because then the laser diode has more than 10 mW of laser light travelling through it. This can destroy the diode.

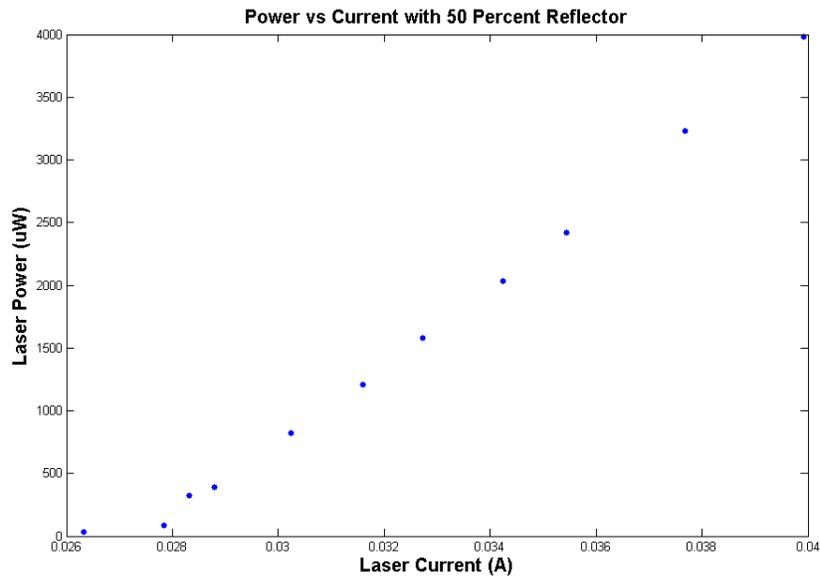


Fig. 7.2: Laser power from threshold with a 50 percent reflector output coupler. The laser diode was rated at 10 mW. Obtaining several mW of output from this laser design was very easy, making it useful for a number of applications.

One can see that the laser reached power levels of as much as 4 mW. Thus its behaviour was similar to our expectations. Data was also taken for the power of the SECDL with the 90 percent reflector as the output coupler, but since

the diode was already damaged, this data does not represent the actual power curve of the laser. It was clear, however, that the SECDL with the 90 percent reflector had much less output power. This was as expected, and since the laser tuned just as well with the 50 percent reflector as it did with the 90 percent reflector, it suggests that for most applications the 50 percent reflector is a better solution because it supplies so much more power.

8. APPLICATION - COOLING AND TRAPPING OF ATOMIC STRONTIUM

This laser can be used in many applications of atomic physics. It was first used in a cooling and trapping experiment with ^{88}Sr . This isotope of Strontium has an atomic transition at 707.202 nm, which cannot be reached by a commercially available laser diode. A chart of the energy levels of Strontium is shown in figure 8.1.

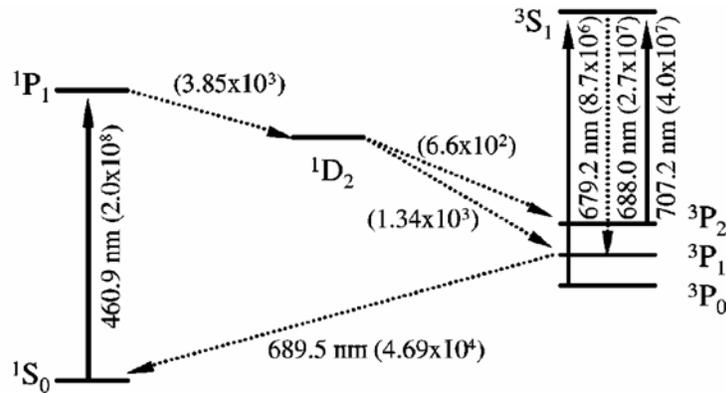


Fig. 8.1: Energy levels of ^{88}Sr . The red MOT operates along the $^1S_0 - ^1P_1$ transition. However, some atoms in the 1P_1 state decay down to the 3P_2 and 3P_1 states. The 3P_2 state is metastable, and does not decay to the ground state to first order. It therefore acts as a 'leak' in the MOT and limits the number of atoms that we can trap. With the 707 and 679 nm lasers, all of the atoms can get 'pumped' into the 3S_1 state and eventually back into the 3P_1 state, which decays to the ground state. Thus the 'leak' in the red MOT is closed.

The experiment uses a Magneto-Optical Trap (MOT) to cool and trap Strontium atoms. This trap operates using a laser that operates along the $^1S_0 - ^1P_1$ transition of Strontium. Atoms that are near the edges of the trap or are moving out of the trap absorb photons from the laser, which pushes them back to the center of the trap. They then decay back down to the ground state. However, as one can see from the energy level diagram, an alternate decay channel for excited-state atoms is present, to the 3P_2 and 3P_1 states. The 3P_2 state is metastable, which means that it cannot decay down to the ground state via single-photon decay, because the transition is spin-forbidden. Thus the life-

time of atoms in this state is much longer than the lifetime of the trap itself, and these atoms are lost from the trap. Although this alternate decay channel is very unlikely, the losses through this path accumulate quickly and limit the number of atoms that can be trapped in the MOT.

Using the 707 nm laser that we have created and a 679 nm Littman-Metcalf laser, we are able to promote all atoms from the 3P_2 state into the higher 3S_1 state. Since this state decays back down to all of the 3P states, eventually all of the atoms will fall into the middle 3P_1 state, which can decay back down to the ground state. Thus, the 'leak' in our MOT is closed and no atoms are lost from the trap.

The SECDL we created was locked to the $^3P_2 - ^3S_1$ transition by cooling it and getting its wavelength near the desired wavelength, and then shining it through a Strontium vapor cell. The laser wavelength was continuously ramped, and as it crossed the atomic transition the transmission through the cell decreased because of the absorption of the photons by the Strontium gas. Using a lock circuit, the laser was then locked to the minimum of the dip in laser transmission, exactly where the laser was in resonance with the $^3P_2 - ^3S_1$ transition. This is a standard method for locking lasers to atomic transitions.

Figure 8.2 shows the fluorescence of the atoms in the MOT with no repumpers on, with the 707 laser on, and with both the 707 and 679 lasers on. This fluorescence corresponds to the number of atoms in the trap, since the trap fluoresces when atoms near the edges of the MOT absorb light and are pushed back into the center of the trap.

One can see that as the 'repumper' lasers were added to the system, the fluorescence of the trap increased. The loading time of the trap also increased, indicating that the maximum number of atoms in the trap was higher, so it took longer to completely fill. In fact, the total number of atoms that were able to be trapped was increased by as much as 6 times when the repumpers were added to the system. This was very useful, because it contributed greatly to signal strength when performing experiments on these cooled and trapped atoms.

This laser is applicable in many similar areas of atomic physics, or wherever lasers locked to atomic transitions are needed. Its small size and simplicity of operation make it ideal for incorporation in a larger experiment. Its electronics also lend themselves to easy integration in a lock circuit, as the circuitry we used was identical to the locking systems used for other, non-SECDL lasers in the lab. It is very cheap, simple to construct and operate, and extremely versatile.

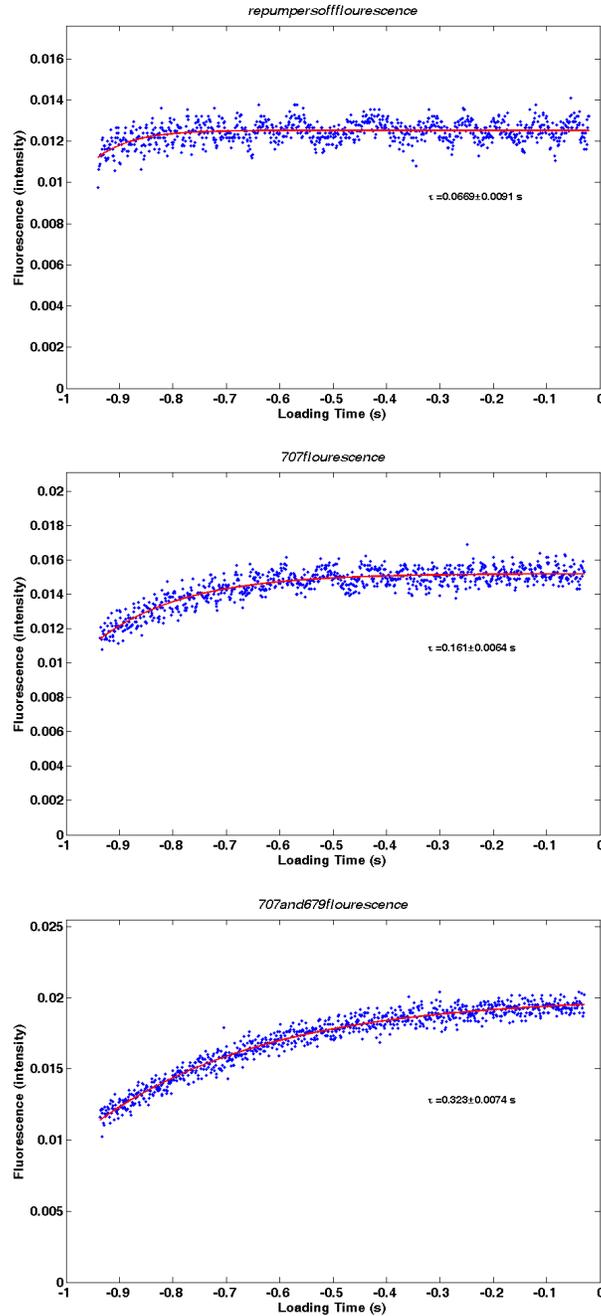


Fig. 8.2: Fluorescence from Magneto-Optical Trap with no repumper lasers on, the 707 nm laser on, and with both the 679 and 707 nm repumper lasers on. The amount of fluorescence indicates the number of atoms in the trap, and the loading time of the trap also indicates the rate of losses from the trap. With the repumpers on, atoms lost from the trap into metastable atomic states are being pumped back into the ground state, where they are once again trapped. The 707 nm laser is the laser described in this paper locked to an atomic transition of Strontium using a vapor cell.

9. CONCLUSION

In conclusion, we have constructed a novel SECDL that has immediate applications in laser cooling and trapping, and should be applicable to many other experiments. This laser not only is easy to operate and control at room temperature, but it can be easily cooled to allow access to wavelengths not commercially available in diodes without losses in its performance. Its performance has been characterized here, and the laser has been shown to exhibit good mode-hop-free tuning over at least 20 GHz when tuning the laser current, which is comparable to other diode lasers.

We believe that the combination of a SECDL with long range temperature tuning of the laser diode is a new system, and we believe that it has many applications in physics beyond the application that we have used it for. This is especially true because of the extreme ease of construction of the laser, due to its simple design, and the relatively low cost of all of the parts involved.

Because of the thickness of the output coupler, the collimation of the laser light with the aspheric lens was not perfect, and external optics had to be used to collimate the laser. We believe that using a thinner output coupler would remedy this problem, and make our laser even more versatile in its applications. It also might be possible to explore tuning the laser with the PZT and the current simultaneously, to achieve an even larger tuning range. This concept has been explored before[13], and has been shown to be effective in extending the mode-hop-free tuning ranges of ECDLs. Without improvements, however, our laser operates admirably and should be considered in many atomic physics applications.

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APPENDIX

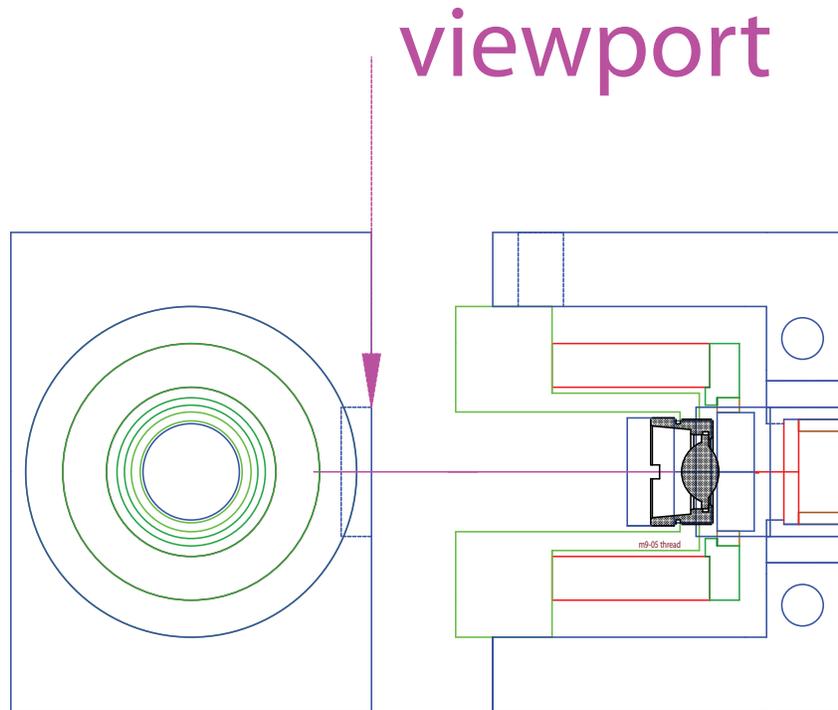


Fig. .1: Laser assembly drawing with aspheric lens from ThorLabs. The rectangular viewport allows the user to see how close the face of the output coupler is to the diode.

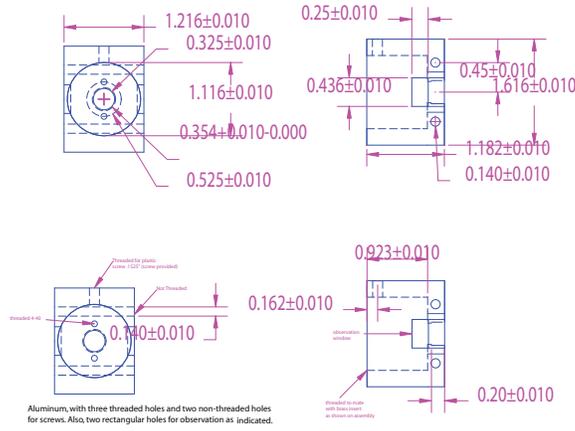


Fig. .2: The outer body of the laser. The brass cylinder threads into the main hole of the body. The diode slides a slot on the opposite face. All other parts are held to the aluminum body using screws - nothing is glued to this piece.

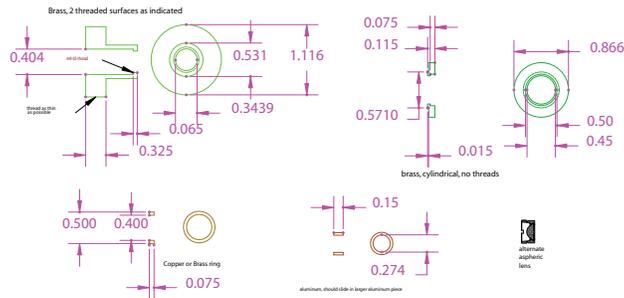


Fig. .3: These are the other parts of the laser. The large brass cylinder, along with one of the brass rings, the cylindrical PZT, and the output coupler, are glued together to make the barrel of the laser. This piece is then screwed into the aluminum body and held in place with a plastic screw. The aspheric lens threads into the brass cylinder as shown in the assembly drawing. The final aluminum ring is used to press the diode into its slot in the aluminum body. It is held in place with screws and washers.

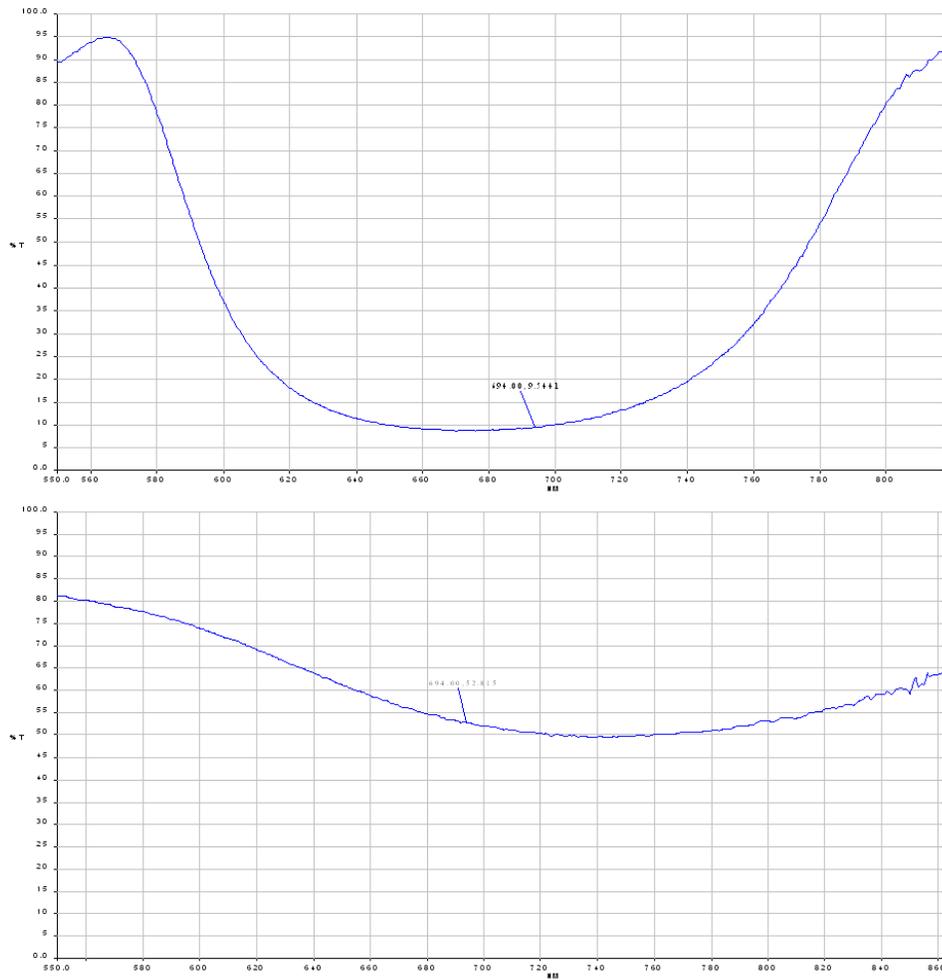


Fig. 4: Transmission curves for 90 percent reflector (top) and 50 percent reflector (bottom) provided by CVI. We can see that the reflectivity is not constant as the wavelength changes over several nm, but our laser wavelength did not change enough for the change in reflectivity to alter the performance of the laser.