ABSTRACT

NARROW-BANDWIDTH OPERATION AND IMPROVED BEAM QUALITY OF A SEMICONDUCTOR BROAD AREA LASER IN AN IMPROVED VARIABLE-LENGTH EXTERNAL CAVITY.

by Ryan W. Coons

We have devised an improved collimation system for a variable-length Littman-Metcalf external cavity diode laser (ECDL), which greatly improves the quality of a broad-area laser (BAL). We expand on previous work by determining the spectral bandwidth, modal linewidths, and $M^2$ beam quality factor of the ECDL. We have found that the improvement of beam quality is critical to spectral narrowing, and that a BAL will behave in the same way as any other laser would in an external cavity. The beam profiling techniques used to determine the $M^2$ beam quality factor are discussed, along with other supplemental techniques to further enhance spectral narrowing.
Narrow-bandwidth operation and improved beam quality of a semiconductor broad area laser in an improved variable-length external cavity.

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In memoriam
William John Coons
1950-2006
None of this would have been possible without my parents, Bill and Darla. They’ve stood behind all me in all of my endeavors – even when they didn’t understand what I was doing, or why I was compelled to do it.

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Chapter 1
Introduction

The laser is an ubiquitous tool within the fields of science, manufacturing, and communications. The origin of the laser goes back to the dawn of modern physics. The concept of a laser originated with Einstein’s proposal of stimulated emission, an additional radiative process, which will be discussed in Section 2.1. This principle was employed in the maser, which was used to emit a coherent beam of microwaves. Maser theory was independently developed around 1951 by both Townes and Schawlow in the United States, and by Basov and Prokhorov in the Soviet Union. Gordon, Zeiger, and Townes later confirmed this by constructing a maser, using an ammonia gain medium. Masers quickly found applications in radio astronomy, military radar, and as a frequency standard, for use in atomic clocks [1].

The groups of Townes and Schawlow [2], and by Basov and Prokhorov further developed their theories, both proposing an “optical maser” or “laser,” which emitted coherent visible light [1]. This was first achieved in 1960 by Maiman using ruby as a gain medium [3]. Other schemes for creating lasers were proposed using various different gain media, including semiconductors [4]. Shortly thereafter, stimulated emission was observed in semiconductors made from GaAs [5], and they were quickly adapted into gain media for masers [6] and lasers [7,8]. The first double-heterostructure CW laser which could operate at room temperature was made in 1969 from a GaAs/GaAlAs semiconductor by Hayashi and Pannish [9]. Since then, semiconductor lasers of various powers and wavelengths have become available [10].

Semiconductor materials are the basis for the microprocessor industry, and a great deal of time and money has been invested into finding cost-efficient methods to produce semiconductors. Because of the low cost of semiconductor lasers, they are well-suited for fiber-optic communications and optical storage applications [1]. This line of research is a continuation of the work pioneered by Sands [11], who created a tunable, high-powered Littman-Metcalf external cavity diode laser (ECDL). This laser can access wavelengths of $\approx 790 \pm 12$ nm with a maximum power of 1 W. Sands determined that the modal linewidth goes as the inverse square root of the cavity length for his ECDL [11]. This is in direct contradiction with the model presented by Littman and Metcalf who state that the linewidth has a inverse linear relationship with cavity length [12]. The Littman-Metcalf model was based from conclusion drawn from his work with single-mode dye lasers, where Sands utilized multimode diode lasers. The deviation from the model when additional modes are present suggested that Metcalf’s model was incomplete. However, this was not a definite conclusion, but rather a hypothesis drawn from four points of preliminary data. Further investigations were necessary to determine the true nature of the linewidth vs. cavity length relationship for external cavity lasers.

This ECDL was originally constructed for the optical pumping of $^{87}$Rb through excitation of the $D_1$ line at 794.7 nm. The $^{87}$Rb was to be used in the electron-spin polarization of $^{129}$Xe [13]. Using a spectrally narrow high-power laser for this purpose is a more cost-effective method of producing hyperpolarized noble gases [14, 15], which can be used to greatly enhance medical imaging [16].
However, due to the fact that it would take considerable time (on the order of four years) to build the nuclear magnetic resonance (NMR) equipment needed to confirm our findings, it was decided to abandon this line of research.

The properties of this ECDL, up to this point, are assumptions based entirely from preliminary data. The characteristics of this laser’s output need to be fully determined. In addition to refuting the work of Littman-Metcalf or Sands, this will provide a benchmark from which other spectral narrowing techniques can be applied. Also, the behavior of the ECDL will be better documented, giving an idea of what to expect in future alkali excitation and frequency doubling experiments.
Chapter 2

Background information

In this section we will present the necessary background needed to understand my research. Laser principles, semiconductor lasers, external cavities, filamentation, and laser beam quality will be discussed.

2.1 Laser theory

To understand lasers, we must first understand the three radiative transitions of electrons between two different atomic energy levels. In absorption, an incident photon gives an electron the energy it needs to be excited from its ground state to some excited state. From this excited state, there is a probability of the electron to decay and return to its ground state, emitting a photon of incoherent light. This referred to as spontaneous emission [17]. In 1916, Einstein proposed another process, stimulated emission. For a electron already in the excited state, an incident photon has a probability of disturbing the excited electron, causing it to decay back to the ground state and emit a photon of the same energy, direction, phase, and polarization as the incident photon [18].

In order for a laser to operate, there must be a population inversion within the gain medium; that is, there must be a larger amount of electrons in the excited state than in the ground state. This will allow stimulated emission to be the dominant process. A population inversion in achieved through pumping, where the electrons are constantly being excited either optically or electrically.

![Figure 2.1: Fabry-Pérot resonator. Energy applied from an external source, E, excites the gain medium, G, to induce stimulated emission. The emitted light reflects between a near-perfect mirror, \( M_1 \), and a perfect mirror, \( M_2 \), such that a standing wave is formed, amplifying the emitted light. Light exits the resonator as the losses from \( M_1 \).](image.png)
The light emitted from the stimulated emission is then amplified by a resonator cavity. The simplest laser resonator is the Fabry-Pérot waveguide-type resonator. This consists of an pumped gain medium, and two mirrors, one in the direction of light propagation, and one in the opposite direction. The light waves emitted from the gain medium reflect off of both mirrors, which are spaced such that light will form a standing wave pattern. This amplifies the light through the superposition principle. This light is then emitted from the resonator as the losses from the near-perfect mirror.

2.2 Semiconductor lasers

The basic model for a laser, as described in Section 2.1, is for a simple material comprised of atoms which do no interact with one another, like a monatomic gas or metallic vapor. A solid however, does not have discrete energy levels. The atoms of a crystalline solid are chemically bonded to one another, causing their electron clouds to overlap. These many overlapping energy levels blend together to form a energy band. Interactions between the atoms divides the energy bands into two, discrete energy bands, which are analogous to the energy levels discussed in Section 2.1. The valence band is comprised of the outermost electron shells, and represents the highest energies an electron can possess while still being bound to the atom. The conduction band represents the area outside of the electron shells, corresponding to electrons with enough energy to break free from the atom. Electrons in the conduction band are free to move about the material. This is the flow of electric current, and a material with electron in the conduction band is said to be an electrical conductor. Insulators and semiconductors have populated valence bands, but empty conduction bands. An insulator requires a large amount of energy for a electron to break free of the valence shell, this corresponds to a large gap between the energy bands [19].

Electrons that receive energy from an outside source can jump from the valence band to the conduction band, if the applied energy is equal to the separation between the bands. This is the bandgap energy, $E_g$. When an electron leaves the valence band, there is room for another electron in that band. This is said to be a “hole” in the valence band. Likewise, when the valence band is full, there is room for an electron in the conduction band. This is an electron-hole pair (EHP).

A semiconductor in its lowest energy state, has no electrons in its conduction band, and behaves like an insulator. Because of its smaller bandgap, a semiconductor requires less energy than an insulator would to allow electrons to jump into the conduction band. Because of this, a semiconductor can function as either a conductor or insulator by applying different energies.

When a electron in the conduction band falls back to the valence band through stimulated or spontaneous emission, a photon is emitted. This photon has an energy equal to the bandgap energy, as described by Planck’s Law:

$$E_g = h\nu. \quad (2.1)$$

The sizes of the bandgaps can be altered by doping, the adding of impurities into the semiconductor material. These additional atoms cause the energy shells to superimpose differently, and materials can be custom-made to a desired bandwidth specification. Doping can have a profound effect on the band structure, and typically, dopants comprise only 0.0001% of the gain medium [19]. When a material is doped to have a surplus of electrons, it is called a p-type semiconductor, and a n-type semiconductor when doped for excess holes. When these two material types are brought together, they form a p-n homojunction, or diode [19]. The two layers are separated by the depletion layer, a neutral zone where electrons and holes combine, and there are no mobile carriers. A potential develops because of this. This is the bias voltage needs to be applied to allow current to flow. Homojunction diode lasers are inefficient because it is difficult for them to obtain a high carrier density in the active region, and they cannot maintain a population inversion. This can be resolved by mating a heterostructure
A double heterostructure confines the active gain medium by isolating it with a cladding material on both sides. This cladding has a larger bandgap than the active area, confining all the charge carriers to a confined area. The cladding also has a smaller refractive index, causing the gain media to act as waveguide for the emitted light [17, 21, 22].

**Figure 2.2:** A double heterostructure diode with a bandgap of width \( d \). The cladding has a greater energy gap, \( E_{g,cl} \), than the bandgap, \( E_g \) [21].

**Figure 2.3:** A cross-section of a typical GaAs double heterostructure laser diode [22].

### 2.3 External laser cavities

Any given laser can have its intensity amplified and its spectral output narrowed by allowing certain modes to dominate through the placing the laser into an external cavity. Optics are positioned around the laser, causing a portion of the beam to couple and constructively superimpose with itself. Essentially we are building a laser out of a laser. Our ECDL uses our BAL as a coherent light source, and the external cavity optics to complete the laser resonator.
There are many external cavity laser geometries, with the most popular being the Littman-Metcalf cavity, and the Littrow cavity. Ours cavity is of the Littman-Metcalf design, which was originally designed to serve as an improved resonator for dye lasers [12]. In a Littman-Metcalf laser cavity, the laser beam shines on a diffraction grating at grazing-incidence, illuminating the entire surface of the grating. The grating is used as a beam splitter, the zeroth-order beam is emitted as the output, while the first-order beam is reflected from a mirror, which feeds the first-order beam back to the grating. The grating again acts as a beam splitter, sending the first-order diffraction into the BAL where it couples with the incident beam [12,23,24]. The zeroth-order feedback is diffracted out of the laser, and is lost. Because of this beam dumping, Littman-Metcalf cavity lasers have only 50-70% of the power of the same BAL would have when placed in a Littrow cavity [23]. The bandwidth of the cavity laser (BW) is given by:

\[
BW_{d_1 > z_r} = \frac{\lambda^2 \sqrt{2} z_r}{\pi d_g (\sin \Theta + \sin \Phi) d_1}
\] (2.2)

where \(\lambda\) is the peak wavelength of the laser, \(z_r\) is the Rayleigh length of the laser (see §2.5.2), \(d_g\) is the width of the diffraction grating, \(d_1\) is the distance from the BAL to the diffraction grating, \(\Theta\) is the angle from the incident beam to the grating normal, and \(\Phi\) is the angle between the grating normal and the mirror normal [12]. For our laser, \(d_1 \approx 7-15\) cm, and \(z_r = 9m\), so the \(d_1 > z_r\) condition is well satisfied. By rotating the plane of the feedback mirror, a laser in a Littman-Metcalf cavity can be tuned to various wavelengths:

\[
\lambda = \frac{2}{N} (d_1 + d_p \sin \Phi)
\] (2.3)

where \(N\) is the mode number, and \(d_p\) is the distance from the grating to the pivot point [24].

**Figure 2.4:** A BAL in a Littman-Metcalf cavity. The laser is collimated by a lens, L, and grazes a diffraction grating, G which is of width \(d_g\). The zeroth-order diffraction is emitted as the output. The first-order diffraction is reflected from a tuning mirror, M, and diffracts back into the BAL. The grating normal is separated from the BAL by a distance \(d_1\) at an angle \(\Theta\). The grating normal is also at an angle \(\Phi\) from the mirror normal, and at a distance of \(d_2\).

In a Littrow laser cavity, the laser diffracts from a grating at the Littrow angle, \(\theta_L\), the angle
where the first-order diffraction is equal to the incident beam [25]:

\[ \theta_L = \arcsin \left( \frac{\lambda}{2d} \right) \]  \hspace{1cm} (2.4)

where \( d \) is the width of a single groove of the grating.

The first-order diffraction send back into the laser to couple with the incident beam, and the zeroth-order diffraction is emitted as the output. This is conceptually simpler, requires fewer components and is easier to implement than a Littman-Metcalf cavity. However, the Littrow cavity has a smaller tunable range than an Littman-Metcalf cavity. This is because the laser does not diverge enough to fully illuminate the diffraction grating. This can be corrected with beam expanding optics, such as a microscope objective lens [26]. These additional intracavity optics cause losses from additional reflective surfaces and cause ghost reflections which can disrupt the laser coupling. A Littman-Metcalf cavity illuminates the entire grating by shining at a grazing incidence, eliminating the need for a beam expander [12].

Figure 2.5: A BAL in a Littrow cavity. The laser is collimated by a lens, L, and grazes a diffraction grating, G. The first-order diffraction is fed back into the BAL, while the zeroth-order diffraction is emitted.

In a Littrow cavity, wavelength tuning changes the position of the output, which is undesirable in second harmonic generation applications or when the ECDL is placed within another external cavity [27]. This can be resolved by installing a plane mirror which is fixed with respect to the grating. When the grating is rotated, the mirror is rotated as well, correcting the position changes of the output [28]. In a Littman-Metcalf cavity, the grating remains stationary at all times, and the output does not change its position during wavelength tuning [12].

2.4 Filamentation

In the early 1960’s, Soviet scientists proposed [29] and later observed [30] and explored the nature of filaments produced by the self-focusing of laser light [31]. Self-focusing is the focusing on a beam through some nonlinearity within the beam itself [32]. In our BAL, self-focusing is caused by spatial-hole burning [33], brought on by impurities in the gain medium. These impurities impart a sudden, nonlinear perturbation in the dielectric constant of the gain medium, slightly changing the
way which the electromagnetic wave propagates through it [31]. The perturbed beam then creates a standing-wave interference pattern with the unperturbed beam [34].

Filamentation is an example of a chaotic system [35]. Chaotic systems are very sensitive, and their behavior varies wildly with the slightest variations of the initial or previous conditions. Because of this, there is no simple, general way of explaining a chaotic system, or to determine whether a system will behave chaotically. These systems can only be solved numerically, [36] and several models have been proposed to allow computer simulations of filamentation [37,38]. In addition, these impurities cause nonlinear dielectric amplitude phase perturbations, which causes the electromagnetic wave to decay into individual beams, each with different self-focusing lengths. The size of the self-focusing lengths is dependent on the size of the initial perturbation. Filament formation depends on the nonlinearity of the medium, the intensity of the emitted beam, and the ellipticity of the electromagnetic wave [31].

The power of a filament does not depend on the power of the initial beam. As power increases, the number of filaments increase, but their intensity remains constant. [31]. These filaments, take the form of a explosive intensity spikes at random places within the laser. These “hot spots” can damage the output facet and burn out individual elements in a semiconductor laser [39]. Even a perfectly uniform beam will have microscopic fluctuations imposed upon it by non-uniformities within the waveguide. These fluctuations will serve as the seed of filament formation, and because of this, all laser will eventually collapse into filaments, regardless of how small their powers are [40]. Thus, there will always be some degree of filamentation in a semiconductor laser. With greater power, there is greater filamentation, which rapidly degrades the beam quality [31,33,41].

![Figure 2.6: A photograph showing the many filaments within our ECDL output.](image)

Self-focusing is also partially due to the optical Kerr effect in air [42], where the electric field of the wave induces non-linear polarization in the electron shells of the air molecules, changing their refractive index [25]. Thermal lensing is another source of self-focusing. The Joule heating of the laser diode warms the surrounding air, changing its density, and lowering the index of refraction near the diode. The changes in the refractive index cause the beam to diverge as it propagates [43]. Placing the laser in a vacuum would resolve the self-focusing due to thermal lensing and the optical Kerr effect, but the only way self-focusing could be truly eliminated is with a pure gain medium, which is completely homogenous on a molecular level.
2.5 $M^2$ beam quality factor

The $M^2$ factor is the international standard for laser beam quality [44]. It represents the divergence of a given beam to the divergence of an ideal, Gaussian diffraction-limited beam. In this case, $M^2 = 1$, and $M^2$ increases with decreasing beam quality. BAL’s, due to filamentation, their astigmatic output, can typically have $M^2$ values in the hundreds or thousands [45]. This is because the emitting region of the BAL is relatively wide compared to its height. Since there is more material in the lateral dimensions, there are more impurities there as well. Thus, there will be more induced nonlinearities, which will result in more self-focusing and divergence (see §2.4) [40,46,47].

2.5.1 ISO method of determining $M^2$

The ISO method calculated $M^2$ through a Wigner distribution, a phase space distribution of two sets of angular and spatial coordinates. For a point in the direction of beam propagation, $z$, the Wigner distribution gives the amount of the beam’s power which propagates through the point $(x,y)$ in the direction of $(\Theta_x, \Theta_y)$ [44], as illustrated in Fig. 2.7.

![Figure 2.7: The coordinate system used in the calculation of the Wigner distribution moments.](image)

The Wigner distribution must be calculated to the second order to obtain an accurate measurement. This is accomplished by integrating over the power distribution of the laser beam, and fitting three independent parabolas to the spatial moments. These measurements must consist of no fewer than twenty measurements in different planes spaced equidistantly over no fewer than three generalized Rayleigh lengths after the focal point. These integrations yield the second-order moments [44]:

$$\langle x^2 \rangle \langle z \rangle = \frac{\int_{-\infty}^{\infty} E(x,y,z)\{(x-\langle x \rangle)^2\} dx dy}{\int_{-\infty}^{\infty} E(x,y,z) dx dy} = \langle x^2 \rangle_0 + 2\Delta z \langle x \Theta_x \rangle_0 + \Delta z^2 \langle \Theta_x^2 \rangle_0,$$  

(2.5)
\[ \langle y^2 \rangle (z) = \frac{\int_{-\infty}^{\infty} E(x, y, z)(y - \langle y \rangle)^2 \, dx \, dy}{\int_{-\infty}^{\infty} E(x, y, z) \, dx \, dy} = \langle y^2 \rangle_0 + 2\Delta z \langle y \Theta_y \rangle_0 + \Delta z^2 \langle \Theta_y^2 \rangle_0, \] (2.6)

\[ \langle xy \rangle (z) = \frac{\int_{-\infty}^{\infty} E(x, y, z)(x - \langle x \rangle)(y - \langle y \rangle) \, dx \, dy}{\int_{-\infty}^{\infty} E(x, y, z) \, dx \, dy} = \langle xy \rangle_0 + \Delta z s_0 + \Delta z^2 \langle x \Theta_x \rangle_0 \] (2.7)

These represent the expected value of the beam power at the point \((x, y)\). We define \(E(x, y, z)\) to be the power density function at a given point \(z\), and the focal point, \(\Delta z_0\), is defined to be our reference point where

\[ \Delta z_0 = \frac{-\langle x \Theta_x \rangle_0 + \langle y \Theta_y \rangle_0}{\langle \Theta_x^2 \rangle_0 + \langle \Theta_y^2 \rangle_0}, \] (2.8)

and the generalized Rayleigh length, \(\Delta z_{R,g}\), can be found by using [44]:

\[ \Delta z_{0,g} = \sqrt{\frac{\langle x^2 \rangle + \langle y^2 \rangle^2}{\langle \Theta_x^2 \rangle + \langle \Theta_y^2 \rangle^2} - \frac{\langle x \Theta_x \rangle + \langle y \Theta_y \rangle^2}{\langle \Theta_x^2 \rangle + \langle \Theta_y^2 \rangle^2}}, \] (2.9)

The second-order moments are functions of the position and its angle with respect to the reference point. All ten second-order moments of the Winger distribution are then used to create the beam matrix, \(P\), given by [44]:

\[
\begin{bmatrix}
\langle x^2 \rangle & \langle xy \rangle & \langle x \Theta_x \rangle & \langle x \Theta_y \rangle \\
\langle xy \rangle & \langle y^2 \rangle & \langle y \Theta_x \rangle & \langle y \Theta_y \rangle \\
\langle x \Theta_x \rangle & \langle y \Theta_x \rangle & \langle \Theta_x^2 \rangle & \langle \Theta_x \Theta_y \rangle \\
\langle x \Theta_y \rangle & \langle y \Theta_y \rangle & \langle \Theta_x \Theta_y \rangle & \langle \Theta_y^2 \rangle 
\end{bmatrix},
\]
(2.10)

From the beam matrix, the effective beam quality, \(M^2\) can then be calculated by [44]:

\[ M^2 = \frac{4\pi}{\lambda} \left| \text{det}(P) \right|^{\frac{1}{2}}, \] (2.11)

Once all of the second-order moments have been determined, other beam-quality parameters can be calculated easily from these measurements. One of these is the twist parameter, \(t\), where [44]:

\[ t = \langle x \Theta_y \rangle - \langle y \Theta_x \rangle. \] (2.12)

This describes the rotational properties of the front phase of the beam, as well as the orbital angular momentum that the beam may carry. It is an invariant quantity through free space and spherical lenses, but not cylindrical lenses. Another parameter that can be calculated from the \(M^2\) data is the intrinsic astigmatism, \(a\), where [44]:

\[ a = \frac{8\pi^2}{\lambda^2} \left( \langle x^2 \rangle \langle \Theta_x \rangle - \langle x \Theta_x \rangle^2 \right) + \left( \langle y^2 \rangle \langle \Theta_y \rangle - \langle y \Theta_y \rangle^2 \right) + 2 \left( \langle xy \rangle \langle x \Theta_y \rangle - \langle x \Theta_y \rangle \langle y \Theta_x \rangle \right) - \left( \langle x \Theta_x \rangle \langle y \Theta_y \rangle \right) - \left. \frac{(M^2)^2}{(M^2)^2} \right|, \] (2.13)

for any general astigmatic beam, this describes how close it can be transformed into a stigmatic beam using lenses and free spaces. An intrinsically astigmatic beam has \(a = 0\), whereas an intrinsically astigmatic beam will have \(a > 0\). This is an invariant quantity.
The ISO method is defined to be the “proper” method of calculating $M^2$, and allows the calculation of the twist parameter and intrinsic astigmatism without any additional data collection. The ISO method is requires the power function of the beam to be measured at many different locations, and requires a complex calculation to arrive at a result. Beam profilers, which can measure and calculate $M^2$ automatically are commercially available, but only at great expense. [48, 49] In the next section, we will present the Rayleigh method, an alternate way of calculating $M^2$ which is conceptually simpler and less expensive.

2.5.2 Rayleigh method of determining $M^2$

The Rayleigh method is the earlier method of determining $M^2$. It yields results comparable to the ISO method, and has the advantage of being simpler to execute, requiring a minimum of two measurements, and requires only a CCD camera and a focusing lens. The Rayleigh method does not meet the ISO standards, but is endorsed by NIST [45, 50]. For these reasons, beam-quality measurements are often carried out in this way. Several optics companies sell $M^2$-measuring apparatus based upon this method. [51]

To take $M^2$-measurements using the Rayleigh method, the beam must be focused with a converging lens. The focused beam shines on a CCD detector array mounted on a translation stage. This must be a stage whose positions can be measured and recorded, such as micrometer or stepper motor stages.

The CCD detector is placed at the focal point, where the image on the CCD yields a minimum beam waist, $D_m$. When the focal point is found, its position and the beam waist are recorded. Any translation towards or away from the focal point will cause the image to enlarge. The CCD is then translated to a point $\sqrt{2}$ times larger than the minimum beam waist. The distance from that point to the focal point is the Rayleigh length of the laser, $z_r$. A typical divergence measurement is shown in Fig. 2.8 [45, 50].

![Figure 2.8](image)

**Figure 2.8:** The profile of a laser beam after being focused through a converging lens. The difference from the minimum beam waist diameter, $D_m$ and the point where the beam waist is $\sqrt{2}$ times larger, is the Rayleigh length, $z_r$.

From this, the imbedded gaussian beam parameter, $d_0$ can be calculated [45]:

$$d_0 = 2\sqrt{\frac{z_r\lambda_0}{\pi}},$$  \hspace{1cm} (2.14)

where $\lambda_0$ is the peak wavelength of the laser. This gives the beam waist of an idealized, Gaussian diffraction-limited beam. This is then compared to the minimum beam waist of the laser to determine
its beam quality [45]:

\[ M^2 = \left( \frac{D_m}{d_o} \right)^2. \] (2.15)

### 2.5.3 An \( M^2 \) sample calculation using the Rayleigh method

This section contains a step-by-step instructions on how to calculate \( M^2 \) using the Rayleigh method and the device described in Section 3.4.

![Figure 2.9: A photograph of a beam waist measurement in our ImageJ setup. A line is drawn across output, which measure the beam waist in pixels.](image)

1) Hook the USB plus into a computer loaded with both with Logitech QuickCapture and ImageJ.

2) Adjust the micrometers perpendicular to the beam, such that the beam is centered on the CCD. Using the wavemeter, find the peak wavelength of the laser, \( \lambda \).

3) Adjust the micrometer parallel to the beam, until the image appears as small as possible. Record the position indicated on the micrometer. This is the focal point, \( z_1 \).

4) Record the image using QuickCapture. Save the image as a JPEG and remove all color information, to allow the image to be analyzed by ImageJ.

5) Use ImageJ to draw a horizontal line from one side of the output beam to the other, and measure its waist, as in Fig. 2.9. This will give the beam waist in pixels.

6) Find \( \sqrt{2D_m} \). This is defined to be the beam waist at the Rayleigh length.

7) Translate the camera so the image expands. Repeat steps 4 and 5 until a beam waist \( \approx \sqrt{2D_m} \) is found. Since pixels are discrete quantities, all measurements will be integers, so \( \sqrt{2D_m} \) must be rounded to the nearest integer. Record the micrometer reading. This position is \( z_2 \), one Rayleigh length away from the focal point.

8) These are all the measurement needed to calculate \( M^2 \) using the Rayleigh method. For our example, we will use the values obtained for the ECDL set at a 33 cm, and operating at an injection current on 1 A, as shown in Table 2.5.3.

9) From \( z_1 \) and \( z_2 \), we find the Rayleigh length, \( z_r \), which was defined to be the distance a beam, of waist \( D_m \) needs to travel to diverge into a beam of width \( \sqrt{2D_m} \):

\[ z_r = z_1 - z_2. \] (2.16)
Table 2.1: Values needed to calculate $M^2$ from the 33 cm cavity length running at 1 A.

<table>
<thead>
<tr>
<th>Position of the focal point</th>
<th>$z_1$</th>
<th>0.320''</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position one Rayleigh length from the focal point</td>
<td>$z_2$</td>
<td>0.296''</td>
</tr>
<tr>
<td>Beam waist at the focal point</td>
<td>$z_1$</td>
<td>30 pixels</td>
</tr>
<tr>
<td>Peak wavelength</td>
<td>$\lambda$</td>
<td>789.977 nm</td>
</tr>
</tbody>
</table>

For our sample calculation,

$$z_r = 0.320'' - 0.296''$$

$$z_r = 0.024''.$$  \hspace{1cm} (2.17)

(2.18)

10) All our values must be converted to MKS units:

$$z_r = 0.024'' \left( \frac{0.0254 \text{ m}}{1''} \right) = 6.096 \times 10^{-4} \text{ m}$$  \hspace{1cm} (2.19)

$$D_m = 30 \text{ pixels} \left( \frac{3.00 \times 10^{-6} \text{ m}}{1 \text{ pixel}} \right) = 8.95 \times 10^{-5} \text{ m}$$  \hspace{1cm} (2.20)

$$\lambda = 789.977 \times 10^{-9} \text{ m.}$$  \hspace{1cm} (2.21)

11) Calculate the Gaussian beam parameter, $d_0$, as given in Eq. 2.14:

$$d_0 = 2\sqrt{\frac{z_r \lambda_0}{\pi}} = 2\sqrt{\frac{6.096 \times 10^{-4} \text{ m}(789.977 \times 10^{-9} \text{ m})}{\pi}} = 2.48 \times 10^{-5} \text{ m.}$$  \hspace{1cm} (2.22)

12) Calculate the $M^2$ beam quality factor, as given in Eq. 2.15:

$$M^2 = \left( \frac{D_m}{d_0} \right)^2 = \left( \frac{8.95 \times 10^{-5} \text{ m}}{2.48 \times 10^{-5} \text{ m}} \right)^2 = 13.0.$$  \hspace{1cm} (2.23)
Chapter 3

Experimental Design

This section describes the equipment and techniques used in this experiment.

3.1 High-power variable length ECDL

The centerpiece of experimental setup is the external cavity diode laser (ECDL). A Littman-Metcalf cavity is utilized, so that the angle of the output beam remains constant during tuning, as opposed to a Littrow cavity. Figure 3.1 shows our ECDL setup and Littman-Metcalf cavities in general [24]. The cavity arms are made from 1/2" copper plate, with holes tapped every 1/2" along it to allow the grating and mirror to screw into the cavity arm. Copper was chosen because it exhibits a low thermal expansion, and behaves as a heat sink to the optics mounted to it [11, 52, 53]. Heat sinking helps control the temperature inside the cavity, which decreases any beam divergence caused by thermal lensing [43]. The grating arms operate at an angle of separation between 50° and 70°. With a 2400 lines/mm grating, this allows our cavity to access lasers from 756 nm to 806 nm. We are able to access the Rb D\textsubscript{1} and D\textsubscript{2} and K D\textsubscript{1} bands without changing our setup. [11,52,53]

The effects of mechanical vibration was mitigated by securing the cavity arms to a heavy steel baseplate, which is attached to an aluminum baseplate, that is screwed to a floating optical table. The ECDL is surrounded by a plexiglas case to prevent air currents from disrupting the beam. The case is not airtight, so the pressure and temperature are ambient at all times. The inside of the plexiglass case is covered in black flock paper to absorb stray reflections. The ECDL is smoothly tuned by a Zaber model T-LA28A actuator with a 50 N stalling load pressing against the mirror arm. A rubber boot is placed on the mirror arm to suppress vibrations from the actuator. Our cavity design is completely modular, and the grating and mirror can be removed and replaced to create ECDL with cavity lengths between 17-45 cm. The removal and realignment of cavity optics can be done in a little as one hour. We use a 2" Optometrics holographic gold coated grating, because its size allows the entire beam to be diffracted. The grating was recorded on a Pyrex® substrate. The first order diffraction required a 1" diameter mirror to complete the cavity. We utilized a Coherent Inc. S-780-2000C-150-C 2 W CW single-stripe BAL, measuring 150 x 1 x 1000 µm, in our ECDL. Similar lasers have been used in other ECDL designs [15,54]. The BAL was powered and thermoelectrically cooled by a MPL-2500 laser diode driver from Wavelength Electronics. The driver can provide up to 2.5 A of continuous current with an RMS noise level < 10 µA [11,52,53].
Figure 3.1: The ECDL configuration. The laser beam (shown in red) is emitted from the laser diode, L, and sweeps across the entire surface of the grating, G. The first-order diffraction is sent to the feedback mirror, M. The reflected beam is diffracted off of the grating and is feed back into the laser. The angle of the mirror can be adjusted by the movable arm, MA, to add tunability to the system.

3.2 Improvements to the ECDL

A number of improvements to the ECDL have been proposed previously [11], but were not pursued due to time constraints. Since then, these issues have been addressed, improving the laser’s collimation, along with its reliability and ease of use.

3.2.1 Combined lens mounting system

The original configuration for the ECDL featured the BAL mounted on a XY translation stage with coarse, thumbscrew actuators, secured to the cavity mount. This allowed movement of the BAL to allow different grating positions within the cavity, as well as altering the fine tunability by allowing the BAL to move to compensate for slight misalignments in the feedback mirror. The beam was collimated by an aspheric lens and a cylindrical lens, which were placed in front of the BAL output with a system of rods, mounted to a linear stage for fine adjustment. This lens system was then mounted to the cavity mount, next to the BAL’s XY stage. When a cavity length is changed, the BAL must be translated perpendicular to the direction of the beam, in order to illuminate the entire grating. Then, the collimating lenses had to be repositioned at well. This meant a complete re-collimation of the laser, forcing the user to essentially start from scratch each time, a procedure that would take an experienced user ≈6-8 hours. The re-collimation problem was solved by creating a common mount for the BAL and the collimating lenses.

The 3"x 3" thumbscrew actuators were replaced with larger (3"x 4"), more precise micrometer stages (ThorLabs PT1). Rarely does the BAL need to be moved parallel to the beam, since the BAL must remain over the pivot point at all times. However, if it were to need adjusted, it would need to be by a very fine amount, requiring the precision an micrometer can provide. The cavity mount,
in its original configuration was too small to accommodate these new translation stages. A pocket had to be milled out of the aluminum mount to the Zaber stepper motor actuator that tunes the laser, because it obstructed the micrometer actuators of the new BAL translation stages. Also, the original cavity mount contained a number of extra Plexiglas walls which have been removed.

With the introduction of these new translation stages, the BAL was raised slightly. Precision shims were machined for the cavity grating and mirror to compensate for this. The BAL was mounted on the front half of this stage, while a XY translational stage to support the collimating lenses was mounted behind the BAL. A U-shaped adapter (here forth, the “U”) piece was machined, to wrap around the BAL and hold the collimating lenses in front of the output. Thus, whenever the BAL moved, the collimating lenses would move along with it, eliminating the need for re-collimation.

However, the initial collimation was still a time-consuming affair, especially for an inexperienced user. Once the laser was collimated, it would need re-collimation only when the optics are disturbed. This was partially corrected by changing the collimation control from a linear stage to a XY stage, allowing the user to use a micrometer to orient the lenses perpendicular to the beam, where as before the lenses had to be adjusted manually.

The “U” suffered from a number of critical design flaws, which ultimately led to it being replaced. The “U” was comprised of three, lightweight aluminum pieces, and each extended out farther and farther from the mounting point, which magnified any vibrations the point that the collimation would be affected. The XY stage to which the “U” was mounted was comprised of linear stages that happened to be in the lab at the time, and required several adapter plates to combine them together, since each stage had their own unique threads. This resulted in the “U” being unnecessarily high, and this contributed to the vibration problems. Also, the screws holding the various components of the “U” together had a tendency to act as pivot points, and any shifting of any component of the “U” would move the lenses, putting the laser out of collimation. In light of these problems, a second, complete overhaul of the collimating lens mounts was the only reasonable course of action.

The next lens mounting system was “L” shaped, and made from three robust pieces of brass to minimize vibration. This was mounted on to a smaller XYZ translation stage (ThorLabs MT3), which in addition to performing all the functions of the old lens mounting system, allowed the user to have control over the height of the lenses, greatly simplifying aspheric lens alignment. Though initially promising, the weight of the “L” proved too great for the springs in the Z-axis linear stage. This was corrected by making a new “L” from aluminum, and re-positioning its mounting holes for greater stability. Though the current “L” is lighter, there continues to be no problems with vibrations affecting the beam. The schematics for the custom pieces used in the combined lens mounting system are provided in the Appendix.

This new design greatly improves the output and the ease of use in reconfiguring the laser: an experienced user can typically perform a complete re-collimation of the laser in less than one hour. other Littman-Metcalf cavities can take days to re-collimate.

### 3.2.2 New design for an aspheric lens holder

The beam would also eventually fall out of collimation over a period of time due to the poor design of the aspheric lens mounting system. The ECDL system requires the aspheric lens to be closer to the BAL than allowed by any aspheric lens holder that is commercially available. The original design called for the aspheric lens to be enveloped in a PVC sleeve, which was then placed inside a right angle post clamp (ThorLabs RA90). However, this was not a sturdy design and the aspheric lens would eventually slide downward within its sleeve. Several designs were proposed to replace this, before settling on a small aluminum rectangle, with a hole counterbored to the size of the aspheric lens, which was held in place by a nylon setscrew. Though a threaded holder would be more slightly
more stable, the threads on the lens casing were proprietary (M8-0.5 mm), and a threaded lens holder could not be manufactured without ordering a custom tap to cut these threads. This would require considerable time and cost for such a simple piece. The schematics for the aspheric lens holder are provided in the Appendix.

### 3.2.3 Repairs to the laser driver

The ECDL is driven by a homemade package of driver electronics, comprising of a DC power supply, a thermoelectric cooler (TEC) and a laser driver. This home-brewed driver system, though it has saved us a great deal of money, has also been a constant pain in the sense that it has required frequent repairs which endanger the safety of the laser diode, sapping up valuable research hours.

The power supply experienced a degradation of the insulation within one of the transformers, brought on by its advanced age. The insulation breakdown caused internal arcing within the transformer package. The external insulation remained intact, causing a buildup of heat at ionized gas until the sealed transformer burst, expelling ionized gas and molten wire. This explosion would have cut all current to the laser driver and temperature controllers. This abrupt voltage drop would could have destroyed the BAL. Fortunately, the transformer explosion occurred when the laser driver system was disconnected from the BAL for routine potentiometer replacement.

The faulty transformer could not be replaced due to its proprietary nature. Also, there was no guarantee this would have improved the situation, as many of the other components in the power supply were at, or close to, the point of failure. Since this model of power supply was longer in production (Sola 86-12-312; 12 V at 12.5 A), it had to be replaced with its closest equivalent (Sola 17...
A new design for a spherical lens holder was implemented in the new collimation system of the ECDL. The lens is tilted to prevent reflections from the surface of the lens from re-entering the BAL.

GLS-02-110; providing 12 V at 9 A).

Other repairs and modifications had to be made to the driver electronics, but these were typically minor. These small problems often required more time to diagnose than to repair. However, since there is only one BAL available for this experiment, great care must be taken to preserve it. Any problem with the driver electronics needs to be resolved immediately.

Over time, dust and dirt enters the potentiometers on the front panel, causing the wipers inside to skip, which can cause abrupt changes the voltage or current that is being modulated. All of the commonly used potentiometers have been replaced with new components. Another problem encountered was a combination of current drifting and voltage jumps, caused by a number of poor solder connections within the power supply. On another occasion, no current was entering the diode, though there was still a voltage across it. This was due to a loose connection within the driver case between the current monitor on the laser driver and the voltmeter on the front panel. A poor connection with the thermistor sensor which controls the TEC caused it to read an anomalously high 9V, causing the TEC to work far harder than it needs to. These connections have since been repaired.

### 3.2.4 Miscellaneous

Since there is no longer a need for re-collimation, and collimation has been greatly simplified, the only obstacle in taking additional cavity length measurements is the constant reconfiguring of the grating and mirror. This procedure is fairly simple: a laser pendulum and a cylindrical lens to crate an alignment beam along the edge of the cavity and aligned to the cavity’s pivot point. However, by mounting the alignment beam setup onto a translation stage, the entire beam can be shifted slightly, making alignment easier.
3.3 Determination of modal bandwidth and linewidth

The linewidths of the laser are measured with an scanning parallel-plane Fabry-Pérot interferometer (Burleigh RC-110) with a free spectral range (FSR) of 1 GHz. The interferometer adjusted to a FSR of 15 GHz to measure the bandwidths. The interference pattern was read with a photodiode (ThorLabs FDS100), which displayed it on a 500 MHz HP 54522A oscilloscope. This particular oscilloscope was chosen because it allows for the storage of patterns, on-screen markers, and has a sharp resolution (up to 1 ms). Each bandwidth and linewidth was measured 10-15 times at both extremes of the tunable range. This was repeated for several different injection currents, 0.6 A (slightly above threshold) 1.2 A, and 1.976 A (the maximum safe current for our diode). A Faraday isolator (Electro-Optics Technology LD38I780) was placed in front of the ECDL output to prevent the back reflections from the interferometer from entering and disrupting the laser.

Figure 3.4: A block diagram of the experimental set-up based around the external cavity diode laser (ECDL). The dotted box represents the $M^2$ measuring device, consisting of a focusing lens, a CCD detector, and computer (PC)

3.4 Determination of beam quality

Beam quality is measured by employing the Rayleigh method with a CCD detector mounted to an XYZ stage. The detector is a Logitech QuickCam Messenger webcam. The focusing lens has been removed, enabling the CCD to be addressed directly. It is a 640 x 480 CCD array with integrated USB interface, bundled with driver software and sold at department stores for about $30.

The camera is translated back and forth until the image on the bundled QuickCapture program appears its smallest. This image is captured, and its diameter is measured using ImageJ, a Java-based image processing and analysis program. This yields the beam diameter in number of pixels. The active area of the CCD array measures 0.075″ x 0.055″, for an approximate pixel size of 3.00 x 3.00 µm.

The micrometer readings at both the focal point and the Rayleigh length, along with the laser’s peak wavelength and minimum beam waist are all entered into an Excel spreadsheet which calculates $M^2$ using the formulas in Section 2.5.2. This is repeated for a number of different injection currents, at every 0.050 A increment from threshold (≈0.435-0.500 A) to the safest maximum (1.976 A). Two
Figure 3.5: A photograph of our $M^2$ measuring device. The CCD is housed in the spherical structure (CCD). Black paper is placed around the focusing lens (L) to keep ambient light from entering the detector. The beam can be centered on the detector with the XY translation stage (XY) and position from the lens can be measured with the micrometer (Z) to determine the Rayleigh length.

Complete sets of these measurements are taken on two separate days, as to ensure the repeatability of the experiment. This data is plotted in Origin to display any trends.

The peak wavelength of the laser is measured using a Coherent Inc. Wavemaster® wavemeter. The wavemeter has difficulty measuring wavelengths of lasers at or near threshold, so the injection current must be 0.600 A before an $M^2$ measurement can be taken.

This approach can be complicated by filamentation, which can obscure the beam image, as shown in Fig. 3.6. With this method, the beam waist can become lost in the filamentation. Further attenuation of the beam with neutral density filters (OD 2.70) is needed to filter the beam such that its waist can be accurately determined.

Figure 3.6: Photographs showing typical beam waists of the ECDL output beam (a) being obscured by filamentation, (b) resolved by further attenuating the beam before it enters the focusing lens.

The ISO method cannot be performed with this CCD camera. Under extreme beam attenuation (the reflection of two glass slides is filtered through an OD > 7.00 neutral density filter), when the
beam image becomes lost in the ambient light of the room, the CCD will still saturate, and not give a linear response. This makes measuring the beam’s power function impossible with this detector. Even if this CCD was able to measure power functions, the ISO method would require an additional eighteen measurements to generate a single $M^2$ reading, taking ten times longer than the Rayleigh method. Using the Rayleigh method, collecting two complete data sets takes two to three days. Thus, the ISO method would then require 20-30 days to calculate measure $M^2$ for various injection currents through each cavity length. A beam profiler would use the ISO method and find $M^2$ automatically, but such equipment is prohibitively expensive ($\approx$13,000), and is only suited for measuring beams where $1 > M^2 > 4$ [48].
Chapter 4

Results

4.1 Bandwidth and modal linewidth

We have constructed an external variable-length which has improved the bandwidth, linewidth, and beam quality of the ECDL output. Our results on the measurements of linewidth and bandwidths narrowing are shown in Figs. 4.1a and 4.1b. Each data point represents an average of over 60 data points taken at different times over several days. The error bars represent a standard deviation (1σ).

The bandwidths show a linearly decreasing trend with injection current, as seen in Figure 4.1a. This would indicate that the cavity has a greater bandwidth narrowing at higher powers. The trend is not constant within the error bars, but the 1.976 A data point is only 1.47% away from allowing a constant trend. Preliminary data from Sands indicated that the bandwidth should increase with injection current. This is due to the divergence of the beam, because the feedback will not shine upon the portion of the BAL which originally created it. Because of this, the feedback couples with higher-order modes, which would have been lost in the noise otherwise. The resulting laser linewidths are spaced further from one another then they would be for a beam with less divergence, causing bandwidth to increase [11]. This has been resolved by the new collimation system (see §3.2.1) which reduces laser divergence, as demonstrated by the improved beam quality of the ECDL (see §4.3). With less divergence, the higher-order modes do not couple, and there is no increase in bandwidth with high injection currents. The modal linewidths remain constant. This would indicate equal-sized linewidths becoming spaced closer together as power increases.

The Coherent Inc. S-780-2000C-150-C BAL has a laser threshold current of 0.450-0.500 A. After passing through the beam splitter, a beam at threshold does not have enough intensity to be detected by our instruments. Because of this, the low end of our current measurements needs to be slightly above threshold, at 0.600 A. The power supply limits the injection current from increasing past 1.976 A, which is the maximum current which this model of BAL can be operated without causing damage. Measurements were also conducted at 1.2 A, which is roughly in the middle of the two extremes.

Figure 4.1b shows the bandwidths and linewidths versus cavity length. The bandwidths have a linearly decreasing trend with the cavity length, as predicted by Littman and Metcalf (§2.3) [12]. This indicates that despite being comprised of numerous smaller modes, a multimode semiconductor laser behaves as single mode dye laser would in an external cavity.

The modal linewidths increase gradually, varying from 309 MHz at its smallest, and 509 MHz at its largest. This trend could also be interpreted as being a constant function measuring 419.5 ± 89.5...
MHz. This is in direct conflict with the observations made by Sands [11], which indicated an inverse square root relationship between linewidth and cavity length. This trend was based from four points of preliminary data, and and spans a region of only 70 MHz, which would be within the uncertainty of our constant function. Sands also applied the Littman-Metcalf model of the overall beam to the individual linewidths. This was under the assumption that the a narrowing of modal linewidths was causing the narrowing of the bandwidth. However, the linewidths do not appear to be affected by the external cavity. This could be explain by stating that the overall spectral bandwidth of a laser in an external cavity broaden or narrow due to equal-sized linewidths becoming spaced closer or further apart.

It should also be noted that our linewidths (≈300-500 MHz) are notably larger than those reported by Sands (≈135-205 MHz) [11]. This could possible be attributed to aging effects of the diode laser, which causes spectral width to increase [55].

4.2 ECDL tunability

The tunability of the ECDL was determined by viewing the output of the Fabry-Pérot interferometer (see §3.3) and rotating the feedback mirror about the pivot point until the laser hops to a different mode. This is accomplished by adjusting the Zaber actuator gradually until the beam begins to tune itself, which occurs before a mode hop. This typically requires > 0.1 mm of adjustment. The bandwidth can be tuned over an average range of 6.50 ± 0.25 GHz, which corresponds to 0.013 nm of fine adjustment.
4.3 ECDL beam quality

Figure 4.2 shows $M^2$ versus injection current. $M^2$ does not increase with increasing current. For our ECDL, $M^2$ is averaged to about 22, where as a typical BAL has $M^2 \approx 10^2$-$10^3$ [45]. Our external cavity improves the BAL’s beam quality by at least an order of magnitude. This is an important feature of our design, the beam quality does not degrade at higher injection currents as a result of thermal lensing, as is typical with BAL’s [56].

Ideally, $M^2$ should be 1, where the laser operates as a single mode, Gaussian diffraction-limited beam. $M^2$ factors of 1.1-1.7 have been reported for low-powered semiconductor lasers (6.5-11.0 mW) [57]. High-power ECDL systems with $1 > M^2 > 2$ are now commercially available, but only at tremendous cost ($\approx$ $23,000)$. [58]

Figure 4.2: $M^2$ as a function of the BAL’s injection current with and without our external cavity.

The improved consistency of the beam quality is likely due to improved collimation, brought on by the combined lens mounting system (see §3.2.1). The XYZ stage allows a 0.001” fine adjustment of the lenses, and this precision in alignment allows collimation to $\approx 4.25$-$4.50$ mm beam waist at the Rayleigh length. For the emitted beam waist of 3 mm, this is very close to the Rayleigh length limit of $\sqrt{2}(3 \text{ mm}) = \approx 4.23$ mm. Before the addition of the XYZ stage, adjustments had to be made manually and a Rayleigh length beam waist of $\approx 4.50$-$5.00$ mm was typical.

The beam quality is limited by filamentation, a complex phenomenon causing an incoherent output beam as a result of self-focusing [37]. This is a process which is intrinsic to semiconductor lasers [38], and is discussed in greater detail in Section 2.4.

The ECDL operates in a TEM$_{01}$ mode, as shown in Figure 4.3a. Spatial filtering through the partial blocking of the feedback mirror will enable single-mode operation [59], as can be seen in Figure 4.3b, but with significant power loss. When the mirror is partially blocked, there is less feedback, and the higher-order modes do not couple. These higher-order modes become lost in the noise. [33]. This proves the multimode operation of the ECDL. The single-mode operation can be confirmed by coupling the beam to a single-mode fiber. Alternative methods to promote single-mode operation are discussed in Chapter 6.
Figure 4.3: The ECDL operating in a (a) TEM$_{00}$ mode when the feedback mirror is partially blocked and (b) a TEM$_{01}$ when unblocked.

Figure 4.4: False-color intensity vs. position plots for the ECDL operating in (a) a TEM$_{00}$ mode when the feedback mirror is partially blocked and (b) a TEM$_{01}$ when unblocked.
Chapter 5

Conclusions

We have improved the collimation and ease of use of a high-powered BAL in a completely modular, variable-length Littman-Metcalf external laser cavity. We have determined that the spectral bandwidth, modal linewidths, and beam quality of our ECDL have been improved by these changes. The laser linewidths have been found to remain constant. The bandwidth of the laser is inversely proportional the cavity length, in agreement with the theoretical model presented by Littman and Metcalf. The bandwidth does not increase with increasing injection current, because the improved collimation reduces the divergence of the beam, preventing the excitation of higher-order modes. This also demonstrated by the consistency of the $M^2$ beam quality factor. The only way to increase the performance of the ECDL is to improve its beam quality. This could be achieved by the suppression of beam divergence, filamentation, or the higher-order free-running modes.

A BAL does not behave as any other laser would in an external cavity, though the inferior beam quality of the BAL could make it appear otherwise.
Chapter 6

Future research

A few interesting applications and improvements for the ECDL have been conceived, but have not been pursued due to time constraints. These improvements have been recorded here to encourage future graduate students to continue this line of research.

6.1 Variable concavity mirror (VCM)

A variable concavity mirror (VCM) is a reflector with a curvature that can be easily altered to suit the needs and desires of its operator. This is a form of adaptive optics, which were originally conceived by astronomers to correct for atmospheric turbulence which inhibits the angular resolution of their telescopes [60]. I believe applying adaptive optics to cavity lasers will be of great benefit to future research.

6.1.1 Application

The geometry of the ECDL works best for a single TEM$_{00}$ mode laser. As the injection current increases, higher order transverse modes on the BAL chip become active, and the output beam will degrade into a double-lobed TEM$_{01}$ mode structure. This pattern is unique to multimode lasers. These lobes are diverging, and continue to diverge upon reflection by the feedback mirror. The result is the beam is not reflected onto the portion of the chip which originated it, which leads to poor laser locking and mode hops. This is illustrated in Fig. 6.1.

This can be easily resolved with a spatial filter, such as a card to block out one of the diverging lobes, but only at a great loss of power, since that would block half of the beam. To prevent a loss of power, the divergence of the beams could be compensated for by focusing the lobes to a single point, through replacing the cavity’s feedback mirror with a parabolic mirror, as shown in Fig. 6.2.

However, this approach would require a mirror with a very precise curvature, and would likely need to be a custom piece. In addition, by changing the cavity length, we change the amount of divergence. This would require replacing the mirror with one of a different concavity for each of the cavity lengths. This could be resolved by using a single, variable concavity mirror.
Figure 6.1: A diverging, double-lobed laser beam not being back-reflected into the BAL

Figure 6.2: Focusing the diverging lobes back into the BAL with a concave mirror

6.1.2 Theory

Spherical deformable mirrors are a form of adaptive optics, and are available commercially, but they are expensive, and always have a significant amount of aberration [61]. Since the feedback beam only requires focusing in the vertical direction, a cylindrical concave mirror would best suit our needs. Such a mirror could be created from a piezoelectric bending actuator using a vapor deposition chamber. The system would consist of a piezoelectric actuator with a vapor-deposited reflective coating, which is secured at the top and bottom, but not at the middle. When a voltage is applied, the piezoelectric actuator will take on a concave shape. At this time, I do not know if the deflection of any available piezoelectric actuator will be great enough to provide the concavities that we need for this experiment.

Again, the construction of the variable mirror depends on the completion of the vapor deposition chamber. Controlling the thickness of the coating will be of great importance. The film must be $\lambda/4$ thick to ensure maximum reflectance [62]. If the coating is too thick, then bending the piezoelectric actuator too far could cause the coating to crack. It is unknown if the actuator needs that large of a deflection to reach the desired concavities, so this may not be an issue.

One method of preventing a thick coating from cracking would be to use a mask when depositing the film, so that instead of one solid coating, it would be several small coatings spaced apart, allowing greater flexibility. However, a piezoelectric actuator coated in this way would behave as variable concavity diffraction grating rather than a mirror, since it would be a reflective surface with fine grooves, where the mask had been.
6.2 AR-coating of the BAL output

The reflectance of the laser output facet is dependent on the refractive index of the gain medium. For a semiconductor lasers, this is typically about 30%. Because of the low reflectivity, ghost images from the reflective surfaces of the equipment can enter the laser oscillator. This deteriorates the mode structure through destructive interference, even when the optical feedback is a little as 0.01% of the emitted beam [1].

The Fabry-Pérot interferometer produces a significant amount of back reflection comes from the The addition of a Faraday isolator in front of the laser output prevents this feedback from entering the oscillator. The only feedback entering the cavity is the reflections from the grating and cavity mirror. This is necessary for an external cavity to operate.

BALs operate in several longitudinal modes at once, resulting in a output comprised of numerous beams of random wavelengths in addition to the peak laser. These intrinsic “free-running” modes are also fed back and coupled as well, resulting in a wider spectrum more prone to mode hops.

This can be corrected by using a vacuum deposition chamber to apply a anti-reflective (AR) coating to the output facet of the laser diode. These can be custom designed to cancel out incident light of any unwanted wavelengths by creating destructive interference within the coating. Only the desired wavelengths will be transmitted [62].

The reflectance, \( R \), of the coating is [62]

\[
R = \left( \frac{n_c(1 - n_s) \cos kl - i(n_s - n_c^2) \sin kl}{n_c(1 + n_s) \cos kl - i(n_s + n_c^2) \sin kl} \right)^2, \tag{6.1}
\]

where \( n_c \) is the refractive index of the AR coating, \( n_s \) is the refractive index of the semiconductor gain medium (our substrate), \( l \) is the coating thickness, and \( k \) is the angular wave number, where \( k = 2\pi/\lambda \), and \( \lambda \) is the reflected wavelength.

To be the most effective, the AR-coating must completely cancel the free running when they are at total reflection; this is when there is no transmittance of these wavelengths. This occurs when \( l = \lambda/4 \), setting \( kl = \pi/2 \). This reduces the previous equation to [62]

\[
R = \frac{(n_s - n_c^2)^2}{(n_s + n_c^2)^2} \tag{6.2}
\]

so the reflectance will go to zero when

\[
n_c = \sqrt{n_s}. \tag{6.3}
\]

The choice of coating material depends solely on the semiconductor material. Applying multiple coatings of varying thickness will allow multiple wavelength regions to be filtered out [62]. AR-coated diode lasers are commercially available, but not at the powers that we use. Laser diodes undergo vapor deposition in large batches, as this is the most cost-efficient method. The experiment does not require a whole batch of laser diodes, and coating of a single diode to our specifications would then be prohibitively expensive. The only alternative is to AR coat the laser ourselves.
6.3 Frequency doubling

Another area of interest is to expand the versatility of the ECDL system by seeing if it can be converted from a tunable, high-powered near-IR laser (≈790 nm), to a near-UV laser (≈395 nm). This could be accomplished by second harmonic generation through by means of a frequency doubling crystal [63]. However, the effect of tuning through this crystal, and the range of wavelengths accessible with this method has yet to be determined.

6.3.1 Theory

If any medium has a permeability, $\mu$, and permittivity, $\epsilon$, dependent upon the magnitude of the applied EM field, then it said to be a nonlinear medium. [64] The nonlinear polarization, $P^{(2)}$, of an electric field, $E$, can be expressed as

$$ P^{(2)} = \epsilon_0 \chi^{(2)} E^2 $$  \hspace{1cm} (6.4)

where $\epsilon_0$ is the permittivity of free space, and $\chi^{(2)}$ is the susceptibility tensor, which governs how the material will polarize an electric field. The elements of the susceptibility tensor are determined by the symmetry of the medium’s crystal structure.

This nonlinear polarization becomes the source of new waves, of frequency $\omega = \omega_1 \pm \omega_2$. These waves are the result of constructive interference, so the phase velocities of the incident and emitted beams must match. This is satisfied by meeting the phase-matching condition

$$ k(\omega_1 \pm \omega_2) = k(\omega_1) \pm k(\omega_2) $$  \hspace{1cm} (6.5)

where $k(\omega)$ is the angular wave number of the wave. This is the conservation of momentum between the emitted photon and two incident photons. In the case where $\omega = \omega_1 = \omega_2$, the phase matching condition becomes

$$ k(2\omega_1) = 2k(\omega) $$  \hspace{1cm} (6.6)

and the emitted beam is the second harmonic of the incident beam, and their phase velocities are equal. The emitted beam has twice the frequency (and therefore, half of the wavelength) of the incident beam [25].

6.3.2 Application

There are a number of techniques which can be employed to achieve frequency doubling of laser light. The simplest of these methods is the angle tuning or critical phase matching method, using a bismuth borate (BiB$_3$O$_6$; BiBO) crystal.

The BiBO crystal is 16% more efficient at converting light than the $\beta$-barium borate (BaB$_2$O$_4$; BBO) crystals used in the past. [65] A BiBO crystal has a nonlinearity that is 1.5-2.0 times larger than a BBO crystal, and 3.5-4.0 times larger than a lithium triborate (LiB$_3$O$_5$; LBO) crystal.

To achieve frequency doubling, the ECDL must be running in a single-mode, allowing the whole beam to pass through the crystal, and in a non-diverging path. This could be accomplished by beam chopping, as discussed in Section 4.3 or as a result of the variable concavity mirror as discussed in Section 6.1.1, or by the volume Bragg grating, which is discussed in Section 6.4.
6.4 Volume Bragg Grating

External cavities, though physically large and highly sensitive, have been the preferred method of spectral narrowing. Spectral narrowing can also be achieved through the use of intracavity devices, (e.g., etalons, metallic films, birefringent filters, prisms, or surface Bragg gratings) to select specific frequencies to propagate through the cavity. However, intracavity devices cause a significant loss of power [66]. A volume Bragg grating (VBG) behaves similar to an etalon, but rather than using the reflections from surface coatings, a VBG operates from the reflections of the varying index of refraction within the material itself.

The key to this lies in the use of photo-thermo-refractive (PTR) glass. These lithium-aluminum-silicate and sodium-zinc-aluminum-silicate glasses are doped with silver and cerium. A Bragg grating is etched within the glass with the interference pattern from a 35mW He-Cd laser, peaking at 325 nm. The glass is then heat treated. The result is a holographic Bragg grating running through the entire glass slab, as opposed to the just the surfaces. The holograms within these glasses have absolute diffraction efficiencies of 90-95%, transmissions of up to 50% and are stable up to 400°C [67]. These gratings have a ≈4% loss due to reflection from the glass surfaces, which results in a multi-beam output, again, similar to an etalon. These losses can be recovered by applying anti-reflection coatings to the surfaces, and allows a single-beam output [68].

Replacing a cavity mirror of a tunable, solid-state laser with a VBG has been shown to narrow its spectral linewidth by a factor of 2000. Similar experiments have been performed with Ti:sapphire and Cr:LiSAF lasers, and the VBG was able to reduce their FWHM bandwidths from 0.5-1.0 nm and 6 nm to ≈2.5 pm and ≈3 pm respectively. Similar results can also be achieved with a three-plate birefringent filter into the resonator, but only with extreme power loss [68].

Spectral selectivity is a function of grating thickness. Gratings several mm thick can produce FWHM bandwidths of 0.01 nm for UV beams and 0.1 nm for near-IR lasers. [67]

VBGs are superior to Littman-Metcalf cavities, because they can produce similar results, but with a simpler implementation and smaller insertion losses. The only way to improve the performance of VBG laser is to combine spectral narrowing methods, by placing a VBG in an external cavity. This would allow a single mode output [68], and dramatically improving beam quality (see §4.3) and allowing other lines of research (see §6.3).
Appendix A

Schematics

We present as an appendix the schematics of the custom pieces used to make the combined lens mounting system. The drawings in the lab notes are of the prototypes, and differ slightly from the final product.

These schematics were created using AutoCAD 2000.
Figure A.1: The rod which the collimating lenses are secured to.

Figure A.2: Piece which mounts onto the XYZ translation stage.
Figure A.3: Piece which supports the lens holding rod.
Figure A.4: Aspheric lens holder.
Figure A.5: A metal shim placed under the grating to compensate for the increased beam height.
Figure A.6: A metal shim placed under the feedback mirror to compensate for the increased beam height.
Bibliography


[65] Newlight Photonics. BiBO (bismuth borate, BiB$_3$O$_6$) properties and applications.

