Mode Stabilization of a Diode Laser Using Radio-frequency Lock Noise

Enoch Lambert

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Dallin Durfee, Advisor

Department of Physics and Astronomy

Brigham Young University

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ABSTRACT

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Extended-cavity diode lasers (ECDL's) are an important tool in atomic, molecular, and optical physics. Preventing ECDL's from mode-hopping can enable further advances in these fields. The research described in this paper seeks improvements in the frequency stability of a diode laser by using feedback techniques. The diode laser is locked to a frequency reference, in this case a simple optical cavity. Radio-frequency (RF) noise is measured at various points in the combined laser-cavity system and used to generate an additional feedback signal to help control the laser. The added feedback system improved the laser's stability range by a factor of three when the laser was scanned.

Keywords: Diode lasers, Laser stabilization, Modes, Optical systems, Lock-in amplification, Mode-locked lasers

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Chapter 1

Introduction

1.1 Extended-cavity Diode Lasers

Diode lasers are an important tool in atomic, molecular, and optical physics [1]. Applications range from cancer therapy [2] to quantum computing [3]. Diode lasers have many properties which make them particularly useful. They generally cost a small fraction of comparable laser systems and have greater physical durability. They are available in a wide range of wavelengths, allowing the same techniques involving diode lasers to be applied to many different systems. A particularly important benefit of diode lasers is their tunability; while an individual diode will have a tuning range of less than a nanometer, this is sufficient for dealing with atomic and molecular transitions. The tunability of diode lasers is made even more useful by their fast frequency response to changes in the current, which allows a diode laser to scan quickly through an atomic resonance. Unfortunately, diode lasers naturally have a wide linewidth that is not suitable for atomic physics.

An extended-cavity diode laser (ECDL) can overcome this limitation. An ECDL is a system of a laser diode and a reflective element placed outside the diode to form a larger external cavity. Typically the cavity is formed by a reflection grating [4, 5]. The reflection grating is placed so that

Figure 1.1 In an extended-cavity diode laser a reflection grating reflects a specific frequency of light back into the laser diode. Here the frequencies are illustrated by different colors.

the first order diffraction goes directly back to the laser diode (see Fig. 1.1). The light that returns to the diode is amplified, and a specific frequency is favored by the complete ECDL system. The reason this optical feedback works is the process of mode competition. When laser diodes produce light, the amount of light produced of a given frequency is proportional to the amount of light of that frequency in the laser cavity. On the other hand, the diode has a limit on how much light it can produce. Thus once one frequency is lasing it will tend to use up the available gain power and prevent other frequencies from lasing. ECDL's take advantage of this mode competition to suppress unwanted light frequencies.

Unfortunately, ECDL's have several factors which interact to determine their frequency output. First, there are the natural modes of the laser diode. The laser diode forms a small cavity between its front and back faces, providing a set of resonance frequencies. The precise resonance frequencies of the cavity are determined by the current powering the diode as well as the temperature of the diode. Second, there are the modes of the external cavity formed by the grating and diode together. These modes are much narrower and more closely spaced than the native diode modes, which are relatively broad due to the low finesse and small size of the diode. Third, there is the effect of the grating selecting a specific frequency. The angle of the grating strongly influences the

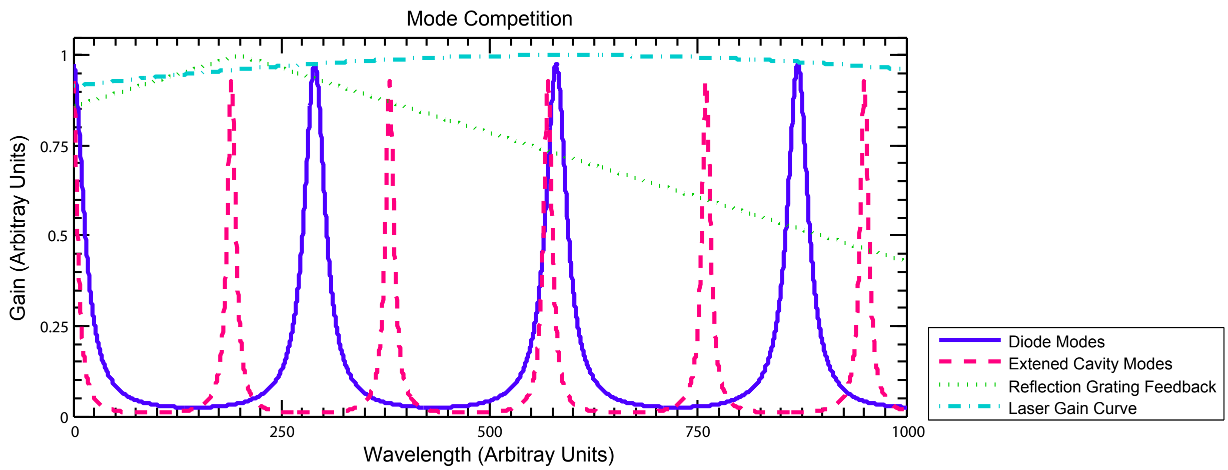

Figure 1.2 A diagram of how diode modes, cavity modes, laser gain medium, and reflection grating angle interact to determine the output of an extended-cavity diode laser. This diagram is of generic functions to show an idea of relative effects rather than being calculated from specific parameters. The relative widths of the modes are not to scale; extended cavity modes are much narrower and have smaller spacing than shown here.

ECDL output frequency. Finally, the gain of the lasing medium has an effect the specific frequency output, favoring frequencies towards the middle of the gain curve.

As can be seen in Fig. 1.2, the specific frequency selected by the system is highly dependent on the exact overlap between the modes of the diode laser and the external cavity. Mode competition causes ECDL's to unexpectedly change their output frequency during operation. These unexpected changes, called mode hops, are discontinuous jumps in the output frequency [1]. Mode hops are a severe limitation on the usefulness of ECDL's in work requiring a precise, stable frequency. For many applications, particularly in atomic, molecular, and optical physics, it is necessary to stabilize the ECDL in some way to prevent or minimize mode hops.

1.2 Standard Methods to Reduce Mode-Hops

There are a variety of methods already used to keep ECDL's in single-mode operation. These methods include a range of both passive and active techniques, each with its own advantages and disadvantages.

Passively stabilizing the diode means making the inputs to and environment of the ECDL stable [5]. There are several main components of passive stabilization. First is current stabilization [6]. Because the output frequency is determined by the current, the stability of the diode's current input provides a limit on the possible stability of the ECDL system. Second is mechanical stabilization, as illustrated in [7]. Because the external cavity modes are determined by the precise length of the grating-diode system, limiting mechanical variations is key to keeping the modes stable. Third is temperature control [8], which is important because the temperature determines the precise length, and thus the modes, of both the diode cavity and the extended cavity, as well as affecting the gain curve of the lasing medium. Temperature control can be implemented for just the diode itself, or for both the diode and the entire ECDL system. Fourth is optical isolation; because the diode is so sensitive to optical feedback it is important to use an optical isolator to prevent back-reflections from the rest of the optical system outside of the ECDL. These passive stability techniques can be quite powerful for stabilizing an ECDL, but are limited, e.g. if an experiment requires the laser to be scanned these passive options cannot account for the relative changes between the laser modes and the external cavity modes. When other techniques are used, they generally build on the foundation of passive stability.

One way to reduce the relative effects of the laser and cavity modes is to use an anti-reflection coating on the diode face. Anti-reflection coatings are a common and simple way to get stable operation [9], but are expensive. These coatings enable more stable operation by substantially reducing the finesse of the cavity formed by the diode itself. This expands the width of the diode modes to the point where there is easy overlap between the diode modes and the selected cavity mode. Unfortunately, to implement an anti-reflection coating requires opening up the diode package, which can impact the diode's reliability and lifetime. Also, while anti-reflection coatings are helpful, they cannot completely remove the effects of the diode modes.

In addition to stabilizing the diode, mode hops can be prevented when tuning the laser by changing the current, grating angle, and grating position together. This technique, known as feed-forward, requires these parameters to be controlled in precise ratios [10–12]. With careful calibration this method can account for the predictable variations of the diode cavity and external cavity, allowing scanning over substantial frequency ranges of up to 80 GHz, [12]; this method, however, cannot compensate for unpredictable variations that also lead to mode-hops.

1.3 Overview of Thesis

The research described in this thesis is focused on reproducing and extending research from Stanford [13] on a new method of stabilizing ECDL's. This new method makes use of radio-frequency (RF) amplitude noise in the laser system to produce a feedback signal. This amplitude-noise feedback signal is used to make adjustments to the current driving the laser in an effort to prevent mode-hops.

The rest of this Thesis is organized as follows: First, I will briefly describe the work at Stanford, which I reproduced, and the previous efforts made at BYU to reproduce the Stanford research. Then I will describe my experimental setup and methods, with particular focus on the implementation of the new stabilization system. Finally, I will present the measurements I made to characterize the effectiveness of my implementation of the stabilization system. I first reproduced the Stanford work and then extended it by using the electronic noise in the frequency-lock rather than the laser amplitude noise as the source for the control signal.

Chapter 2

Overview of Theory

2.1 Previous Work at Stanford

A team working at Stanford has described a new technique for keeping an ECDL stable by using the RF amplitude noise on the laser output as the source for a feedback signal [13]. Using a laser locked to a vapor cell, they found that the RF noise on the laser output increased as the laser approached a mode hop. Based on this observation, they created a system to produce an error signal based on the laser's RF amplitude noise. This error signal was then fed back to the laser current, changing the current independently of the ECDL grating.

With this setup they were able to achieve a 100 times increase in stability lifetime from half an hour to almost 50 hours using a non-anti-reflection-coated diode. Using a similar diode with an anti-reflection coating, they were able to achieve stable operation for longer than a week.

2.2 Expanding on the Stanford Work

Prior to my involvement with this project, attempts were made here at BYU to reproduce the work reported by the Stanford team. These attempts were unsuccessful.

The researchers here first attempted to use radio-frequency noise intrinsic to the laser itself as the signal for their control system. They found that they could not reproduce the relationship between noise and mode hops reported by Stanford. Instead they found that the RF amplitude noise increased as the laser approached a mode hop from one side, but would not increase when approaching from the other side of the mode hop. Without an increase in both directions, this noise signal was unsuitable as the source for an error signal.

Between their failures and a careful analysis of the Stanford results, we have determined that the laser must be locked to an external frequency reference for a suitable noise signal to exist. This method does not work for free-running laser systems; the laser must already have a feedback system controlling its frequency for the RF noise to be used. Due to the requirement that the laser be locked to a frequency reference, it seems likely that the noise being measured is actually coming from the lock circuit. A possible mechanism to produce this noise could be that as the laser approaches a mode hop it starts to create some light in another mode, which creates frequency noise in the laser. This frequency noise is then converted to amplitude noise by the frequency lock, leading to the observed amplitude noise.

Suspecting that the noise providing our control signal was really a result of the frequency lock, we realized that we should be able to make use of this noise without observing the laser at all. Thus, after first verifying that the method described by the Stanford team did in fact work, I changed my system so that instead of the RF amplitude noise on the laser, I used RF electronic noise in the frequency lock circuit as the source for my control signal. Measuring the electronic noise is substantially easier than measuring the optical noise, and by only using the electronic noise this method can be implemented for existing ECDL systems with minimal adjustments to these existing systems.

Chapter 3

Experimental Setup and Methods

3.1 Overview of Methods

In this chapter I present my experimental methods in detail; however, a brief overview will give a sense of the bigger picture. First I describe the electronics used to control my ECDL and regulate its environment. Then I describe the optical system used in my experiment as well as the method of locking my laser to a specific frequency. Next is a description of my specific implementation of generating a control signal from the RF noise, both reproducing the Stanford method as well as my own alternative method. Finally I describe the full system with all these elements put together, as well as a description of how I acquired the data which is presented in the following chapter.

3.2 Electronics

A stable current is important because the laser diode's output is a function of the input current. For this research I used a current driver developed specifically for diode lasers. As described in [14,15] this current driver design provides a stable current to the laser, and the actual driver used was built specifically for this research. In addition to the current driver circuit being inherently stable, the entire circuit is housed in an aluminum box which shields the electronics from external noise. This current source includes a circuit to add modulation signals to the current supply. This ability is vital for the feedback systems described later.

A temperature controller ensures the diode is at a stable temperature, regardless of the temperature fluctuations of the laboratory. Stable temperatures are important because the diode laser output is sensitive to temperature fluctuations on the frequency scale important to this research. The design for the temperature controller is a standard one used in the lab where this research was conducted. This temperature controller is connected to the thermoelectric cooler in the Thorlabs TCLDM9 laser mount where the laser diode is housed. This setup only controls the temperature of the laser diode, leaving the overall temperature of the ECDL system to vary with room temperature. Like the current driver, the temperature controller is housed in a shielding aluminum box; both are located close to the laser to minimize cord lengths.

3.3 Optical setup

The ECDL is constructed by mounting the reflection grating and diode laser together using a stable cage mount. The cage mount provides the mechanical stability needed to maintain the relative positions of the laser diode and reflection grating. This mechanical stability is important due to the dependence of the ECDL output on the modes of the laser-grating cavity.

After being passed through an optical isolator the laser output is coupled into a matching pair of 10 cm long semi-confocal Fabry-Perot cavities, as shown in Fig. 3.1. One cavity is used as the reference for locking the laser frequency, while the other is used to monitor the laser output. The 10 cm length gives the cavities a 0.375 GHz free spectral range. Piezoelectric crystals in each cavity allow the length to be changed precisely. Additionally, each of the cavities has a photodiode placed on the end opposite the input to pick up transmitted light. The monitor cavity is scanned at

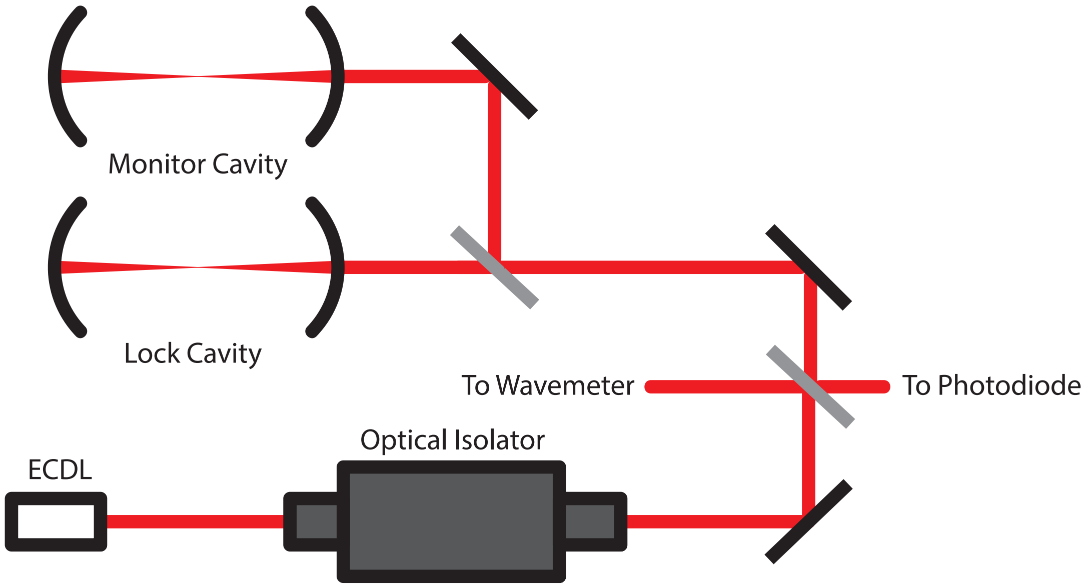

Figure 3.1 Diagram of the layout of the optical system used in this research. Some mirrors used for aligning the light path have been removed for clarity. The optical isolator is important due to the sensitivity to optical feedback that makes an extended-cavity diode laser (ECDL) possible; it stops any back-reflections from the system before they can affect the laser.

about 10 Hz and the output goes to an oscilloscope which monitors the laser output in real time. See Fig. 3.2 for a scan of the laser in single-mode operation, and Fig. 3.3 for a scan of the laser in multi-mode operation.

To prevent back-reflections from affecting the laser system I installed an optical isolator. The ECDL works because of the sensitivity of the diode laser to optical feedback; unfortunately, this also includes back-reflections from the optical system beyond the ECDL. Aside from stray reflections, there are several known sources of back-reflections.

There are several parts of the optical system that produce back-reflections. Two sources of back-reflections are the photodiode to measure the laser amplitude and the optical fiber coupler to take light to a wavemeter for wavelength measurements. The fiber coupler in particular has a strong back-reflection. Also providing strong back-reflections are the two optical cavities. As can be noted in Fig. 3.2 most of the time the monitor cavity is reflecting almost all of the light incident

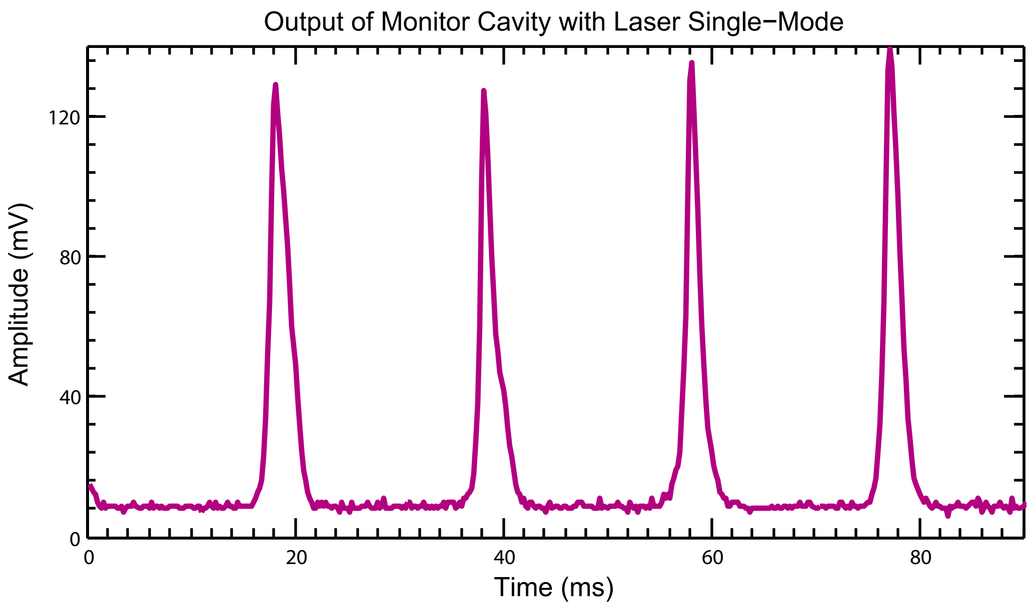

Figure 3.2 A representative scan of the monitor cavity while the laser was in single-mode operation. Note that the signal is always zero or positive; the matching lock cavity is likewise limited in its range of outputs.

on it, and due to the type of lock used, the lock cavity generally reflected most of the light incident on it as well.

3.4 Locking Laser to Optical Cavity

The output from the photodiode at the far end of the lock cavity is used to lock the laser to a resonance frequency of the cavity. The Fabry-Perot cavity only lets light through at specific resonance frequencies. As the laser varies close to one of these frequencies, the amplitude of the light allowed through the cavity will vary dramatically. The photodiode measures this variation and provides a signal proportional to the intensity allowed through the cavity.

This signal by itself is not a suitable error signal. See Fig. 3.2 to see output from the monitor cavity illustrating the possible outputs from one of these cavities. Since this signal is never negative, it does not work as an error signal. There are several possible methods to convert this signal

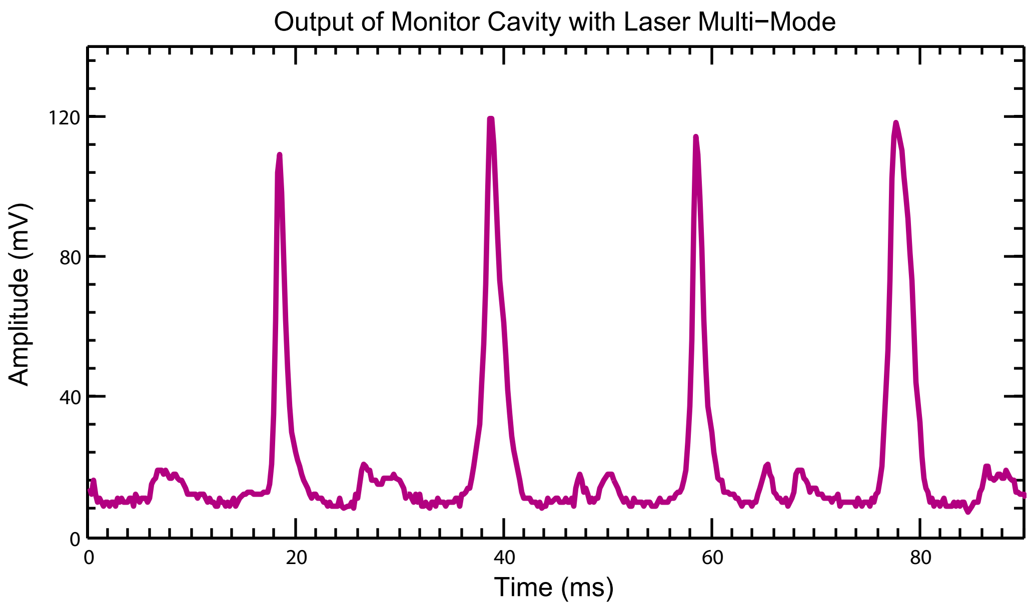

Figure 3.3 A representative scan of the monitor cavity while the laser was in multi-mode operation. Note the clear difference from the single mode-operation displayed in Fig. 3.2. This illustrates the difference in performance between single and multi-mode operation.

into a suitable error signal.

The standard method for generating a suitable error signal for locking is the Pound-Drever-Hall technique [16]. This technique involves dithering the laser with something such as an acoustical-optical modulator. The dithering creates a signal that crosses zero at the resonance of the lock cavity, rather than the peak at resonance generated by my system. This allows the lock to be insensitive to laser amplitude, while providing automatic lock-in detection. Despite the advantages, I did not use this standard method due to the complexity of implementation and the cost of the equipment needed to implement it.

Instead, I used a side-lock. The side lock is easily implemented using only the output of the diode on the back of the optical cavity. As its name implies, a side-lock involves locking the laser to the side of the resonance peak rather than the center. While simple to implement, the side lock has many disadvantages, including being sensitive to laser amplitude variation. Despite the weakness of the side-lock it proved to be sufficient for the research described in this paper.

To implement the side-lock, the diode signal is sent through a subtracting op-amp to create the error signal. I use an op-amp in a spring-mount breadboard to perform the voltage subtraction. I found the lock was most reliable when the lock point was low down on the side of the resonance peak. In order to get a large signal from the photodiode I use $1M\Omega$ resistors in the subtraction circuit.

The side lock provides a difficult-to-use, asymmetrical error signal. Particularly for large variations in the diode output, the asymmetry causes difficulties in locking the laser.

The error signal is fed into a lab-standard PID controller which provides feedback to both the laser current and the piezo crystals controlling the ECDL's reflection grating. For this research, only the proportional and integral portions of the PID control were used. The ECDL system exhibited substantial instability when subjected to the higher frequency feedback provided by the differential control. The current control signal is sent to the modulation input of the current driver circuit, which converts the voltage signal to a current signal [1]. The piezo control signal is sent to a Thorlabs MDT691 piezo driver, which amplifies the signal to high-voltage to drive the piezo crystals controlling the ECDL grating position.

3.5 Measuring the Radio-frequency Noise

The radio-frequency (RF) amplitude noise requires substantial amplification to be measured. First, the photodiode used to measure the beam has a built-in amplifier. Then a Microcircuits ZFL-500LN RF amplifier further amplifies the signal. As an RF amplifier, it also provides high-pass filtering, allowing only the time-varying part of the signal through.

To reproduce the Stanford experiment, part of the laser beam is split off and sent to a photodiode. The output of this photodiode is sent to a spectrum analyzer [2] for observation. The signal is

[1] The conversion is one milliamp per volt.

[2] The analyzer is an HP 8568B OPT E44.

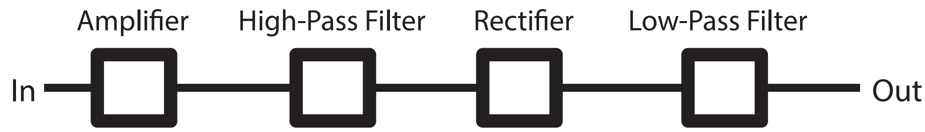

Figure 3.4 Schematic of the circuit used to convert the radio-frequency noise into a usable signal. The input is first amplified by an op-amp. The next stage high-pass filters the signal to ensure only high-frequency noise is measured. Then a rectifier circuit converts the signal into purely positive values. Finally a low-pass filter smooths out the signal to provide a slowly time-varying signal.

split, and the second part is sent into a feedback circuit. Even with the dual amplification, the RF noise was on the low end of the spectrum analyzer's amplitude range.

A custom-built circuit, shown in Fig. 3.4, translates the RF noise into a near-DC signal. The input is first amplified by an op-amp. The next stage high-pass filters the signal to ensure only high-frequency noise is measured. Then a rectifier circuit converts the signal into purely positive values. Finally a low-pass filter smooths out the signal to provide a slowly time-varying signal. This slowly varying signal provides a suitable input for either measurement or further processing.

At this point we come to my new method. In my method, instead of measuring the RF amplitude noise of the laser, I measured the RF electronic noise on the feedback from the lock cavity to the laser. In this case the signal does not require extensive amplification to be used. As described later in this thesis, I found this method to be just as effective as the Stanford method.

3.6 Full Feedback System

The full feedback system is shown in Fig. 3.5. A lock-in amplifier provides a modulation signal which is added to the PID current control output. These are added together by a simple op-amp adder circuit on the same breadboard as the subtraction circuit for the side-lock. This modulation signal operated at several different frequencies over the course of making measurements, but based on the previous research, I made sure it was slow enough that the PID controller was able to

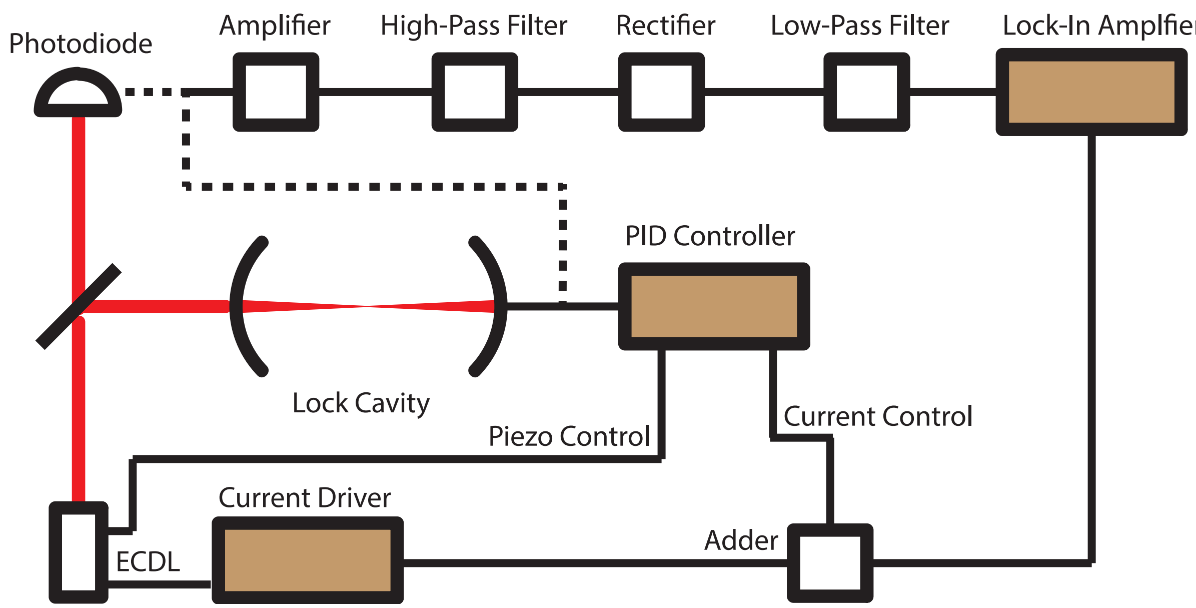

Figure 3.5 Diagram of the full feedback system used. The dashed lines indicate the two different methods used to send the system noise into the noise-measuring circuit. The lock-in amplifier provides the modulation signal as well as processing the output of the noise-lock circuit.

compensate for the variation and keep the laser at a consistent frequency. Because this modulation is only on the current, while the PID controller compensates using both the current and the piezo control of the grating, the effect of the modulation is to vary the relative effects of the current and grating position.

As this modulation occurs, the slowly varying RF noise signal is sent to the lock-in amplifier; this then measures correlations between the RF noise and the modulation. If the ECDL is at a minimum noise point then the RF noise signal will vary with twice the frequency of the modulation and the lock-in amplifier will return a zero output. Otherwise the two will be in or out of phase, depending on whether the current is above or below the ideal point.

The lock-in amplifier output is also added to the PID current control output. First, the lock-in output is sent through an integration circuit which smooths out and inverts the signal. After being integrated the signal is sent to the same op-amp circuit used to add the modulation to the PID current control signal. Over time the lock-in output adds a correction to the relative current and piezo controls, ideally keeping the laser in low-noise operation far away from any mode-hops.

3.7 Detecting Mode Hops

One way to detect mode hops is to measure the wavelength of the laser over time; if the wavelength stays the same, then the laser has stayed in the same mode. In order to make such measurements over time, I used a Bristol 521 wavelength meter. About half of the laser beam is sent to the wavemeter. This amount of power is necessary to provide the wavemeter with sufficient optical power for measurements, due to the low power of the laser and poor coupling into the optical fiber that leads to the wavemeter. The wavemeter readings are read, collected, and saved by a combination of Mathematica and LabVEIW programs. The Mathematica code used is detailed in appendix A. When used these programs take measurements of the laser wavelength every few seconds over a period of several hours.

As an alternative to waiting for the laser to drift on its own, the laser can be scanned. Measuring how far the laser's frequency can change without a mode hop is a quick way to measure the effectiveness of a lock. In my system to scan the laser the length of the lock cavity is adjusted by the built-in piezoelectric crystals. Changing the length changes the resonance frequencies of the cavity, which in turn causes the lock circuit to push the laser to the new lock-point determined by the new resonances. This movement of the laser output frequency is observed using the monitor cavity.

The peaks of the monitor cavity are measured and counted as they move in response to the laser output changing. Measurements of the effectiveness of the lock system are made by converting this number of peaks into a frequency by using the free-spectral range of the cavity. As shown above in Fig. 3.2 and Fig. 3.3, the transition from single-mode operation to multi-mode operation is substantial, allowing for any failure of the lock system to be readily apparent.

Chapter 4

Results and Conclusions

4.1 Mode vs. Time Data

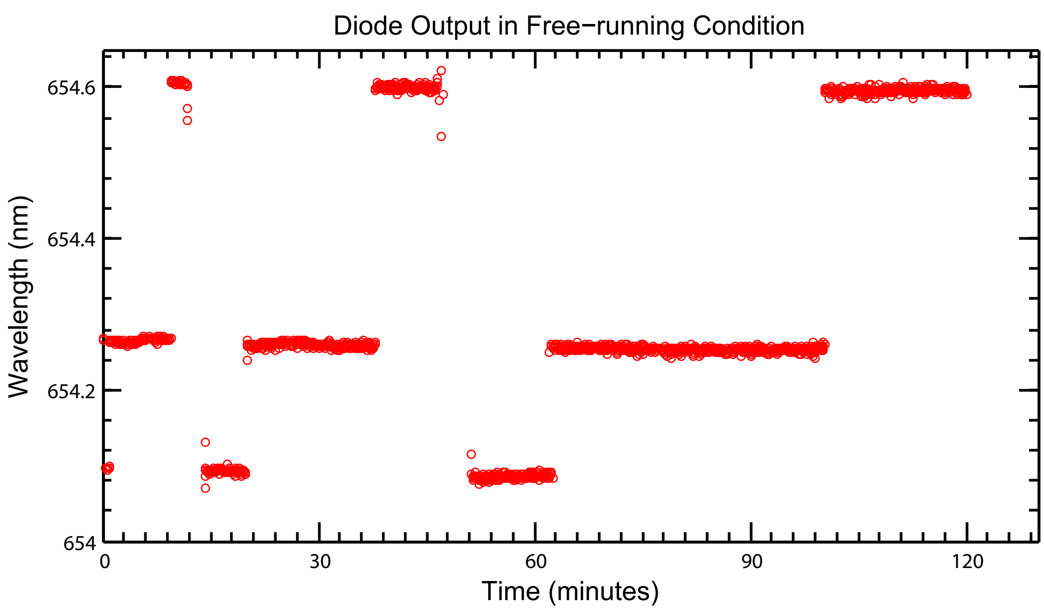

Figure 4.1 Measurement of the ECDL wavelength output over time in the free-running condition. As can be seen in this graph, the time between mode hops for a free-running laser is irregular. Also, note that there are substantial gaps between the modes' wavelengths.

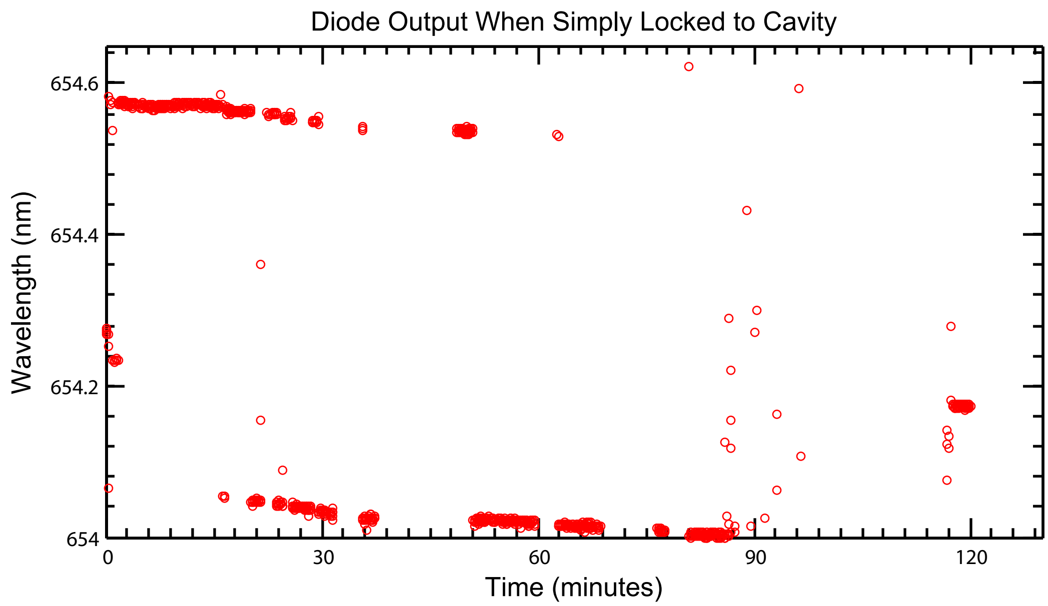

Figure 4.2 Measurement of the ECDL wavelength output over time while locked to a cavity. Note that the frequency control allowed by locking to the cavity results in a very different measurement than the free-running condition. In particular this measurement shows a trade-off between control and maximum stability.

Using the Stanford method, I took data of the ECDL output frequency over time. These data show that I have successfully reproduced their work. Compare the data in Fig. 4.1, Fig. 4.2, and Fig. 4.3 showing the wavelength of the output of the laser diode over time. The data in Fig. 4.1 and Fig. 4.2 were taken without RF noise feedback. Fig. 4.3 on the other hand, shows data taken with the Stanford-type system. Note how much longer the laser stays on a single mode in Fig. 4.3 then in the other two data sets. While the data in Fig. 4.3 was taken after some additional calibration of the feedback system, it shows the vast stability improvement given by the Stanford method.

One thing to note is the difference between a mode hop and mode drift. Observe Fig. 4.1, which shows the output of the laser with no feedback engaged. Even in the free running condition the ECDL manages about 40 minutes of stability during the period of measurement. Compare this to Fig. 4.2, where the diode is locked to an optical cavity. From observing the behavior of the ECDL when locked to the cavity, we can see that while locking to the cavity gives control over the

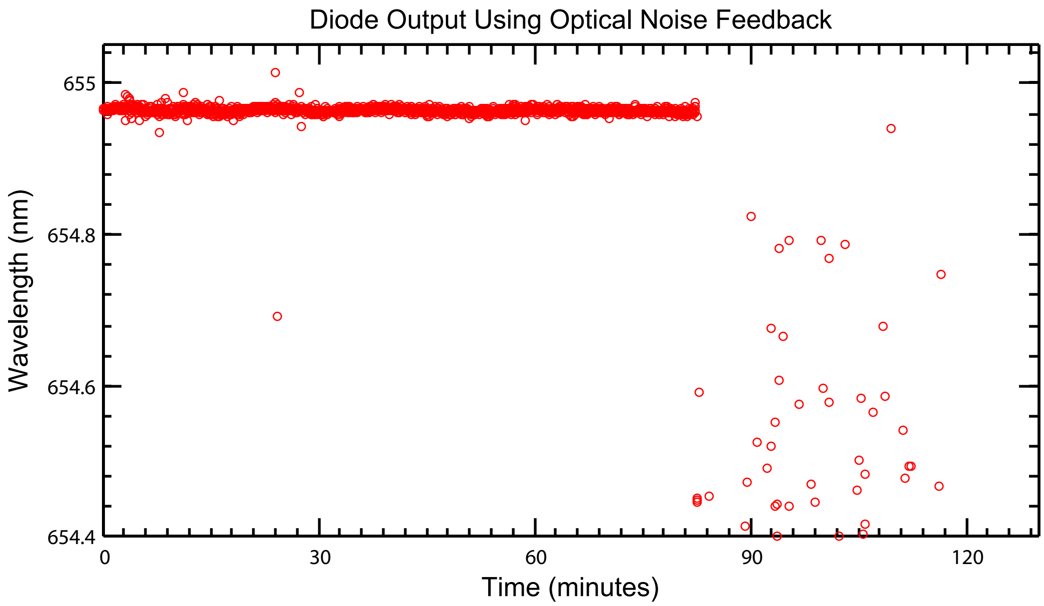

Figure 4.3 Measurement of the ECDL wavelength output over time while locked to a cavity and receiving additional feedback based on the optical noise. In this measurement the ECDL was able to stay single-mode for about 80 minutes. Note that in this measurement the diode was at a slightly higher wavelength than either the free-running condition or the simple cavity lock.

ECDL output frequency, it appears to have a negative effect on the stability of the single mode to which the laser is locked.

While this is no match for the two-orders-of-magnitude improvement described by the team at Stanford, it is a good start. The data given by the team at Stanford are rather impressive, so I would expect that matching their full results would require a more careful and precise approach than the one which I used. Areas for improving my system will be presented at the end of this thesis. With such improvements it should be possible to fully match the Stanford results.

4.2 Scan Data

The data from manually scanning the reference frequency indicate a substantial improvement by using the radio-frequency (RF) noise as a feedback signal. The data in Table 4.1 were taken using

Table 4.1 Range of single-mode scans in various operating conditions.

	Without Noise Feedback		With Noise Feedback	
Scan Date	Range (FSR)	Range (GHz)	Range (FSR)	Range (GHz)
1 Feb	2.5	0.9375	7	2.625
18 Feb	2	0.75	6	2.25

my new feedback system, the electrical noise in the lock system, to produce the feedback signal. These data show a substantial improvement in scan performance when using the feedback vs. only locking to the cavity. The scans were performed with a variety of parameters. The first and second scans were taken on different days with only a single piezo feedback channel to the ECDL grating, meaning the grating angle stayed constant while the length of the extended-cavity was changed. The data for the first set were obtained with a modulation frequency of 20 Hz, while the second set used a frequency of 90 Hz after the 20 Hz modulation failed to work on that day.

While this is not the measurement I was originally seeking, it is important and closely related. The increased range the laser can scan indicates that the added feedback system is performing properly to match the internal parameters of the ECDL such that mode hops are prevented. Since the added feedback system has no knowledge of the laser condition other than the laser output, this suggests that this design should be able to achieve good long-term performance.

The success using the RF electronic noise from the frequency-lock indicates that the noise there is a valid source for a useful error signal. Thus an additional photodiode is unnecessary for implementation of this technique; existing noise in frequency-lock circuits should provide the necessary data to improve the laser lock with my method.

4.3 Review of Data and Conclusions

While direct measurement of the stability lifetime showed clear improvement, several changes to my setup could result in greater improvement. The data was taken with a single piezo channel controlling the ECDL grating; as mentioned in my introduction it is common for systems to have multiple channels of piezo control to precisely control the relationship of the reflection grating position and angle. Lacking such control limits the range of my lock when scanning. Also, my system was not mechanically isolated from its environment, which made it vulnerable to stray vibrations. However, the success of this system despite the limitations of my specific setup indicate that the system is robust and versatile; it will likely work well with many different ECDL systems.

The scan data show that there is a substantial improvement in the stability of single-mode operation during scans when using the RF noise feedback. Using my electronic noise measurement system, the laser was able to scan about three times as far as it could without the noise control. This clearly shows that my system is improving the stability of the laser as the laser is scanned.

In particular, the success of my new control system using purely electronic feedback suggests that the noise signal used is primarily a result of the original cavity locking system. This result is especially nice, because it means that the RF noise feedback system can be added to existing systems without affecting the optical setup. A simple electrical connection to an existing error signal can provide the necessary information for this system to improve the lock performance.

4.4 Direction for Further Work

A clear way to improve my setup would be to provide mechanical isolation for my system. This would primarily consist of floating the optical table where the laser system is located. With mechanical isolation the system should become much more stable, particularly for long-term measurements. The system is sensitive enough that even minor vibrations can cause substantial variations in the various cavities involved in the ECDL and lock systems.

Another simple step that might provide even better stability would be to implement a feed-forward system. Using two piezo drivers to adjust the ECDL grating provides the ability to precisely control the ratio between the change in grating angle and portion. With the right ratio this can compensate for some of the relative drift of the grating and diode modes in the ECDL. This in turn provides a range for ideal overlap, allowing the laser to scan further. Combining this standard method with RF noise feedback should provide substantial stability improvements since the feed-forward accounts for predictable variations while the RF noise feedback can handle unpredictable changes.

Using a different method for generating an error signal from the lock cavity would likely enhance both performance and ease of use. The side lock is non-symmetric which causes the lock to have substantially better performance when scanned in one direction as opposed to the other direction. The asymmetry and the amplitude variation of the lock make it difficult to make a consistent system using a side lock. A Pound-Drever-Hall lock would likely improve the performance of the lock. The properties of such a lock would allow a more consistent calibration of the lock system as well as preventing stray amplitude effects from affecting the lock.

A higher modulation frequency would help the lock to compensate for high frequency changes. Mode hops are one such high-frequency change. As noted above, increasing the modulation frequency was required for the lock to work at all for some of my runs. It is likely that further increases in modulation frequency would continue to aid the performance of the lock until the modulation reaches some resonance in the system.

Appendix A

Code for Automated Frequency Measurement

```
SetDirectory[NotebookDirectory[]];
i = 0;  (*This variable is used to keep track of different runs
on the same day.  It and the SetDirectory command are in a
different cell than the rest of the code so it is only run
once while the rest of the code can be run several times
in a single day.*)
hourstorun = 2; (*Set the length of time to take measurements*)
secondstorun = 60 60 hourstorun;     (*Convert to seconds*)
data = {};  (*Use this to clear the "data" array before taking
measurements*)
i++      (*This iterates the counter to enable taking multiple
data sets in one day*)
start = SessionTime[]    (*Gets a staring time value so that the
```

```
time change while collecting the data can be calculated.*)
iterations = 0; (*Sets an iterations variable to be used in the
loop for controlling pauses*)
AbsoluteTiming[While[SessionTime[] - start < secondstorun,
  Run["z:\\users\\Enoch\\labview-bristol\\getlambdafinal
␣␣\\getlambdav3-8-13-13.exe"];
(* This command runs the labview program, which reads in the
wavelength using the bristol wavemeter and then puts the reading
into the file lambda.txt in the same directory as the executable.
The run command is the way that I found to work around the
windows security settings.*)
  data = Append[
    data, {SessionTime[] - start,
    ToExpression[Import["lambda.txt"]]}];
(* This Append command adds the time of the measurement and the
measurement itself as an ordered pair on the end of the "data"
array.  The ToExpression is so that the measurements are
saved as numbers instead of strings.*)
  iterations++
   If[iterations > (SessionTime[] - start),
    Pause[iterations + start - SessionTime[]]
    ]
    (*Limits the size of the "data" array by limiting to one
    measurement per second*)
  ]]
```

```
(*A single run through the loop takes a couple seconds as a
 result of the time taken in running the labview .exe file.*)
data; (*Used for monitoring purposes*)
Export["Chu-lock␣measurments␣" <>
   DateString[{"Day", "-", "MonthNameShort", "-", "Year"}] <>
   "␣trial␣" <> ToString[i] <> ".csv", N[data]]
(*The Export command saves the data to a .csv file.*)
```

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