Stabilizing injection-locked lasers through active feedback.

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ABSTRACT

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I seek to make injection locking a more reliable tool in atomic physics by active stabilization. An injection-locked diode laser can be actively stabilized by monitoring either the laser's frequency spectrum or the overall intensity. I used the transmission of a Fabry-Perot cavity to measure the frequency spectrum of an injection-locked laser. When the injection lock is about to break, the intensity of the dominant spectral mode decreases while the overall intensity increases. Similarly, a photodiode measures the overall intensity of the laser. Under certain conditions, the injection-locked laser's intensity corresponds to how strong the injection-lock is. To prevent the injection-lock from breaking, an Arduino Uno measures either the amplitude of the main spectral peak or the overall intensity while simultaneously adjusting the current of the injection-locked laser. By so doing, an injection-lock that has an average lifetime of a few minutes can be stabilized to have a lifetime of several hours.

Keywords: injection lock, injection-lock, laser, Fabry-Perot, stabilization, Arduino

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Chapter 1

Introduction

This chapter starts with the purpose of injection locking. This is followed by a description of how injection-locked lasers works. The second subsection sets forth the primary limitations of injection locking. A solution to those limitations is described in subsection 1.3. Then, previous work is acknowledged. Finally, an overview of the thesis is laid out.

1.1 Motivation

Many branches of physics require precise and powerful lasers. Diode lasers are often preferred among lasers; they are cheap, durable, and have lower voltage requirements. However, a bare diode is wildly unstable. It can be stabilized passively by mechanical isolation, temperature control, and a clean current source. Despite these measures, the frequency may still drift. Additionally, when one mode of the laser becomes more favorable than then current mode, the laser will "mode hop" to a different frequency. A more powerful the laser is generally more difficult to control.

Researchers have developed ways to actively stabilize diode lasers, e.g., locking the laser to a cavity or using a diffraction grating to provide optical feedback. Although these methods can effectively stabilize the laser, they are expensive and complicated to implement [1]. Furthermore, these methods often result in lose of usable power. Injection locking, however, does not reduce the usable output of a laser and is simple to implement.

Injection locking involves shining a weak but stabilized laser (the master) into a powerful but unstable laser (the slave). As a result, the slave laser locks to the same frequency as the stabilized master laser. This method does not have moving parts and does not require expensive specialized equipment. A master laser can control a slave laser with very little light. Therefore, one master can control multiple slaves by splitting its output. This potentially allows injection-locking to achieve any level of power.

1.2 Limitations

Although injection locking has many strengths, it has limitations. Injection locking requires that the slave laser has a favorable mode at a frequency very close to the frequency of the master. If the slave drifts too far from the frequency of the master, the injection lock will break, and the slave laser will not lase at the desired frequency. Therefore, the stability of the injection lock is limited by the stability of the slave laser.

Another limitation of injection locking is a narrow bandwidth. This is important in applications that need the laser to change frequencies. If the master sweeps too far from the natural frequency of the slave, the injection lock breaks. Active stabilization solves these setbacks.

1.3 Active Stabilization

Long term stability of an injection-locked system requires active stabilization. In order to actively stabilize the injection lock, there needs to be a way to both assess how far the slave laser has drifted (an error signal), and to adjust the slave laser before it breaks injection lock. I have found two different ways to monitor the injection lock's stability. Both the spectral output and the intensity of the slave laser can be used to predict and prevent the injection lock from breaking.

1.4 Previous Work at BYU

The inspiration for this project was inspired by McKinley Pugh's [2] work with extended cavity diode lasers (ECDLs). While ECDLs are beyond the scope of this thesis, in some sense they can be thought of as a laser that injection locks with itself. They also suffer from sudden changes in mode. Pugh discovered that an ECDL can be stabilized using frequency noise as feedback. The discovery of an error signal in ECDLs naturally prompted a search for an error signal in injection-locked lasers.

1.5 Overview

Chapter two elaborates on the three different methods I used to actively stabilize injection-locks. The equipment is general to all of the methods and so are discussed first. The methods are presented individually following the pattern of explaining the how to how to implement it, its advantages, and its limitations.

In chapter three, the advantages and disadvantages of the three methods will be summarized.

Chapter 2

Methods

This chapter begins by discussing the practicalities of injection-locking in general and in my particular setup. The following sections cover three methods that can be used to stabilize injection-locks. The description of each method will include how the method works, any necessary additions to the existing injection-lock setup, and the method's advantages and disadvantages.

2.1 Injection-Locking Setup

While the concept of injection-locking is straight forward, there are important practicalities that need to be addressed. In particular, the beam from the master laser needs to match the beam leaving the slave laser; both beams need to have the same angle, position, divergence, width and polarization (see Fig 2.1). The angle and position are taken care of by the two mirrors after the master laser. As both the master and slave are collimated, they have the same divergence. Ordinarily, there would need to be telescoping lenses to adjust the width of the master, but the width of both lasers was close enough making telescoping was not necessary. The waveplate insured that the master laser's beam matched the polarization of the slave laser as it comes out of the optical isolator.

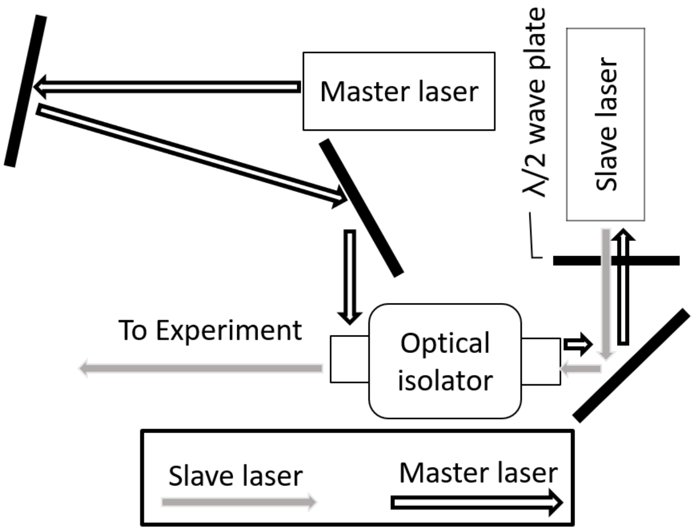


Figure 2.1 Necessary setup for an injection-locked laser

2.1.1 Lasers

The two most important features of the injection-lock setup are the master and slave lasers. The master laser is a 657.450 nm Vortex laser operating at 100 mW. Its wavelength can be fine tuned by adjusting the voltage to the diode. The master has much more power than necessary. I used it because it is a very stable laser that was available in my lab.

The slave laser is a 658 nm ThorLabs diode laser (L658050) operating at 50 mW without an anti-reflective coating. The laser diode's wavelength can be varied by adjusting the current and temperature. This laser rarely lases in a single mode and has a constantly shifting frequency even while under temperature and current control. I chose this laser to show that if my stabilization methods work for a laser as unstable as this one, then it should work for most diode lasers. The longest injection-lock that I observed for this diode without stabilization is half an hour. More typical injection-locks last from a few minutes down to seconds.

2.1.2 Optical Isolator

The isolator acts as a one-way valve for the slave laser; light from the slave laser can go through the isolator to the experiment, but no reflections from the experiment and return to interfere with the slave. Meanwhile, the master shines through a different port of the isolator in such a way that it continues on to the slave laser. As the slave laser does not shine into the master laser, the master is decoupled from the slave laser.

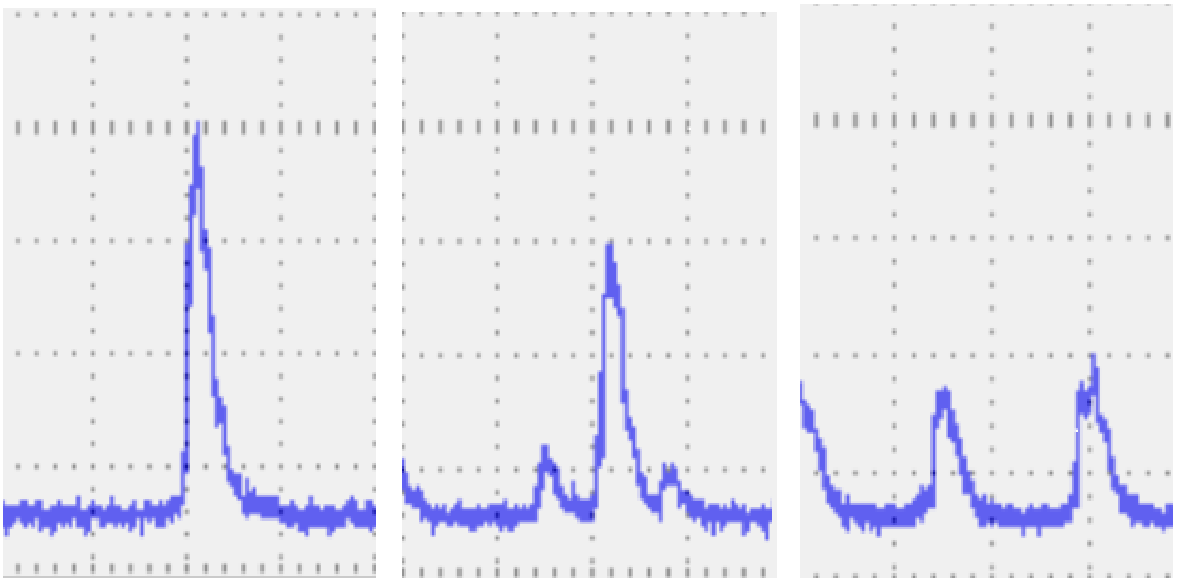
The optical isolator consists of a Faraday rotator between two polarizing beam splitters. The rotator twists the polarization of the light entering it by 45°. The rotation is in the same direction regardless of the direction of the light, so light that goes through and comes back will be rotated a total of 90°. The first polarizing beam splitter polarizes the light going in the rotator and rejects the light coming back out the rotator that has now been rotated 90°. A $\lambda/2$ waveplate aligns the polarization of the the slave laser for maximum transition through the first polarizer. The second polarizer is rotated 45° with respect to the first polarizer. This alows the slave laser to pass through. It is also oriented so that the master laser can enter the isolator in a way that it has the right polarization to pass through the first polarizer and onto the slave laser (see Fig. 2.1).

2.2 Method 1: Stabilization by Spectroscopy

The spectrum of a completely injection-locked laser has tall narrow spectral peaks while a partially injection-locked laser has sidebands that appear and take energy out of the main peak (see Fig. 2.2). The Arduino can detect this and adjust the current to maximize the peaks and thereby keep the laser injection-locked.

Using this method increased the typical lifetime of my injection-lock from minutes to hours.

As further evidence of the efficacy of this method, Saxberg *et al.* [3] independently developed a nearly identical method to stabilize a 120 mW 399 nm diode laser for cooling Yb atoms.



(a) **(b)** **(c)**

Figure 2.2 Spectral Output of Slave Laser While Injection-Locked. *Horizontal scale is in 20 mV increments. a) Stable injection-lock. The peaks are tall and narrow. b) Still injection-locked but side bands have appeared. c) Still interacting with the master laser but the side bands have taken over. As the strength of the injection-lock decreases, so does the height of the main peak.*

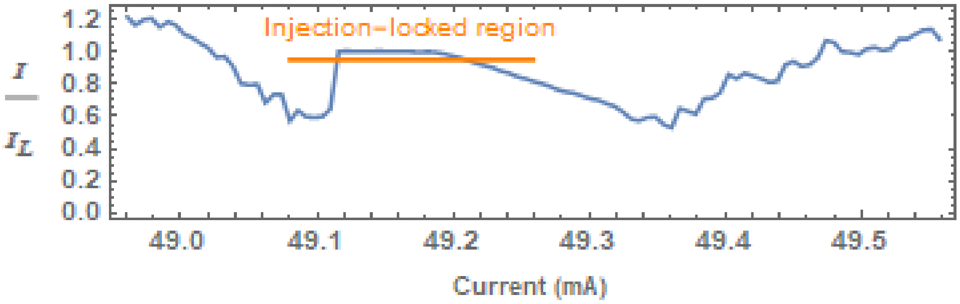


Figure 2.3 Peak intensity vs. current to the slave laser. *The central plateau represents the region where the injection-lock is stable. The peak intensity signal has been normalized so that while injection-locked the peak height is one.*

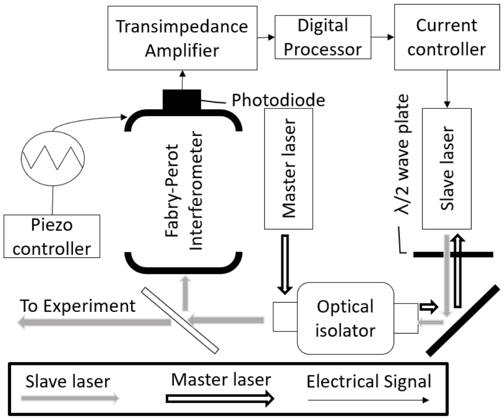
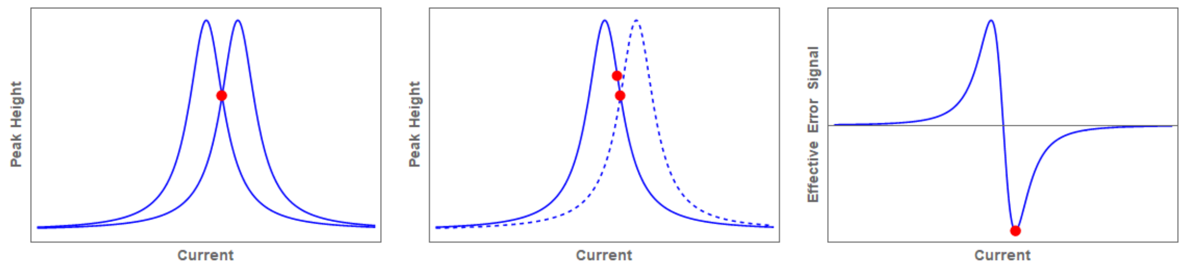


Figure 2.4 Stabilization by Spectroscopy Setup. *The Fabry-Perot scans back and forth due to the triangle wave from the piezo driver. This causes the cavity to become a spectrometer.*

2.2.1 Experimental Design

The only addition to the optical portion of the injection-lock is a Fabry-Perot cavity that acts as a spectrometer (see Fig. 2.4). The length of the cavity is adjusted by piezo-electric crystals. The piezo driver sends a triangle wave to the crystal and causes the cavity's length to vibrate back and forth. At different lengths, the cavity is resonant with different wavelengths of light. This allows the cavity to discriminate between different wavelengths of light and thereby act as a spectrometer. This information is transmitted to the digital processor via a photodiode. The Fabry-Perot cavity is 10 cm long with a an approximate finesse of 100 and a free spectral range of about 2 fm. A cavity used for stabilizing the injection-lock need not have exceptionally high finesse. A lower finesse means that the peaks are broader and easier to detect digitally and that the ring-down time is faster so the cavity responds to changes more quickly.

Most of the additions necessary to stabilize the injection-lock are electronic. The digital processor turns the signal from the spectrometer into an error signal that can be used in active feedback. To provide active feedback, the processor needs to adjust the current to the slave laser to maximize



(a) Without dithering **(b)** With dithering **(c)** Effective error signal

Figure 2.5 Dithering: *Measuring the peak height at the same current only reveals that the current needs to change, but not how it needs to change. If the peak height decreases then the current needs to be adjusted, but there is no indication as to whether it needs to increase or decrease (a). Dithering adds a small oscillation to the current. By comparing the response at higher currents verses at lower currents, it is possible to determine how to adjust the current (b). In this case, the current needs to be lowered. Subtracting the response at the lower current from the response at the higher current results in obtaining the derivative of the response. This serves as the effective error signal (c). When the error signal is zero, the laser is injection-locked. The negative value shown indicates that the current needs to be decreased.*

the peak height in the frequency spectrum. The difficulty is that a single measurement does not give enough information to determine if the signal is at a maximum. Even if the processor detects that the signal is not at a maximum, it does not ’know’ whether to increase or decrease the current to bring the signal back to a maximum. The solution is to find the derivative of the voltage with respect to the current, and drive the derivative to zero. The derivative, however, cannot be passively measured without changing the current. This is where dithering comes in. Dithering involves adding a small modulation to the overall current (I used a square wave). The response for when the modulation is high is compared with when the modulation is low. The high response minus the low response gives the sign of the derivative and, hence, the direction the current needs to be adjusted.

The digital processor used is an Arduino. The Arduino is a micro-controller that can simultaneously read and write voltages, while performing digital analysis. I chose the Arduino UNO because it is inexpensive and easy to operate. It has a clock speed of 16 MHz and a maximum

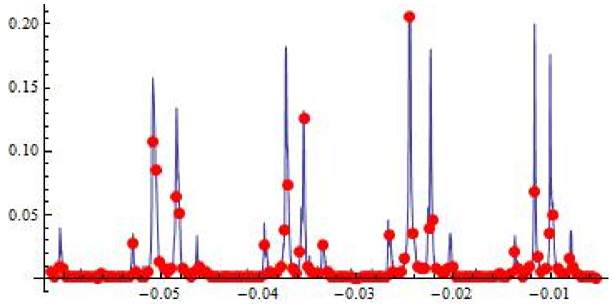


Figure 2.6 Digitally Finding Peak Values. *The speed of the spectroscopy is limited by the number of samples needed to ensure that a sample lands on the peak voltage.*

voltage sampling rate of 10 KHz. There are better micro-controllers, but the Arduino is sufficient.

Advantages

This method is easy to implement. The only addition to the optical setup is the Fabry-Perot cavity. This method is suitable for most applications that require an injection-lock.

Limitations

This method is slow, and is therefore not suited for particularly unstable slave lasers and for applications that require the laser to change frequencies. The Arduino continuously measures the signal from the spectrometer, but only a small number of measurements sample the height of the spectral peak (see Fig. 2.6). The probability of sampling near the top of the peak for a given measurement is proportional to the width of the peak divided by the free spectral range, which is equal to the finesse of the cavity. So the finesse needs to be high enough to separate the different modes such that there is a low probability of different modes landing on top of each other. But increasing the finesse also increases the number of samples needed for an accurate measurement of the peak height. As the Arduino needs to take thousands of samples for each update cycle, the current can only change at a rate of about 10Hz. This method can be sped up by a faster processor.

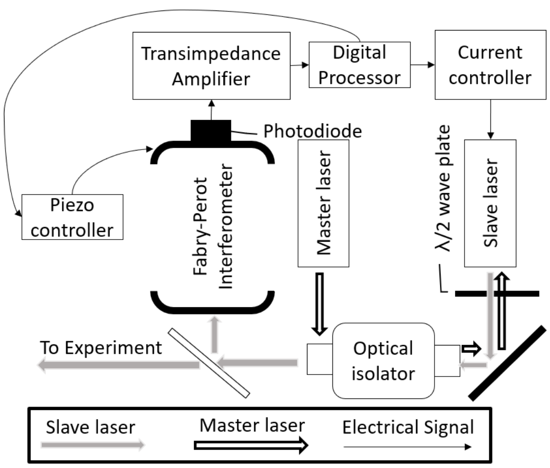


Figure 2.7 Stabilization by Locking the Cavity to the Laser Setup. *The only change from the previous setup is that now the cavity is locked to the slave laser.*

2.3 Method 2: Stabilization by Locking the Cavity to the Laser

This method overcomes the main deficiency in scanning the Fabry- Perot cavity: most of the time spent scanning the cavity is wasted because the only valuable information is in the value of the highest peak (see Fig 2.6). By locking the cavity to main peak, the signal from the cavity always corresponds to the amplitude of the main peak. Instead of taking thousands of samples to measure the height of the spectral peak, every sample is meaningful.

Ideally, the cavity would be locked to the laser via a Pound-Drever-Hall lock (PDH lock). Various technical limitations, prevented me from using a PDH lock. Also, one goal of injection locking is to stabilize the laser in a simple manner. A PDH lock complicates the setup. I have not yet succeeded in locking the cavity to the laser. As such, this method remains a theoretical possibility.

Other than locking the cavity to the slave laser, this method is identical to the spectroscopy method; the signal from the cavity is processed in the same way except much faster, because fewer samples are needed.

Advantages

This method is very fast and can be used on any injection-lock including sweeping lasers. Because the Fabry-Perot cavity is always resonant with the injection-locked wave length, every sample can be used in the error signal, thus this method should be two orders of magnitude faster than the spectroscopy method. It should be broadly applicable to diode lasers.

Limitations

Locking the Fabry-Perot cavity to the laser adds an extra layer of complexity that may not be necessary for many applications.

2.4 Method 3: Stabilization by Monitoring Intensity

The intensity of the slave laser can be used to stabilize the injection-lock. I empirically discovered that the intensity of the slave laser decreases as the injection-lock is about to break (see Fig. 2.9). So, by actively adjusting the current to keep the laser intensity at this local maximum, the injection-lock can be maintained.

There are some technical challenges in using the intensity to stabilize the injection-lock. Notice that in fig. 2.9) the percent change of the intensity is much smaller than the percent change in peak height. Also, the signal is imbalanced. The derivative of the signal is much greater at currents bellow the injection-lock than at currents greater than the injection-lock. This is because increasing the current also increases the intensity. This counteracts the effect that breaking the injection-lock has in decreasing the intensity.

The intensity signal in fig. 2.9 is not consistent between different regimes of the slave laser. It is the typical response, but is not always so clear. While testing this signal at the extreme currents of the laser's operations, the signal was not as clear. On rare occasions, I observed that the intensity of the laser *decreased* inside of the injection-lock. Further testing is needed to understand the intensity of the slave laser while under the influence of the master laser.

Using this method does work. It has increased the typical lifetime of my injection-lock from minutes to hours.

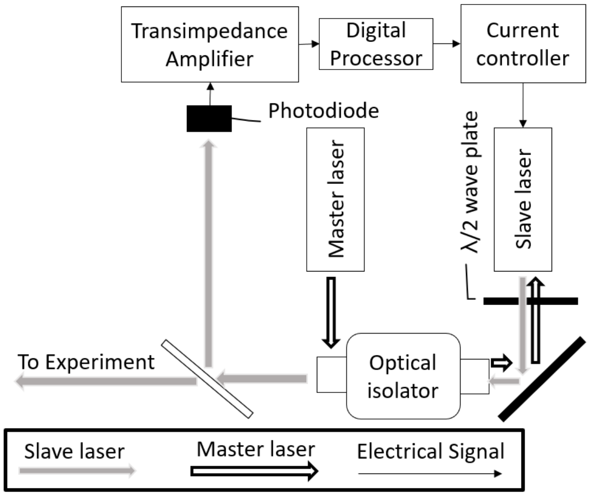


Figure 2.8 Stabilization by Monitoring Intensity. *A photodiode monitors the slave laser's intensity. Both signals were normalized so that while injection-locked the intensity is one.*

I am not certain why this effect occurs, but I have one speculative theory; it may be spatial hole burning [4]. Each frequency forms a standing wave in the cavity of the laser. The gain medium inside of the cavity relies on stimulated emission to power the laser. At the nodes of the standing wave, there is no light to activate the gain medium. Therefore, a single frequency laser does not use the power available in the gain medium at the nodes. The nodes are washed out for a laser operating at multiple frequencies (i.e., a laser that has just broken injection-lock), therefore a multi-frequency laser, in theory, lases with more power than its single-frequency counterpart.

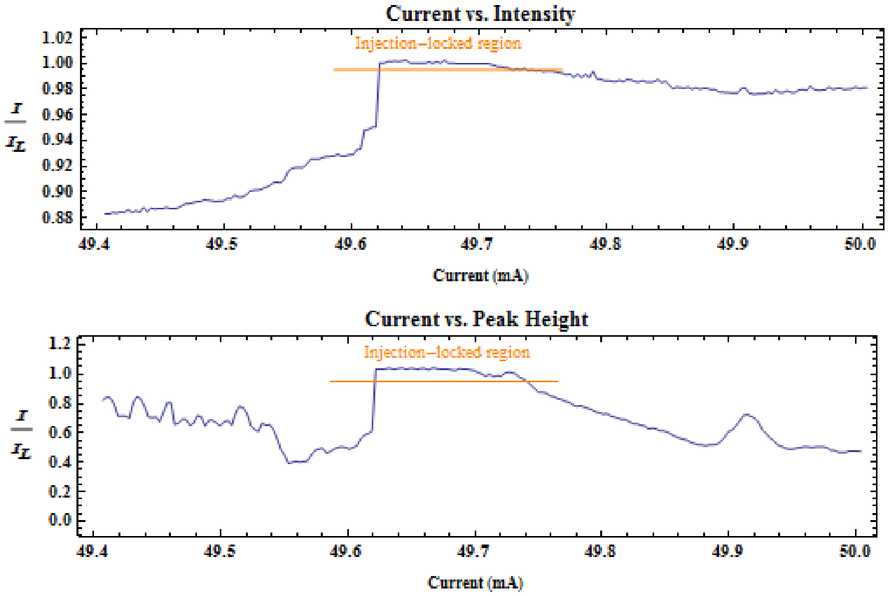


Figure 2.9 Response of slave laser as it goes through injection-lock. *The slave laser's intensity (top) is simultaneously compared with the peak height (bottom)*

Advantages

This is the simplest method to implement and is as fast as locking the cavity to the laser. The only addition to the optical setup is a photodiode which can be added to any stray beam. The rest of the changes are electrical.

Limitations

I do not have a theory to describe why this is happening. This method may not work for every laser all of the time. However, it is worth looking into this method, because it is so easy to implement.

Chapter 3

Comparison and Conclusion

This chapter compares the different methods and describes when to use which method.

3.1 Comparison of methods

If all of the methods work, then why not just implement the easiest method and move on to the research? Each method has its advantages and disadvantages.

The simplest way to stabilize the injection-lock is by monitoring the intensity, because it is fast and simple. It only requires the addition of a photodiode to the optical setup. Unfortunately, the intensity method is not understood and may not work in every situation. However, because the intensity is easy to measure, it is worthwhile to check if this method works. If it fails to stabilize the injection-lock, then at least the electrical components are practically identical for the other methods.

If the intensity method does not work in a setup, then choosing between the first two methods is a matter of speed and complexity. The spectroscopy method works for applications that change slowly. If the slave laser is sufficiently stable[1] and the application requires a constant laser source, then use spectroscopy. If the slave laser is so unstable that scanning the cavity is not fast enough, then consider improving passive control of the slave laser .

The quality of the injection-lock can be improved by insuring that the master laser is optimally coupled into the slave laser. I found that poor coupling dramatically decreases the injection-lock time. Because the level of complexity is much greater for locking the cavity than sweeping the cavity, try using a faster processor. The Arduino Uno I used operates with a clock speed of 16 MHz which is slow among processors. Faster data acquisition can speed up the cavity sweeping method. Hopefully, with all this the cavity sweeping method will work for most applications.

Sweeping the cavity may not be enough to stabilize the laser if the slave laser is too unstable or the frequency of the laser needs to change during the experiment. In such cases, the cavity needs to be locked to the laser. While more difficult to set up, locking the cavity to the laser should work in every injection-lock. It has the speed of the intensity method while being understood by the same principles as the scanning method.

At this point, the injection lock is stabilized, and the laser is ready to be used in research.

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[1] By "sufficiently stable," I mean that the slave laser stays injection-locked without any active stabilization for a reasonable amount of time, i.e., longer than a minute.

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