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Three Ways to Stabilize an Injection Lock

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1 Introduction

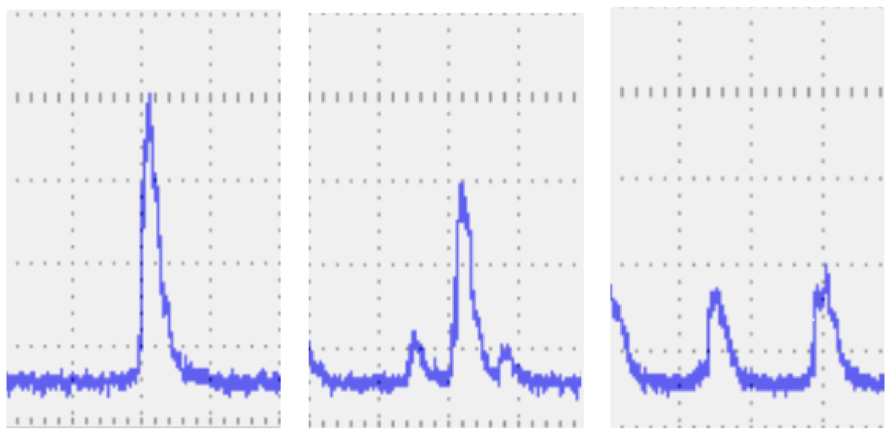
1.1 Why Injection Locked Lasers

Many branches of physics require precise and powerful lasers. For many reasons, diode lasers are preferred among lasers. They are cheap, durable, and have lower voltage requirements etc. However, a bare diode is wildly unstable. Temperature control, and a clean current source go a long way towards stabilizing a diode laser. Unfortunately, for many applications, this is not enough. It should be noted that the more powerful the laser, the more difficult it is to control. There are more complicated stabilization measures such as locking the laser to a cavity or using a diffraction grating to provide optical feedback. Although these methods effectively stabilize the laser, they are expensive and complicated to implement. What is worse is that these methods result in losing usable power. Injection locking overcomes these deficiencies.

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 onto 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, by splitting its output, one master can control multiple slaves, and by so doing, achieve any level of power.

1.2 Limitations of Injection Locked systems

Injection locking is not perfect. Current use of injection locking require that both the master and the slave lasers are already stable. The master needs to be stable in order for the controlled laser to be stable. This is implemented by using a well engineered laser that is not so powerful that it cannot be stabilized by normal means. The slave needs to be stable because injection locking only works if both lasers lase at nearly the same frequency. If the slave laser drifts too much, it will break out of injection lock and lase independently of the master.



(a) (b) (c)

Figure 1: **Spectral Output of Slave Laser While Injection Locked.** *Horizontal scale is in 20mV 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 and the main frequency is no long clear. As the strength of the injection lock decreases, so does the height of the main peak.*

This means injection locks are only stable for short periods of time. In the end, we are still limited by instability of the slave laser.

1.3 Active Stabilization

Active stabilization is required for long term stability of an injection locked system. In order to provide active feedback, there needs to be a signal that indicates how stable the injection lock is. This signal can then be used to adjust the laser so that it never drifts out of injection lock. I have found two such signals.

The first signal comes from the spectral output of the slave laser. When the spectrum analyzer shows that the slave has tall and narrow peaks at the same frequency as the master, the slave is securely injection locked (see Fig. 1a). As the natural frequencies of the lasers grow farther apart, there is an intermediate stage before the injection lock is broken. At this stage, the master still controls the slave, but the slave no longer lases single mode. Side bands appear that add unwanted frequencies and take power out of the desired frequency (see Fig. 1b). When the natural frequencies are farther still, the main frequency is no longer distinguished from the side bands (see Fig. 1c). Finally, the two lasers stop interacting and the slave simply lases its natural frequency. All of this means that by monitoring the power output at the desired frequency we can assess the stability of the system and therefore actively stabilize the injection lock. The first and second methods are based off of this principle.

The second signal was discovered empirically and is currently under continued investigation. At certain temperature and current combinations, the overall amplitude of the slave laser decreases on the order of a few percent. This is the basis of the third method.

2 Methods

2.1 Method 1: The Easy Way

This method directly monitors the height of the spectral peaks from the optical cavity. This utilizes the existing setup as most injection lock setups already use scanning optical cavity as spectrum analyzer in order to know if the laser is injection locked. If the output from the spectrum analyzer is fed into a computer, then the computer can find how high the peaks are. The computer can then adjust the current going to the slave laser and thereby keep the slave's natural frequency within stable injection lock limits.

This method requires very little change to an existing injection lock set up and should work well for experiments that need a constant laser source. However, the update rate for the slave laser is very slow, on the order of a few Hertz. While slow, this method considerably extends the life of an injection lock (from minutes to hours). Also, this method allowed me to scan the laser more than five time farther than without a controller.

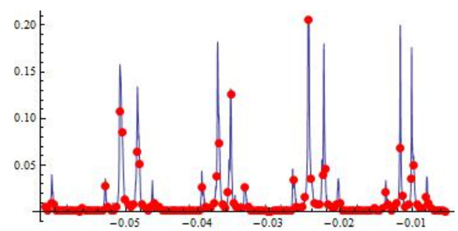


Figure 2: **Digitally Finding Peak Values.** *Finding the peak value is limited by the sampling rate and the narrow width of the peaks. The likelihood of any particular data point measuring the peak voltage is proportional to the width of the peak over the width of a complete scan (i.e. the width before it repeats itself).*

The greatest limiting factor of this method is how slow data acquisition is. Unfortunately, measuring the peak voltage has to be done digitally, because no analog circuit can return only the peak voltage. For data acquisition, I used the Arduino Uno©. It can read a signal at about one measurement per millisecond. Unfortunately, one measurement is not enough to find the peak value. I find that I need to take about 500 measurements to ensure that one of my measurements falls on the narrow peak value (see Fig. 2). So many measurements are required because the peak value occupies such a small proportion of the spectrum analyzer output. The next method overcomes this shortcoming.

2.2 Method 2: The Advanced Way

This method works very quickly, on the order of several Megahertzs. Once set up, this setup is ideal for stabilizing most injection locks. In particular, experiments requiring modulating injection locked lasers may require this method. Unfortunately, this method may require substantial expensive additions to the experimental setup. In particular, this method requires a Pound–Drever–Hall lock.

Instead of sweeping the cavity to get the spectrum, we lock the cavity to the laser. By doing this, the cavity is always putting out the information we want; the amplitude of the desired frequency. A Pound–Drever–Hall lock can accomplish this at around the order of 10 Megahertz, which is much faster than and will not limit the slave controller. For more information on how the Pound-Drever–Hall lock works, see R. Fox *Stabilizing Diode Lasers to High-Finesse Cavities.*

Because the cavity now only outputs the voltage corresponding to the highest, the controller can work much faster. Additionally, an analog controller can now replace the digital controller. The benefit would be that analog controllers are much faster than their digital counterparts. Because this controller works so quickly, it should be able to keep a secure injection lock even as the laser modulates. The opens up injection locking for use in chirped lasers and other similar applications.

2.3 Method 3: Using Laser Amplitude

As previously discussed, the overall amplitude of the laser decreases when injection locked. When this method works, it is the simple and fast. The only change needed to implement it is the addition of a diode reading the amplitude of a stray laser beam and an analog controller. Using the amplitude and

Unfortunately, we do not yet understand why the amplitude goes down when injection locked. We then cannot generalize and say that the amplitude goes down when every laser is injection locked. Regardless, it works on Thorlabs' L658P050 laser. This method to extend the life of an injection lock from minutes to hours.

3 Experimental Details

3.1 Using the Signals to Adjust the Current

On their own, the signals mentioned above are not very useful. For example, monitoring the height of the peaks can only tell whether or not the injection lock is unstable. It cannot measure which way the slave laser is drifting and therefore cannot adjust the current to counteract the drift. This is where we add dithering. Dithering involves sending a small oscillating signal – in my case a square wave– on top of the overall current going to the slave laser. This signal must be much smaller than the range of currents within a stable injection lock (a few μA). The computer measures the peaks (or whatever the signal) when the square wave and the current are at a maximum and then compares it with the peaks it measured at low current. It is this comparison that tells the controller how to adjust the current to prevent the injection lock from breaking. If the signal indicates a better injection lock when the current is at a maximum, then the current needs to increase or vise versa.

3.2 Arduino Uno©

I used the Arduino Uno as my controller. This board has analog input pins read the signal from the laser, internal process while digital output pins control the laser current. The primary benefit of using an Arduino is that as a single unit it can be a complete controller. While there are faster Arduinos than the Arduino Uno, I chose the Arduino Uno because it has an easily replaceable microprocessor. This was desirable because the controller is still in its developmental stage, and developmental stages are prone to mishap.

4 Further Work

4.1 Characterization of Signals

While the two signals explained above have worked in the environments they have been tested, there is a need to quantitatively characterize them. In particular, we need to see how the peaks and the amplitude respond at different temperature-current combinations. Hopefully, knowing how the laser reacts in different circumstances will help us understand why the amplitude changes as it does. At the very least, we will know which conditions lead to the best signal.

4.2 Stability Tests

Previous long term stability tests were limited because we do not have a good way for the computer to know if the laser is injection locked at a particular moment. The computer can only read and maximize the peak height from moment to moment. If the injection lock breaks suddenly, there will still be peaks to maximize but they will not be injection locked peaks. This means that long term stability tests can only run as long as there is a human watching the spectral output.

In addition to testing the lifetime of an injection lock, we need to measure the limit of sweep range and sweep speed. The sweep range is how far the master laser can scan its frequency before the injection lock breaks. The sweep speed is how fast the master can change frequencies and while the controller still maintains injection lock. The results of these test will determine which practical applications the methods will be suited for.

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