Mode-Locked Diode Laser for Precision Optical Frequency Measurements

A thesis submitted in partial fulfillment of the requirement for the degree of Bachelor of Science with Honors in Physics from the College of William and Mary in Virginia,

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Williamsburg, Virginia April 2008

Abstract

This thesis presents the design, construction, and testing of an actively mode-locked diode laser. This laser will be used in the William and Mary Ultra-Cold AMO Lab to make high precision measurements of optical frequency. These measurements are obtained by making use of the optical frequency comb created by the mode-locked laser.

Acknowledgements

I would like to thank a number of people who have contributed in different ways to the work presented here. First, I'd like to thank my advisor Dr. Seth Aubin for making this research experience possible and enjoyable. His guidance and encouragement throughout the year have been invaluable. Second, I would like to thank Dr. Irina Novikova for the use of her fast detector, spectrum analyzer and for providing the mirrors used in our scanning Fabry-Perot cavity. Also, I would like to thank Dr. Jan Chaloupka for allowing me to test our detector on his laser. Lastly, thank you to all friends and family who have supported me throughout my educational career.

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1 Introduction

One of the most important instruments for an atomic physicist is the laser. Lasers can be used in a wide variety of experiments and give the experimenter a high degree of control over the atoms being studied. One of the characteristics of a laser that an experimenter is most interested in is the frequency since this corresponds to the energy of the photons emitted via the formula $E = \hbar \omega$ where \hbar is Planck's constant, ω is the optical frequency and E is energy. If a laser is locked to a peak in an atomic absorption/emission spectrum, the frequency can be known to a very high degree of accuracy since atomic transitions have been measured very accurately. Using various techniques, researchers have developed methods which can transfer the accuracy of atomic transition measurements to measuring the optical frequency of a laser that is not locked to an atomic transition.

One device with this capability is known as a wavemeter. It is essentially a Michelson interferometer where fringes per unit distance are counted to measure the optical frequency difference between a locked and unlocked laser. This method yields an absolute accuracy of 30MHz, but comes with the downside of a high price tag. A second device which performs this measurement is a scanning Fabry-Perot cavity. While this device is more cost effective than the wavemeter, it suffers from a hysteresis as well as non-linearities due to the piezo element which drives the cavity. The final device used to make these measurements is an optical frequency comb. A mode-locked laser provides a ruler in frequency space against which the difference between the locked and unlocked frequencies can be measured. This method has the advantages of linearity and speed of measurement. Previously, this method has been implemented using Ti:Sapphire lasers which can yield combs spanning 500 - 1000nm.

While the optical frequency comb method is an excellent way of measuring optical frequency differences, the use of Ti:Sapphire lasers makes this an expensive option. The goal of this project is to create an optical frequency comb using a diode laser, thus significantly reducing the overall cost of the comb. To my knowledge, diode lasers have never been used for this application before.

Once completed and fully tested, this laser will be used primarily for molecular spectroscopy in the Ultra-Cold AMO lab at William and Mary. It can be used to do precision spectroscopy of molecular photo-association transitions, which will be used to fabricate ultracold molecules from ultra-cold atoms. The diode frequency comb will also allow us to lock to atomic transitions of difficult atoms to work with, for example Francium from which one cannot make a vapor cell [1].

2 Theory

2.1 Optical Frequency Combs

Optical frequency combs provide a simple and elegant means of measuring optical frequency difference. The method is based on the idea of creating a ruler in frequency space against which measurements can be made. Such a ruler must be a light source with a discrete, broad spectral output with even spacing between the optical frequencies emitted. For the purposes of this section, it will be assumed that such a light source exists to describe how it can be used. The technical details of creating this light source are addressed in the following sections.

Suppose we want to measure the optical frequency difference between lasers of frequency ω_1 , which is locked to an atomic transition and ω_2 , which is not. Figure 1 illustrates this situation in frequency space.



Figure 1: Power vs. Optical Frequency. This plot shows the quantities to be measured in order to measure optical frequency difference.

The first step is to measure how far the lasers' optical frequencies are away from the nearest comb tooth. This can be done by simultaneously shining light from the laser and from the comb light source onto a photodetector. This produces a beat at a frequency equal to the frequency difference between the laser and the nearest comb tooth which can be measured. It should be noted that the nearest comb tooth may be at either a higher or lower optical frequency than the laser.

The next step is counting the comb teeth between the two laser frequencies and determining whether the beat measured came from a higher or lower frequency comb tooth. This is done by using some other method of measuring optical frequency difference. The resolution must be great enough to show which tooth each laser is nearest and to allow the counting of teeth. For example a scanning Fabry-Perot cavity would be an inexpensive option for this measurement. From this information, N, the number of comb teeth between ω_1 and ω_2 has been measured as well as $\Delta\omega_1$ and $\Delta\omega_2$ which are defined as illustrated in figure 1. Using these measurements, the total optical frequency difference is calculated using the following equation:

$$\Delta\omega_{total} = \Delta\omega_1 + \Delta\omega_2 + N\Delta\omega_{cavity} \tag{1}$$

2.2 Optical Cavities

The measurement described in the previous section required a light source with a broad, discrete spectral output. To explain how such a light source could be created, we begin with an overview of the physics of optical cavities [2].

An optical resonant cavity is created by placing two mirrors parallel to one another such that light can bounce back and forth between them. For a linear cavity with a distance of L between the mirrors, the steady state is solution requires that the initial electric field amplitude ε_1 is equal to the electric field amplitude at the same point after one round trip of the light in the cavity ε_2 . Mathematically, the following equation must be satisfied:

$$\frac{\varepsilon_1}{\varepsilon_2} = 1 = e^{\frac{-i2\omega L}{c}} \tag{2}$$

where $e^{\frac{-i2\omega L}{c}}$ is the round trip phase shift of the cavity. This is satisfied under the following condition:

$$e^{\frac{-i2\omega L}{c}} = e^{-iq2\pi} \tag{3}$$

where q is an integer. This puts a requirement on the optical frequency of the light in the cavity.

$$\omega = \omega_q = q2\pi \frac{c}{2L} = q2\pi FSR \tag{4}$$

where FSR is the free spectral range of the cavity. This is defined as the inverse of the round trip travel time of light in the cavity. By using FSR, this expression can immediately be generalized to cavities with more complicated round trip paths such as confocal and bowtie cavities.

From the previous expression, it can be seen that there are an infinite number of modes that exist within the cavity with an equal spacing given by:

$$\Delta\omega_{cavity} = 2\pi FSR \tag{5}$$

The optical resonant cavity is one of the primary components of the laser. All that is necessary to change the cavity into a laser cavity is to add a gain medium between the mirrors. The mode structure previously described is unchanged by the presence of gain in the cavity. Therefore, the light emitted by a laser must have only the allowed optical frequencies of the cavity modes. As long as there is sufficient gain per mode in the cavity, it is possible for the cavity to lase at a number of the allowed frequencies simultaneously. This is known as multi-mode operation.

2.3 Mode-Locking

Mode-locking is a specific type of multi-mode laser operation which results in a pulsed output. To see how this works, first consider the electric field amplitude of a multi-mode laser with j modes simultaneously oscillating:

$$\vec{E} = \vec{C}_0 e^{i\omega_0 t + \phi_0} + \vec{C}_1 e^{i(\omega_0 + \Delta\omega_{cavity})t + \phi_1} + \dots + \vec{C}_j e^{i(\omega_0 + j\Delta\omega_{cavity})t + \phi_j} \tag{6}$$

where ϕ_i are arbitrary phases associated with each mode, ω_0 is the central optical frequency of the laser and $\Delta \omega_{cavity}$ is the mode spacing of the cavity. The intensity of the output is given by the following equation:

$$I = \frac{cn\epsilon_0}{2} |\vec{E}|^2 \tag{7}$$

For 10 modes oscillating with equal amplitude and a linear phase relationship, figure 2 plots the output proportional to the intensity. As can be seen, a pulsed output is achieved. Figure 3 shows the same situation with all phases equal. This is the best case scenario and produces the shortest pulses.



Figure 2: Output of laser with 10 modes oscillating, equal amplitudes and a linear phase relationship



Figure 3: Output of laser with 10 modes oscillating, equal amplitudes and phases matched

The relationship between the temporal width of the pulses and the spectral bandwidth of the laser is given by the following equation known as the time-bandwidth product:

$$\Delta \omega \Delta t \ge 1 \tag{8}$$

Pulses related by the equality of equation 8 are called transform limited.

To achieve mode-locking, one needs to match the phases of the modes in the laser. The first method of doing so is known as passive mode-locking. This can be done by placing a saturable absorber into the laser cavity. A saturable absorber is a material which blocks light below a threshold intensity. Above the threshold, the material becomes transparent [3]. As the gain medium is pumped with light a noise signal starts to build in the cavity with random phase and amplitude. However, after many round-trips the individual mode signals die away because the loss they experience due to the saturable absorber overcomes the gain of each pass. A larger multi-mode spike in the signal will experience less loss once it crosses the intensity threshold. It will then be preferentially amplified by the cavity and a short pulse signal oscillates within the cavity. The peak pulse power of the signal is maximal when the phases are matched, so by using a saturable absorber with a sufficiently high saturation intensity a signal with matched phases will be the one selectively amplified. This results in a pulsed output at a repetition rate of the cavity FSR. This method yields very short pulses, which according to the time-bandwidth product requires a broad spectral bandwidth. Therefore a frequency comb created by passive mode-locking is very broad.

Active mode-locking in diode lasers is achieved by modulating the current into the gain medium. When the gain is driven at a given frequency ω_m , the modes of the cavity develop modulation sidebands at $\omega_q \pm \omega_m$ where ω_q are the cavity modes. This is why a laser in single mode operation will acquire sidebands when the gain is modulated. However, if the gain is modulated at the cavity FSR, the sidebands generated will fall on top of the neighboring modes. These modes will then injection lock to one another and become coupled so that phase information can be transferred. This coupling produces the required fixed phase relationship between modes. Active mode-locking produces a pulsed output at a repetition rate equal to the cavity FSR as well. This method also gives a very stable phase relationship between modes provided that the RF source being used is stable.

Hybrid mode-locking takes advantage of both of these methods and is illustrated in figure 4. The gain is modulated at the cavity FSR and a saturable absorber is placed into the cavity. This results in a broad and stable frequency comb which would be ideal for making optical frequency difference measurements. It will also yield the shortest pulses and therefore highest intensities which may be necessary for other techniques to broaden the frequency comb.



Figure 4: A schematic diagram of hybrid mode-locking

3 Experimental Setup

To begin with, a Sanyo DL-7140-201W diode laser with a wavelength of 780 nm is used. Current for the laser is supplied by a LDD2002P laser diode driver from Wavelength Electronics. The laser current is modulated via a bias tee by a HP 8657B option 001 (1 part in 10⁹ stability timebase) RF source. This can produce a 13 dBm sinewave over the range of 100 KHz to 2.1 GHz. A circulator is also used to protect the RF source from possible reflections coming from the bias tee. Finally, the temperature is controlled by the use of a WTC3293 - 14002 temperature control circuit from Wavelength Electronics. This drives a single stage thermoelectric cooler attached to the diode casing. The temperature controller is powered directly by a 12V, 5.1A transformer based power supply from International Power. The same power supply is used to run a 9V linear voltage regulator which is used to power the laser diode driver. Originally, the full 12V was used to power the laser diode driver, however in this mode of operation the driver malfunctioned (though it is not known whether the supply voltage caused the malfunction). After replacing the driver, the lesser supply voltage was used and since then no other problems have been encountered.



Figure 5: A block diagram of the experimental setup

3.1 Control Board

The control board is composed of the majority of electronic elements needed to handle the basic operation of the diode laser. Power to the temperature controller and the laser diode driver is controlled by a switch on the side. Figure 6 shows the layout.

The current is controlled by two 12-turn trim potentiometers on the laser diode driver. One controls the output to the laser and the other sets a maximum limit to be delivered. The temperature controller is also adjusted by a trimpot and the temperature is read-out by a digital display. Another switch on the temperature controller board allows enabling and disabling of the temperature control. There are two other switches that allow the user to choose between scanning mode and constant current mode. In either mode, the current delivered to the diode may be measured on an oscilloscope through the "Current Monitor" BNC connector. Since the current monitor is directly connected to the laser diode driver, a unity gain buffer circuit was used on the output between the driver and the BNC connector. The control board only had a power supply of +12V so it was necessary to use a single sided



Figure 6: Picture of the control board with labels

op-amp (TLV2372). This buffer is important because it provides protection for the driver in case anything other than a voltmeter is attached to the BNC.

After testing and calibration of the current monitor, it was found that the output voltage of the current monitor is related to the current delivered by the following equation.

$$V_{monitor} = (0.0121 \pm 0.0001)I_{diode} + (0.0416 \pm 0.0090)$$
(9)

In the previous equation, $V_{monitor}$ was the voltage coming out of the current monitor in Volts, and I_{diode} was the current through the laser diode given in milliAmps.



Figure 7: Circuit diagram of unity gain buffer. This circuit is used to provide protection for the laser diode driver.

3.1.1 Scanning Mode

Scanning mode is used only for the purposes of aligning an external cavity. To enter scanning mode, the "Current" switch must be open, the "Scan" switch must be closed and a function generator must be attached to the "Scan" BNC connector. This configuration allows the modulation feature of the laser diode driver to be used. The voltage input from the function generator changes the output voltage via a negative transfer function given below:

$$I_{mod} = I_{op} - V_{mod} \frac{200mA}{5V}$$
(10)

 I_{mod} is the modulated current delivered to the laser diode in milliAmps, I_{op} is the operating current as set by the user in milliAmps, and V_{mod} is the voltage from the function generator. Care must be taken to not obtain negative values of I_{mod} as this will break the laser diode.

As can be seen from the previous equation, by using a triangle wave with a DC offset, one can modulate around a desired current. When aligning a cavity, the output of the diffraction grating should be directed onto a photodiode and the current modulated around the threshold current. As the alignment of the diffraction grating is improved and more light is sent back into the diode, the threshold current will decrease. Therefore by minimizing the threshold current, one can properly align the external cavity.



Figure 8: Circuit diagram of switches

3.1.2 Constant Current Mode

Constant current mode is used when the laser diode is in its normal operating condition. To enter constant current mode, the "Current" switch must be closed. This will allow the full operating current to be delivered to the laser diode. This mode is to be used for CW mode lasing and as the DC offset for the high frequency modulation used in active mode-locking.

3.2 Laser Cavity

Figure 9 shows a picture of the diode laser in the extended cavity. As it is currently built, only active mode-locking is possible.



Figure 9: Optics setup (Bottom Left: Bias Tee, Bottom Right: Diode laser in collimation tube, Top Right: Mirror, Top Left: Diffraction grating)

Rather than using a partially silvered mirror as an output coupler, a diffraction grating was chosen. In Littrow configuration, the first order diffracted laser beam is sent back into the diode giving optical feedback. The zero order beam is used as the output of the cavity. This configuration gives the experimenter a range of frequency tunability, making the comb more versatile as it can be shifted in frequency space. The cavity length of 14 cm was designed to yield a FSR of approximately 1GHz. However, for the work presented here, longer cavities were used to make detection easier as we only have the oscilloscope capability of detection up to 1GHz.

The long term goal of this experiment is to create a frequency comb spanning 1000 GHz with a resolution of 1 MHz. Some of the shortest pulses reported for mode-locked diode lasers are .65 ps [5]. This would correspond to a comb span of at least 1500 GHz, therefore the proposed goal should be attainable. If the initial setup does not yield the desired results a pulse compressor can be used to stabilize the comb and correct possible phase variations [6]. This will allow us to create transform limited pulses with the greatest intensity possible for our setup. With sufficient intensity, a non-linear fiber can be used to generate extra harmonics and broaden the comb.

3.3 Detection

In order to characterize the laser, it is necessary to view the output in the time and frequency domain. The detectors which give us these views are fast photodiodes and scanning Fabry-Perot cavities. Fast photodiodes are commercially available with sufficiently high bandwidth to see the laser pulses we intend to create. However commercially available scanning Fabry-Perot cavities are not sufficient to see the full breadth of the frequency comb to be created. Therefore, it is necessary to build one of our own.

3.3.1 Time Domain Detection

For the fast photodiode, a DET02AFC fiber input Si photodetector from ThorLabs was used. This detector has a bandwidth of 1.2 GHz [8] whose photo-signal is read on an oscilloscope with an equivalent bandwidth. This detector arrangement was tested on a Ti:Sapphire modelocked laser in Dr. Jan Chaloupka's ultra-fast laser laboratory. The pulses generated by that laser have a temporal width of a few femtoseconds, which is far too short for any electronics to measure. Therefore, testing the detector with this laser allowed a measurement of the limits of the detector. It was found that the shortest pulses the detector could measure were 900ps FWHM. To measure any pulses shorter than this, other techniques will be necessary to provide sufficient resolution. Also, since the active area of the detector is so small, it is necessary to focus the beam using a lens onto the photodetector. Using shorter focal length lenses results in larger signals.

3.3.2 Frequency Domain Detection

In the frequency domain, a SA200-6A Fabry-Perot cavity from ThorLabs was used. The cavity has an FSR of 1.5 GHz, meaning harmonics up to 1.5 GHz away from the central frequency will be easily resolved. This is a significantly smaller width than the comb we intend to generate. For the frequencies used in the work presented here, the first and second harmonic were clearly visible, but the presence of additional modes obscured measurements. Therefore it was possible to know that harmonics beyond the second were being generated, but it was difficult to distinguish them as the modes from one signal overlapped the next signal. To combat this problem, a home-made scanning Fabry-Perot cavity was built. Figure 10 shows the device.

The scanning Fabry-Perot cavity consists of one fixed mirror, one mirror driven by a piezo element and one ThorLabs FDS100 photodiode detector. The tubes visible in figure 10 are only present to block out ambient light which can wash out the signal of interest. The way the device works is that light is only able to pass through the cavity when the cavity length is equal to an integer multiple of half the wavelength of the light. Therefore as the piezo moves the mirror back and forth it allows different frequencies of light through to the detector as a function of time. The output can then be read on an oscilloscope.

For our detector, we attached one mirror to a translation stage. This allows us to change the cavity FSR. As designed, the detector will allow for a FSR between 10GHz and 100GHz. However, the piezo elements used were not capable of scanning a full FSR for the cavity in 100GHz configuration and the setup was overly sensitive to vibration. Until replacement piezo elements with a larger scan range are installed, the detector will remain inoperable.

Figure 10: Picture of 100GHz scanning Fabry-Perot cavity

4 Results

4.1 Characterization of the Diode Laser

Once the laser diode was connected to the current source, power testing was performed to ensure that the diode was working properly. This was done by directing the beam onto a power meter and changing the current delivered to the laser diode. The results from this test are given in figure 11. Note that the error in this measurement was smaller than the data points plotted.

As can be seen in the graph, the threshold current was measured to be 36.02 ± 0.22 mA. Using Matlab, the slope of the linear section was fit to determine the laser diode slope efficiency. This was measured to be $1.02 \pm 0.01 \frac{mW}{mA}$. The detection of a threshold current and a slope efficiency close to unity shows that the laser diode is operating properly.

Figure 11: Power vs. Current for Sanyo DL-7140-201W diode laser

4.2 Frequency Dependence of RF Coupling

Once it was known that the laser was working properly with a steady current, we tested the effects of RF modulation on the output. As explained previously, adding sufficient RF modulation to the current driving the laser diode results in the generation of harmonics in frequency space. The RF is coupled to the laser diode via the bias tee, but due to impedance mismatching not all of the RF will get through to the diode. Also the diode itself complicates this as it has its own limitations. To quantify the overall coupling of the RF into the optical emission of the laser, the RF frequency was scanned over a large range of frequencies while holding the input power constant. When the output of the laser was viewed with a scanning Fabry-Perot cavity, the carrier and first harmonic (or sideband) were visible. The difference in the height of the carrier and the sideband is plotted in figure 12 as a function of RF frequency. The error in RF frequency on this plot and all following plots is smaller than the size of the data points. This is because the RF frequency was calibrated with a spectrum analyzer and found to be accurate to better than $\pm.002$ MHz. The error in relative peak

Figure 12: A graph showing the RF coupling dependence on frequency

height was estimated by observed fluctuations in the peak heights during the measurement process.

As can be seen, the difference in heights of the signal is greater at higher frequencies. This shows that the strength of the coupling between the RF and the optical emission of the diode is greatest at lower frequencies.

4.3 Cavity Effects

After it was seen that we were able to modulate the light, the effects of the external cavity were tested. First, the amount of light reflected by the diffraction grating was calculated by measuring the power of the transmitted and reflected beams. This test showed that $64.8\% \pm 2\%$ of the light was reflected back into the cavity.

Since active mode-locking occurs when the RF frequency is matched with the cavity FSR, the generation of harmonics should be more efficient at this frequency. To examine this effect, the laser was first modulated without the external cavity at a RF power of -2dBm. The light from the diode was sent through an optical diode into a scanning Fabry-Perot cavity. The frequency of the RF was changed and the ratio of the size of the sideband to the size of the carrier was measured. The same procedure was then repeated for the laser in an external cavity. As can be seen in figure 13, there is little frequency dependence on the measured ratio without the cavity. However, when the cavity is present, a resonant behavior is seen and the height of the sideband increases dramatically. This allows us to find the FSR of the cavity that has been built. The error in the following graph was estimated by the largest fluctuations in peak heights during the course of measurement. It should be noted that the error is much greater for the measurement with the cavity since small changes in temperature cause large changes in the peak heights near FSR.

Figure 13: Ratio of sidebands to carrier vs. modulation frequency with and without cavity. This figure shows a factor of 10 improvement in the coupling efficiency when the cavity is introduced.

By then increasing the RF power, more sidebands can be generated showing that more modes are oscillating in the laser cavity. However, at this point it is not possible to claim the laser is mode-locked since the scanning Fabry-Perot cavity cannot detect pulses.

4.3.1 Problems with Cavities

It is important to note that a number of different cavities were built at different times with varying lengths. By using longer cavity lengths, we had hoped to be able to detect more sidebands on the scanning Fabry-Perot and gain better resolution in the time domain. However, cavities with FSR of 100MHz and 250MHz caused serious problems. When viewed with the scanning Fabry-Perot cavity, a continuum of frequencies were observed rather than discrete harmonics. Figure 14 shows the output of the scanning Fabry-Perot when the laser was in CW mode. Therefore a narrow spike should be clearly visible corresponding to the single frequency. The spike should also be narrow since the linewidth of the cavity is small. As a point of comparison, figure 15 shows a cavity with sidebands clearly visible.

Figure 14: FSR = 100MHz Cavity on scanning Fabry-Perot cavity. No distinct peaks are visible.

Figure 15: Properly operating cavity with first harmonic on scanning Fabry-Perot cavity. FSR = 550 MHz

Our interpretation of this result is that with such low values of FSR, the modes are spaced too closely and there is mode competition within the cavity. The gain provided by the diode is not sufficient to support all of these modes and therefore the cavity is unable to lase. We had success with a 416MHz cavity and have since continued to use that cavity length.

4.4 Active Mode-Locking

With the diode in the external cavity, it is possible to achieve active mode-locking by driving the diode at the cavity FSR. To test for active mode-locking, the laser was placed in the proper configuration and the output detected by the fast photodiode. Other researchers have reported using RF power of 30dBm to obtain mode-locking [7]. Since the RF source we used can only output 13dBm an amplifier was used once it was determined that 13dBm was not sufficient to mode-lock. It should also be noted that a circulator was used between the output of the amplifier and the bias tee. The circulator sends any reflections from the bias tee to a 50 Ω terminator so that they cannot return to the amplifier or the RF source itself. After sufficient amplification, active mode-locking was achieved. The pulses are emitted at the expected repetition rate and the pulse width was measured to be $1.0 \pm .3$ ns, showing that the pulses are detector limited. This occurs when the RF power to the diode is over 20 dBm.

Figure 16: Output of mode-locked diode laser as seen on fast photodiode.

Experimentally we observed that at high RF power pulses can be emitted at many frequencies, not just 1 FSR. Since the gain is being modulated by the RF, it is possible that another process is occurring to create pulses at these unexpected frequencies. Other types of pulses should be longer than mode-locked pulses, so in principle we will be able to tell them apart [4]. However, in our current detection scheme, all measured pulse widths are detector limited. Therefore, greater temporal resolution is needed to find exactly at what frequency mode-locking occurs. This will require new detection methods.

4.5 RF Noise

In the detection of pulses, there was a significant problem regarding the RF signal being broadcast into the lab. The results shown in figure 16 were obtained when the output of the detector was coupled to 50Ω via the internal circuitry of the oscilloscope. This is necessary to improve the speed of the oscilloscope to see the pulses, but leads to a signal size of roughly 10mV. If an external BNC tee is used with 50Ω termination, spurious RF signals are picked up and observed on the oscilloscope. This noise is large enough to completely wash out the actual signal. Therefore, an external BNC tee should not be used on the oscilloscope. Also, keeping the detector itself far away from the RF source helps cut down on this source of noise. For the results shown in figure 16, the detector was actually on a completely separate optics table across the room. Figure 17 shows an example of a false signal created by the RF noise.

Figure 17: RF noise picked up by the fast photodiode. The signal from the photodiode goes negative, which clearly indicates a problem.

5 Future Work

In the near future we will need to overcome our difficulties in detection. We have just received new piezo elements for the homemade 100GHz Fabry-Perot cavity. The Fabry-Perot cavity will allow us to measure the bandwidth of the pulse generated frequency comb and can also be used to put a lower bound on the pulse width. Also, Professor Novikova has kindly agreed to lend us a 13 GHz photodetector and a spectrum analyzer to gain more information about the pulses. Finally, plans are underway to build an autocorrelator. The autocorrelator will allow us to determine the shape and width of the pulses from our mode-locked laser. This should provide the greatest temporal resolution and will allow for direct measurement of pulse width.

One problem that we may encounter involves the type of laser diode that we are using. Currently, we are using a standard laser diode without a scientific grade anti reflection (AR) coating. One possible effect of this is that without the high quality AR coating, light can reflect off of the front facet of the diode as well as the high reflector mirror in the back of the diode. This essentially creates a three mirror cavity with a complicated output spectrum involving clusters of modes. The problem is that while each cluster itself will have the desired fixed phase relationship and even mode spacing, there is no such relationship between the teeth of the two separate clusters [7]. If the combs overlap, there will be no way to accurately make the optical frequency difference measurement. Therefore, if this problem arises, it should be solved by merely replacing the non-coated diode with an AR coated diode.

Further into the future, different types of work need to be done. Once we know the width of the comb and the temporal width of the pulses, we will know whether it is sufficient to be a useful tool. As mentioned earlier, a pulse compressor could be used if the pulses are not ideal, however this only brings us closer to the theoretical transform limited pulse

width achievable with the available comb bandwidth. To further shorten pulses and increase bandwidth past this point it will be necessary to move to hybrid mode-locking by introducing a saturable absorber mirror into the cavity. Also, a non-linear fiber may be used to increase the bandwidth of the frequency comb.

When the comb is sufficiently broad, the laser can be put to use. One possibility for a first application would be to lock two lasers together using the optical frequency comb. This would be a first demonstration that diode lasers are a viable option for the creation of optical frequency combs. Once the lab is ready, the laser can be used for it is used for its original intended purpose of photo-associative production of ground state ultra-cold molecules from ultra-cold atoms.

6 Conclusion

We have achieved active mode-locking in our external cavity diode laser. The consistent and reliable generation of detector limited pulses means that we have reached the limits of our current detectors. While the ultimate goal of the experiment has not yet been realized, the work involved has reached an exciting new phase of its development. Much has been learned and many difficulties have arisen, however it still seems that this could be a useful tool ready for use in the lab in the near future. The difficulties encountered have also been relatively easy to surmount. The majority of the problems came from finding the correct way to go about mode-locking, such as choosing an appropriately short cavity and amplifying the RF signal sent to the diode. Other difficulties have included standard problems to be expected with any experimental physics such as faulty electronics and noise issues. Therefore we believe that this system is relatively simple and could be recreated in other laboratories without much difficulty.

References

- W.Z. Zhao, J.E. Simsarian, L.A. Orozco, G.D. Sprouse. "A computer-based digital feedback control of frequency drift of multiple lasers" Rev. Sci. Instrum. 69, 3737(1998).
- [2] A. E. Siegman, *Lasers.* (University Science Books, Sausalito, 1986).
- [3] R. Paschotta, "Saturable Absorbers". Encyclopedia of Laser Physics and Technology.
- [4] P.P. Vasilev [Optoelectronics Division, PN Lebedev Physical Institute, Russian Academy of Sciences], "Ultrashort Pulse Generation in Diode Lasers" (Chapman and Hall, 1992) p.801-824.
- [5] S.W. Corzine, J.E. Bowers, G. Przybylek, U. Koren, B.I. Miller and C.E. Soccolich, "Actively Mode-Locked GaInAsP Laser with Subpicosecond Output". Appl. Phys. Lett. 52 (5) (1988) p. 348.
- [6] M.J. Brennan, J.N. Milgram, P. Mascher, and H.K. Haugen [Department of Engineering Physics, McMaster University], "Wavelength Tunable Ultrashort Pulse Generation From A Passively Mode-Locked Asymmetric-Quantum-Well Semiconductor Laser". Appl. Phys. Lett. 81 (14) (2002) p.2502.
- [7] M.G. Hekelaar [Department of Science and Technology, University of Twente] "RF Mode Locking and Fiber Amplification of Diode Lasers" (2005).
- [8] "DET02AFC Operating Manual-Fiber Input Si Photodetector". Thor Labs Inc. 15829-SO1 Rev C 8/2/2007.