"Construction of an External Cavity Diode Laser for use in Frequency Modulation Spectroscopy with an Electro-Optic Phase Modulator"

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1. Project Overview and Motivation

The main purpose of this project was to test and characterize a new method for frequency stabilization of a diode laser. The present technique involves modulation of the laser's center frequency, which in turn goes in to the main experiment. This is a problem since the experiment requires the frequency of the laser to be at or near the atomic transition of the atoms involved in the experiment in order to image them. This in turn limits the amount of modulation that can be put in the laser, which will have to be much smaller than the laser's line width in order to be able to resolve the small hyperfine structure features of the atoms in saturated absorption. Moreover, the error (derivative) signal generated to lock the laser is limited as well.

My project was then to put together the new setup using an electro-optic phase modulator to modulate the laser beam that goes to saturated absorption in order to obtain an error signal without affecting the laser beam going into the main experiment. However, first I had to put together an external cavity diode laser which was used throughout the summer. The project was done in collaboration with undergraduate student Margot Phelps.

2. External Cavity Diode Laser

2.1 Eagleyard Diodes: Collimation, Grating, and Threshold Curve

Diode lasers are frequently used in atomic physics due to their stability, great tuning range, and narrow linewidth of less than 1 MHz [1]. In this project Eagleyard Diodes with an AR coating and a center wavelength of 767 nm were used.

The output beam from the diode needs to be uniform in order to avoid focusing of this due to optics used in the experiment. Then, collimating the beam was the first step and was done by inserting the diode inside the collimating lens' cavity where the distance between the two was adjusted until having a symmetric beam throughout the path of the beam.

After the beam was collimated, the diode and the lens were inserted into the small cavity inside the laser where the orientation of the long axis of the beam was chosen to be vertical in order to have vertically and linear polarized light outside the laser.

The next step was to attach the grating to its mirror mount and connect the piezo-electric transducer's leads to the connector on the base of the external cavity. The purpose of the grating is to select the wavelength of operation. It does so by reflecting the zero order beam out of the laser and first order back to the diode. By adjusting the orientation of the grating the wavelength can be tuned as desired. The grating equation relates the distance between rulings in the grating, a, the angle between the normal of the grating and the incident light beam, the wavelength of the beam, and the order of reflection, m, is expressed as follows:

$$a \sin \theta = m \lambda \qquad\qquad (2.1)$$

This is where the pzt comes into play since by changing the orientation of the grating one changes the angle θ and thus the operating wavelength λ. Then, a threshold curve was calculated which is a relation between the current send to the diode and the power output of the laser beam outside the cavity. In this graph there are two sets of data, the black data represents the diode outside the cavity where it is observed that there is no threshold, therefore no lasing occurs. The red data shows the data obtained with the diode inside the external cavity with the grating in it. In this set of data there exists a threshold value of the current where the diode starts to lase since all atoms are now in the same quantum state.
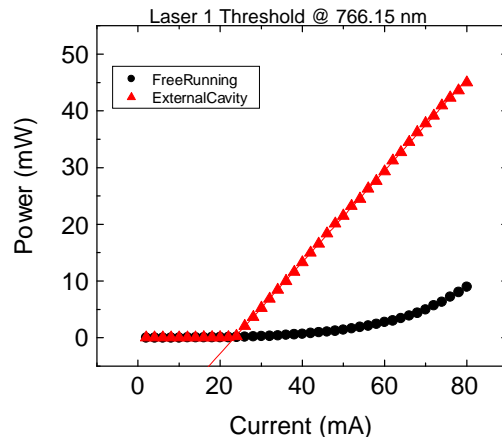
Figure 2.1 Threshold curve for ECDL

2.2 TEC and Temperature Controller

After selecting a specific wavelength, the next step towards having a stabilized external cavity diode laser was to test and connect two thermoelectric coolers (TEC), for both the diode cavity and the external cavity, and the corresponding temperature controllers. The purpose of the TEC is to keep a certain temperature throughout the laser to avoid drift of the frequency of the laser due to changes in room temperature.

The next step was to control the temperature with the help of a thermistor and a servomechanism we call temperature controller. After all the leads were soldered into place the temperature controller was tuned to the specifications of the system by using the Ziegler-Nichols tuning method.

3. Locking Mechanisms

3.1 The purpose

Frequency stabilization is a main component in most atomic physics experiments. For the purposes of this research group, it is needed to take an image of the atoms in the experiment. This requires that the light beam shining on the atoms is at or near the right frequency in order to take the right picture. Then, in order to stabilize the frequency of the laser a feedback loop is used. The feedback loop consists of a set point which is the value that has to be maintained. In our case the set point value is the central frequency controlled by the pzt. Also, an instrument that measures the present value of the quantity being controlled which are a photodiode and an oscilloscope in our case. Also, an error signal that will dictate how far away the system is from the set point and how to correct for this deviation. There are currently two different methods used in this group for frequency stabilization which Margot and I used throughout the summer and are discussed below.

3.1.1 Saturated Absorption

The error signal used in the experiment is the absorption feature of Potassium atoms obtained with Saturated Absorption Spectroscopy. This is all about eliminating the Doppler Effect due to the thermal motion of atoms. Once this is achieved the hyperfine structure levels of the atoms can be observed. The physics of the Doppler Effect are as follow: an atom will absorb the light of a laser beam is the frequency of the laser meets the following condition [3]:

$$f = f_0 \left(1 + v/c\right) \hspace{4cm} (3.1).$$

Then, even if the laser is not at the exact absorption frequency of the atoms, some of them will still absorb light if they have the right velocity v.   To obtain a complete absorption feature the pzt is ramped so that the frequency of the laser can scan over the different frequencies the atoms can absorb. The following image shows the Doppler feature where only a broad dip is seen.
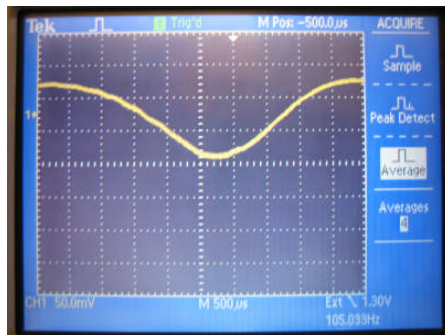

Figure 3.1 Doppler feature

This is where the "saturation" comes into play. The setup for saturated absorption is shown below. Light is separated by a piece of plexi glass; it reflects two weak beams and refracts one strong beam. The two weak beams travel through a cell with potassium atoms but the strong beam is also send through the cell but in the opposite direction.
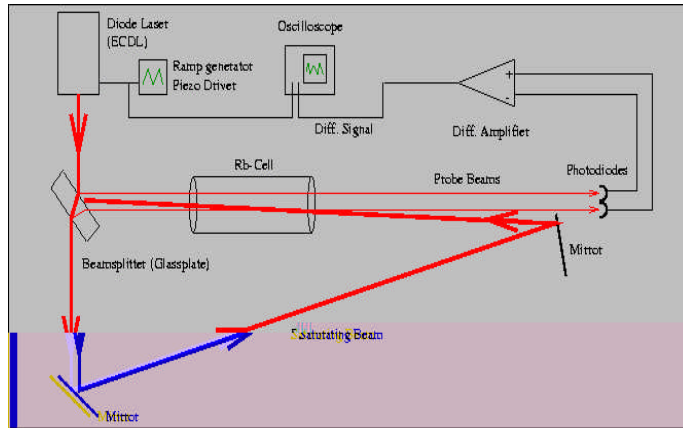
Figure 3.2 Saturated Absorption Setup

The strong beam is included to eliminate some of the broadening of the absorption feature. This strong beam interacts with the same atoms just like one of the weak beams. More specifically, these beams interact with atoms with zero velocity. First, the strong beam excites almost all the atoms in its path with zero velocity and the weak beam is left to interact

way to move the frequency, either increase it or decrease it determined by the change in intensity of the absorption. The disadvantage is that when you lock the frequency of the laser to the side of one of the main features the frequency is around 15 MHz away from the resonance absorption frequency.

Therefore, when it is time to excite the atoms in the main experiment some of them might not absorb light so far way from resonance. Another disadvantage is that by locking to the side of a peak the repeatability of the experiment is not great since it is hard to exactly locate the place of locking. The advantage is that no modulation of frequency is necessary since the error signal is the absorption feature from the photodiode. Therefore, only the central frequency goes into the main experiment.

3.3   Peak Locking

As mentioned before, the disadvantages are greater than the advantages of sidelocking a laser. Moreover, we are interested in locking the laser to the resonant absorption frequency of the atoms. Then, the ideal case is to lock to the peak of a feature of the absorption feature. However, if you drift from the peak there is no way to tell is the frequency decreased or increased since the intensity increased in both cases. The solution is to obtain the derivative of the absorption signal and use it as the error signal.

The derivative signal is obtained by modulating the frequency going out of the laser in the following fashion

$$\omega = \omega_c t + \Delta\omega/\omega_m \sin(\omega_m t).$$

The next step is to compare the changes in intensity across the absorption feature to the changes in frequency. For example, when sitting on a steep slope the changes in intensity from a small change in frequency is much bigger than the change in intensity at a peak. Then, the ratio of intensity change to the frequency change include phase relationship is the derivative signal. The following picture shows the absorption feature and its derivative signal.
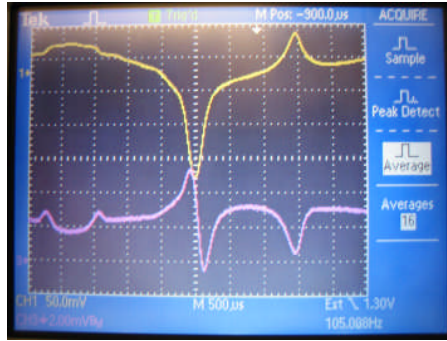
Figure 3.4 Error "derivative" Signal

4. Beat Notes

After setting up all the optics needed for saturated absorption we decided to look at the beat note of the two lasers built in order to characterize the effectiveness of the locking mechanisms used and of the stability of our lasers. A beat note consists of adding two waves of different frequency and sending the combined signal to a spectrum analyzer. The information obtained from the spectrum analyzer was:

1) The difference of the two frequencies of the lasers since the beat frequency is described as follow:

$$f_b = f_1 - f_2 \text{ and } f_1 - f_2 \qquad (4.1)$$

However, the bandwidth of the spectrum analyzer is only capable of showing the first of these two different beat note frequencies and we call this frequency the center frequency of the beat note.

2) The linewidth of the lasers and how stable they are. The width of the beat note is a measure of the frequency distribution of the lasers over time or linewidth. Also, if the beat note is not stable it means that the frequency of our laser is not stable. Therefore, beat notes are a measure of how stable our lock was.

The procedure we followed was to take several beat notes with different locking mechanisms. The best beat note was obtained by sidelocking both lasers and we obtained a beat note of central frequency of 1.46 MHz and full width at half maximum of 220 kHz.
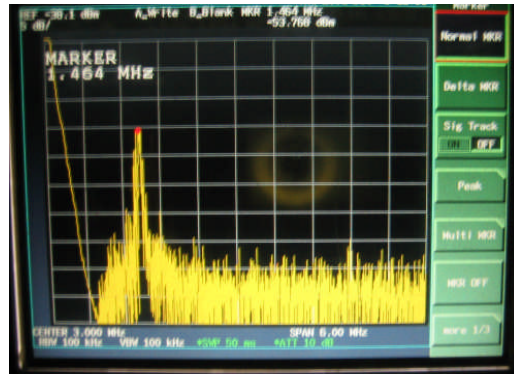
Figure 4.1 Best beat note obtained

However, the beat note was moving around and changing shape. Another reason why we decided to look at the beat notes was to compare the values obtained with the present methods of locking the laser to the values obtained once we had the EOM working. It was going to serve as a measure of the effectiveness of the different locking mechanisms, but unfortunately we did not get that far.

5. Frequency Modulation with EOPM

5.1 Proposed Method

The proposed method involved sending the beam through a beamsplitter with a central frequency f_0 to the experiment and to the locking setup. Then, the EOM came into play by applying a phase shift to the beam which was converted into frequency modulation. Then, the beam was sent to the saturated absorption and to the locking electronics to lock to a specific wavelength. The advantage is that only the central frequency goes into the main experiment which is the ideal case.

5.2 How the EOM Works

The EOM consists of a lithium niobate ($LiNbO_3$) crystal which has the property of changing its refractive index whenever an electric field is applied to it. This is known

as the Pockels effect where there is a linear dependence between the change of index of refraction (Δn) and the applied electric field. Therefore, the change if index of refraction is linearly dependent on the voltage sent to the EOM. In order to observe a phase shift in the incoming light, linearly polarized light needs to be sent thought the EOM and aligned parallel to the principal axis of the crystal [2].

By sending a beam of light through the crystal, some charges are excited from the valence to the conduction band. These charges are now free to move around and since we are applying an external electric field we control how these charges move. The movement of these charges distorts the lattice, which changes the index of refraction of the crystal in the direction of the applied field. Therefore, light traveling parallel to the direction of the field will experience a phase shift. The phase shift will vary according to:

$$\Phi(t) = \Delta\varphi \sin(\omega_m t) \tag{5.1}$$

This will modulate the E component of the light beam as follows corresponding to phase modulation:

$$E(t)= E_o \sin (\omega_c t + \Delta\varphi \sin(\omega_m t)) \tag{5.2}$$

However, this equation is very similar to frequency modulation represented by:

$$E(t)= E_o \sin (\omega_c t + \Delta\omega/\omega_m \sin(\omega_m t)) \tag{5.3}$$

Then, if we compare the two types of modulation we observe that phase modulation of the light beam transformed into frequency modulation and we obtain the following formula relating the two:

$$\Delta\varphi = \Delta\omega/\omega_m \tag{5.4}$$

After deriving this formula we knew which parameters to change and we decided to operate at the highest ω_m to obtain the highest value of frequency modulation possible.

5.3 EOM driver

To operate the EOM we needed a driver capable of sending an rf signal big enough to produce the desired phase shift. An EOM Resonant Driver was designed by

Carl Sauer from the Electronics Shop at JILA. The driver contained a step up transformer that had a variable gain depending on the operating frequency. To obtain the maximum gain, the driver was operated at the resonant frequency which is a property of the circuit given by

$$f_r = \frac{1}{2\pi \sqrt{(LC)}}$$ (5.5)

The following graph shows the range of gain values according to the frequency at which the driver is operated and it is easily detected that the maximum value is obtained when operated at the f_r of this specific circuit.
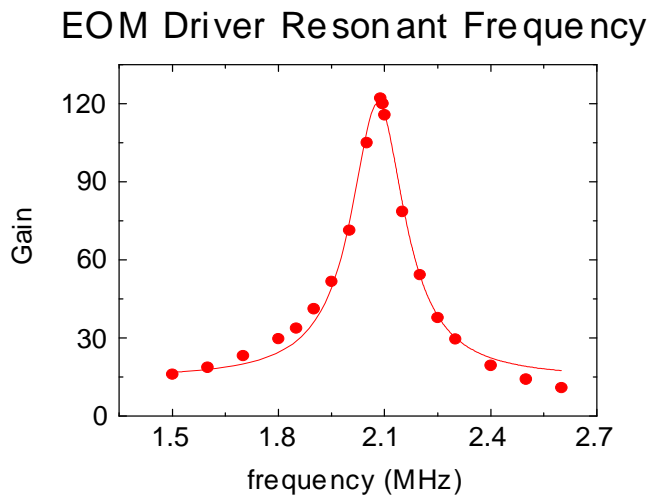

Figure 5.2 Dependence of Gain with Frequency

5.4 EOM Performance

Another way to express the laser's beam with modulation is as follows:

$E(t) = E_o \exp (i(\omega_c t + \Delta\varphi \sin(\omega_m t)))$ (5.6)

But if $\Delta\varphi$ is small we can use a Taylor expansion and obtain the following:

$E(t) = E_o \exp(i\omega_c t)(1 + \Delta\varphi \sin(\omega_m t))$ 5.7)

$= E(t) = E_o \exp(i\omega_c t)(1 + \Delta\varphi/2 (\exp(i \omega_m t) - \exp(-i\omega_m t))$ (5.8)

$= E(t) = E_o \exp(i\omega_c t) + E_o \Delta\varphi /2 [\exp(i(\omega_c + \omega_m)t) - \exp(-i(\omega_c + \omega_m)t)].$ (5.9)

The last expression describes how the phase modulated laser beam can be expressed as a wave at the carrier frequency plus two sidebands that deviate from this frequency by an integer amount of the frequency modulation [5].

To test the performance of the EOM we used a beat note setup was used to see if we could actually observe the sidebands. The test consisted of splitting the light from the laser into two parts, where one part would obtain a phase shift after going through the EOM and the other part would not be modified. Next, the two beams recombined at a photodetector and then sent to a spectrum analyzer. This spectrum analyzer picture shows three signals at different frequencies which are integer multiples of the modulation frequency.
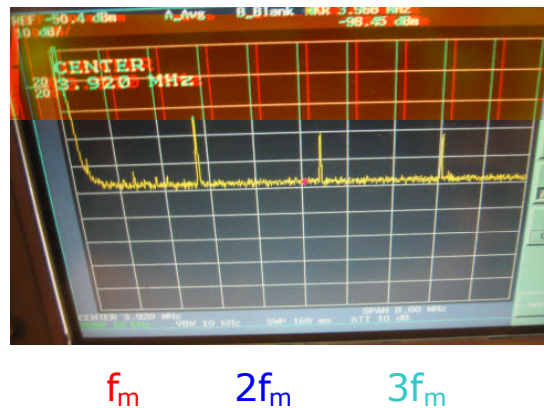

f_m $2f_m$ $3f_m$

Figure 5.4 Sidebands obtained with phase modulation

It effectively showed us the sidebands the EOM was predicted to create. Afterward, the intensity of each sideband was recorded for different values of voltage send to the EOM. The next graph shows the Bessel Functions which relate the power of each sideband (y-axis) to the phase shift applied to the laser beam (x-axis)
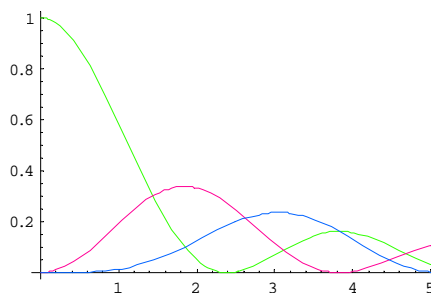

Figure 5.5 Bessel Functions

Then, with the help of the previous graph we obtained a graph that shows the relationship of the depth of modulation versus the voltage applied to the EOM. This graph will help us determine how much voltage to send to the EOM in order to obtain the desired phase shift.
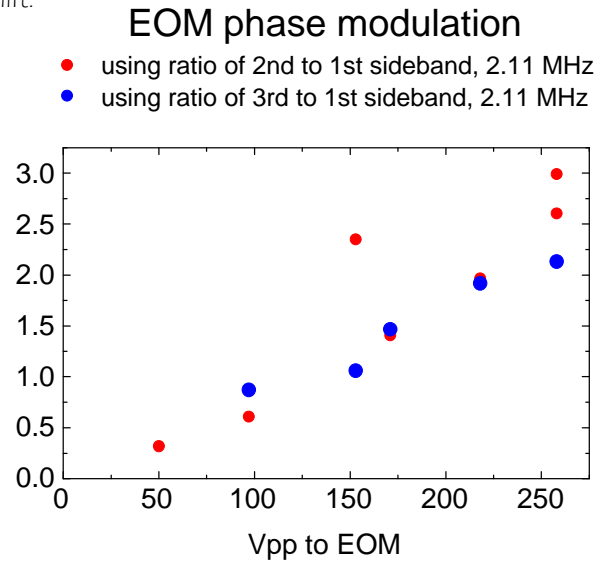
EOM phase modulation

● using ratio of 2nd to 1st sideband, 2.11 MHz
● using ratio of 3rd to 1st sideband, 2.11 MHz

Figure 5.6 Voltage to EOM and phase shift

5.5 Error signal

The next step was to look at the error signal obtained with the EOM. We did this by using a mixer which is an electronic component that multiplies two different waves of frequency f_1 and f_2 and gives you two signals at $f_1 + f_2$ and $f_1 - f_2$. Moreover, unwanted signal can be eliminated by the use of filters.

We used the mixer to compare the changes in intensity throughout the absorption feature to the changes in frequency. The changes in intensity were given by a signal from a photodiode after saturated absorption. The intensity of the light beam detected by the photodiode is a function of the instantaneous frequency which is the time derivative of

$$\omega_c t + \Delta\varphi \sin(\omega_m t) \ [5]. \tag{5.10}$$

After derivating the previous expression and with equation 5.4, the instantaneous frequency is described as

$$\omega_i = \omega_c + \Delta\omega \sin(\omega_m t). \tag{5.11}$$

Then, the intensity at the photodiode as a function of ω_i and expressed as a Taylor series since $\Delta\omega$, ω_m ‹ linewidth of absorption [3] is

$$I(\omega_c + \Delta\omega \, \sin(\omega_m t)) = I(\omega_c) + \Delta\omega \, \sin(\omega_m t) \, \partial I/\partial\omega + \dots \qquad (5.12)$$

A signal from a function generator was used to simulate the changes in the laser's frequency with an extra phase term relative to the signal from the photodiode. . This was achieved by connecting two synthesized function generators where one of them drove the EOM and the other one gave us the signal going to the mixer. The representation of the operation performed by the mixer is

$$I(\omega) * FG \, ; \quad FG = a \, \sin(\omega_m t + \varphi) \qquad (5.13)$$

$$= \quad [\, E_o^2 \, \sin^2(\omega_c t) + \Delta\omega \, \sin(\omega_m t) \, \partial I/\partial\omega] \, a \, \sin(\omega_m t + \varphi) \qquad (5.14)$$

$$= [\, E_o^2/2[1 - \cos(2\omega_c t)] + \Delta\omega \, \sin(\omega_m t) \, \partial I/\partial\omega] \, a \, \sin(\omega_m t + \varphi) \qquad (5.15)$$

$$= (aE_o^2/2) \, \sin(\omega_m t + \varphi) - (aE_o^2/2)\sin((\omega_c{}^+ {}_- 2\omega_m + \pi\varphi/2)t \qquad (5.16)$$

$$+ \, a \, \Delta\omega \, \sin(\omega_m t) \, \partial I/\partial\omega \, [\, \sin(2\omega_m + \varphi) - \sin(\varphi) \,] \qquad (5.17)$$

The last equation tells us that if we eliminate the high frequency signal we are left with the term of interest

$$a \, \Delta\omega \, \sin(\omega_m t) \, \partial I/\partial\omega \, [\, \sin(2\omega_m + \varphi) - \sin(\varphi) \,] \qquad (5.18)$$

If we look at this term on an oscilloscope we will obtain the derivative signal with two components. The first one tells us the phase relationship between the amplitude and frequency changes of the laser beam at the absorption peaks and will determine positive or negative value for the derivative signal. The last one is a DC term that is proportional to the amplitude of the photodiode signal that was in phase with the signal from the function generator and will give us a maximum and minimum value [6].

The biggest derivative signal obtained from the mixer is shown below in pink with the absorption feature in yellow above this.
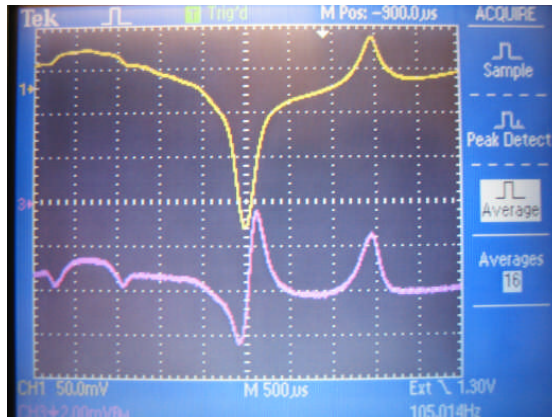
Figure 5.7 Derivative signal obtained with mixer.

The size of this signal in about 8 mV peak to peak and we first thought it was very small. However, we later found out the since we were not using an actual peak lock box we did not have access to a gain knob that would increase the size of it. We then locked the laser to this error signal without having to modulate the frequency out of the laser.

6   Conclusions

After putting together an external cavity diode laser we were able to integrate into the setup an electro-optic phase modulator. Then, the initial goal was accomplished given that the system was locked to a particular frequency due to modulation with this electro-optic phase modulator. The challenge now is to optimize the different variables involved in obtaining the derivative signal. The next step is to increase the size of the error signal to detect changes in frequency easily.

7 References

[1] C