Development of Laser System for AMO Experiments

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I. INTRODUCTION

The invention of the laser in the 1960s has changed physics and has allowed for a great deal of physics to be developed. Many properties that the laser has such as high power, well defined spacial profile, phase coherence, and narrow linewidth are properties which were hard to have before the invention of the laser. For modern experiments in Atomic Molecular and Optical (AMO) physics, these properties of a laser must be measured and enhanced to meet the demands of experiments. This project will cover the development of an External Cavity Diode Laser (ECDL), a saturation absorption spectroscopy setup to facilitate the calibration of a wavemeter, a self-heterodyne laser linewidth measurement setup, and the development of a stable cavity to which a laser can be locked to.

II. EXTERNAL CAVITY DIODE LASER

This project focuses on the External Cavity Diode Laser (ECDL) which was chosen for its narrow linewidth, around a few hundred kilohertz and can be lowered with feedback, easy of building, low cost, simplicity, and availability in a large range of frequencies. All of these properties are ideal for future experiments involving laser cooling of Calcium ions. The construction of an ECDL is shown in Figure 1 [1]. We see that there is a diode which has an anti-reflection coating applied to it, a collimating lens and lastly a grating. Since the diode has an anti reflection coating applied to it, it will not lase. To get around this we can direct one of the orders of diffraction back into the diode. This will form an external cavity and allow for our laser to lase. Given grating equation,

$$d(sin\alpha - sin\beta) = m\lambda \tag{1}$$

where d is the line spacing, α is the angle of incidence, β is the diffraction angle, m is the order of diffraction, and λ is the wavelength used. If we let $\alpha = -\beta$ and letting m = -1, we obtain

$$2dsin(\alpha) = \lambda \tag{2}$$

This means that there is an angle in which the incident beam and diffracted beam are in the same direction, and

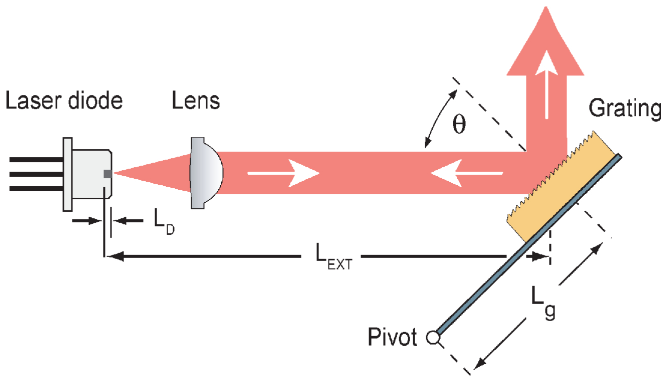

FIG. 1: Diagram of an External Cavity Diode Laser. A Laser diode creates a beam of light which is then collimated and send to an optical grating. The -1 order mode is reflected back into the diode forming an external cavity

thus our grating acts as one side of a cavity along with the other side of the diode. This forms the external cavity. Now by adjusting the grating angle we are able to reflect a slightly different frequency to our diode and thus change the frequency that our laser is lasing at. We are also able to adjust the amount of current we feed into the diode to change the frequency of our laser.

Lastly, if we are able to measure what the laser frequency is compared to some know standard and generate an error signal, we are able to change the current or grating angle to minimize this error signal. This idea of feedback allows us to lock the laser to a know transition, and if we are able to lock the laser well enough then we can reduce the linewidth of the laser. The next sections of this paper will talk about locking this laser to a rubidium transition to callibrate our wavemeter, how to make a measurement of the linewidth of our laser, and creating a stable cavity to lock the laser to.

III. SATURATION ABSORPTION SPECTROSCOPY

Despite having a laser we do not have a way of measuring the frequency of the laser yet. The method we employed was to use a Topica WS-7 wavemeter. However, this wavemeter can drift over time (about 50MHz in a month) and thus we need a way to calibrate the wavemeter. The best stable frequency source we have is atoms and Rubidium was chosen for it simple atomic structure.

However, we face a problem in that the Doppler shift at room temperature is much greater than the width of the atomic lines. So if we were to measure the absorption we would have all of our lines broadened, and none of them could be correctly resolved. To get around this we can have two beams to perform spectroscopy. One beam will saturate our transitions (pump), and the other will probe our transitions (pump). If we have both of these beams propagate in opposite directions then the Doppler shift is blue shifted for one beam and red shifted for the other. In general this means that the pump beam can excite the population, but the probe beam will not be probing the excited population, thus the probe sees no difference due to the pump beam. However, when the atoms are not travelling in the direction of the beam there is no Doppler shift, and both the pump and probe will be interacting with the same atoms. Then the probe signal will be lessened from the normal case because the pump beam is making the material optically transparent through pumping. These features are the saturated spectrum we aim to detect.

The experimental setup is shown in Figure 2.

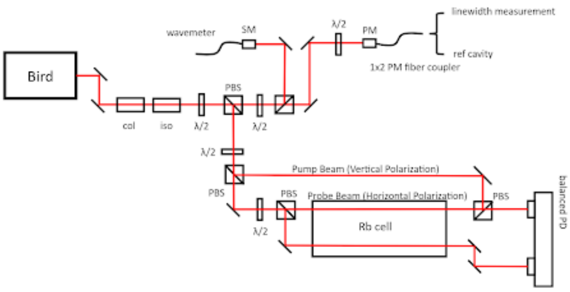

FIG. 2: Diagram for the saturation spectroscopy setup. A laser beam from the "Bird" laser is sent through an optical isolator in order to minimize any back reflections. Then it is branched off to be sent to the wavemeter, another experiment, or to the saturation absorption setup.

We have our laser pass through a collimator and an isolator. Since we are using a diode laser, which has high gain, we want to prevent sending too much power back at our diode. Afterwards it passes through a halfwave plate, so we can change it from a linear polarization into any other linear polarization, combining this with a polarizing beam splitter which splits the horizontal and vertical polarizations, we have a method to split off our light and how much we split off. This light then can go to our saturation absorption setup or it can go to another experiment as well as our wavemeter. The light that goes to our saturation absorption setup is further split into a pump and probe beam, with the probe travelling to the left and the pump travelling to the right. In addition, the probe was split so one of the beams overlaps with the pump and one does not. These then pass through the Rubidium cell, and are collected on a balanced photodectector, which gives the difference between the probe with pump signals and the probe without the pump.

Figure 3 shows the obtained signal, by modulating the frequency of the diode by altering the current.

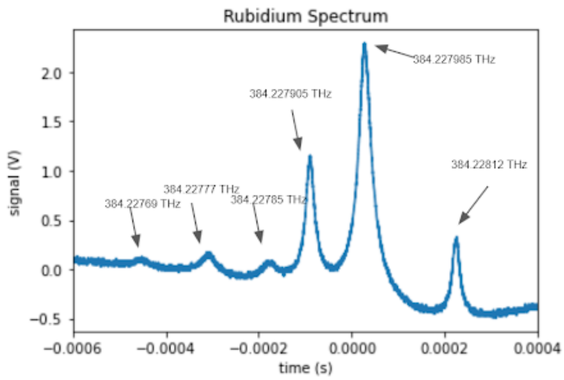

FIG. 3: Obtained signal from Saturation Absorption Spectroscopy. Six peaks are observed, and have been identified to have frequencies of (from left to right) 384.22769 THz, 384.22777 THz, 384.22785 THz, 384.227905 THz, 384.227985 THz, 384.22812 THz

From this signal we see that there are 6 peaks, but looking at the energy levels of rubidium we would only expect 3 peaks. The reason for these other two peaks is due to the fact that if the frequency of our beam is exactly halfway between two transitions then one beam will be redshifted to one peak and the other will be blueshifted to a different peak. Thus when the probe beam probes a population it will see less signal because the pump beam is exciting everything out of the ground state to a different energy level.

Using the distance between each peak, and previously tabulated value for the frequency of transitions[2], we were able to assign a correct value to each of the peaks and cross peaks we found. From this we were able to lock our laser to the strongest peak at 384.227982 and with this known frequency standard we were able to callibrate our wavemeter.

IV. SELF-HETERODYNE LASER MEASUREMENT

The main mechanism for a laser is the process of stimulated emission, where one photon interacts with a two level state in a population inversion, and two photon with the same phase are produced. Under this model a laser would have only one frequency and the linewidth would be a dirac delta peak. However, if we include the effects of that the photon has on the material we obtain the Schawlow-Townes limit[3],

$$\Delta\nu_{laser} = \frac{4\pi h\nu(\Delta\nu_c)^2}{P_{out}} \tag{3}$$

Where $\Delta\nu_{laser}$ is the laser linewidth, P_out is the power of the laser, and $\Delta\nu_c$ is the resonator bandwidth.

For a diode based laser, a current is ran through the diode and thus the current noise we usually be the dominating factor for broadening the linewidth of the laser. Since the exact construction of the diode is difficult to know, a measurement of the laser frequency must be done. To measure this we choose to perform a self-heterodyne laser measurement. The aim of this measuement is to measure a beat note between to laser beams. This could be done with two lasers, constructed in the same manor, however this is not ideal in many situations. Instead we can split the light from a laser into two paths using a beam splitter. These two beams will be very coherent and thus if we intend to measure a beat note we would only be measuring the coherence of the laser, to get around this we can one arm down a long fiber (2km), so the two beams are uncorrelated. To measure the beat signal the frequency between the two arms would need to be in the range of a photodectector, we employed an Acoustic Optical Modulator (AOM) to shift one of the arms by 40 MHz. This experimental setup is shown in figure 4.

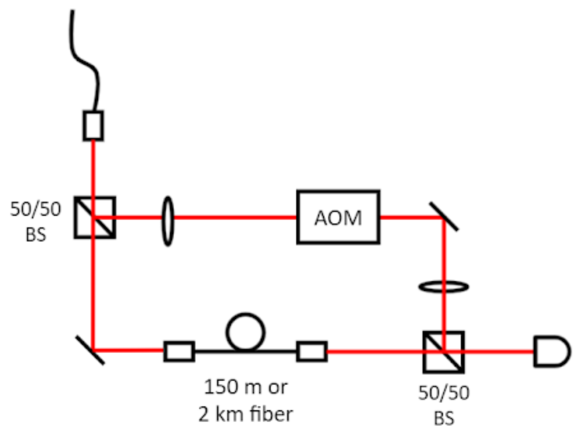

FIG. 4: Experimental set-up for self-heterodyne laser linewdith measurements. A beam is split by a beam splitter with one arm passing through a 2 km fiber and the other passing through a Acoustic Optical Modulator (AOM) to shift the frequency by 40 MHz. These are then recombined using another beam splitter and the beat note is read on a photodetector.

The results for the linewidth of the laser are shown in figure 5 along with a Guassian and Lorenzian fit. For a laser if the current noise is mainly white noise (evenly distributed noise) then the overall lineshape will tend to be Lorenzian. However, if the noise has more low noise components then it will tend to be Gaussian. From our fit we can say that we are in between these two extremes. From the Lorenzian fit we obtain a linewidth of 62 kHz and from the Gaussian we obtain 70 kHz. Despite these two fits appearing to not agree near the ends of the fit they agree quite well near the center peak which is the main on of interest.

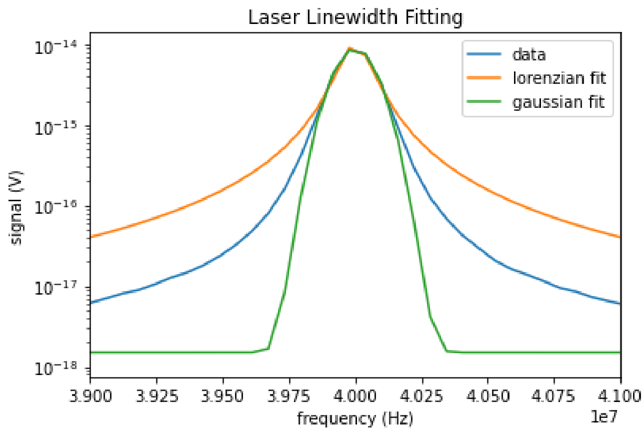

FIG. 5: Diagram of our measured laser linewidth in blue along with the Lorenzian fitting in orange, and the Gaussian fitting in green

V. STABLE CAVITY

With the Saturation Absorption Spectroscopy we have now calibrated our wavemeter and have the ability to lock our laser to a Rubidium transition. However, Rubidium does not have transitions everywhere, so there are only a few places we can lock onto. In addition, if we want to lock our laser to a stable reference to lower its linewidth, then Rubidium will suffer intensity broadening, limiting the maximum power we can use and thus limits our signal to noise ratio.

There problems are fixed by using a cavity to lock our laser to. A cavity is an optical pass where light can stay for a certain amount of passes and if there is a phase shift each pass it will partially destructively interfere with the previous pass. In this way the cavity will only support wavelengths which are a multiple of the total cavity length. Thus our constructive interference condition is

$$m\lambda = 2nd \tag{4}$$

where m is the order of diffraction, d is the cavity length of 125 mm and n is the refractive index. This will give many evenly spaced frequencies, with a spacing called the free spectral range of 1.2 GHz, and each peak has a linewidth of 4 Mhz.

For our cavity we choose a rather low finesse of 300, meaning that light will stay in the cavity for around 300 passes. Since using two perfectly flat mirrors would lead to a hard alignment, we use on curved mirror and one flat mirror. The curved mirror has a focal length of 125 mm and both of the mirror have a reflection coefficient of .99.

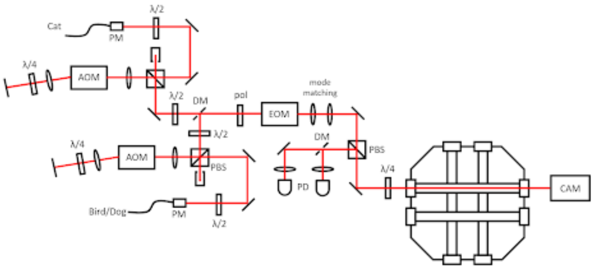

FIG. 6: Diagram for the stable cavity setup

Since the frequencies allowed by the cavity depend on the length of the cavity, any changes to the cavity length are unwanted. The biggest change to the cavity length is due to any change in the refractive index of air. This means that putting the cavity in a vacuum is required. The second biggest change to the cavity length will be due to thermal expansion. To prevent this the main body of the cavity was made of Ultra Low Expansion glass, which has a negligible thermal coefficient. While this made up the body of the cavity, the mounting of the mirrors could not be made with this material. Instead we created a two piece mount shown in Figure 7. This mount consisted of three washers. On washer being the base and attached to it two concentric washers. The bigger washer attaches to the ULE glass and the inner has a Piezo Electric Transducer (PZT) and the cavity mirror. The PZT allows for us to change the length of the cavity by applying a voltage. This configuration means that if there is a thermal drift the difference in thickness between the outer and inner washer can be made to compensate for this difference.

Now that we have a stable cavity we need a way to lock our laser to it. Since light that is on resonance with a cavity transition will enter the cavity, it will stay there for a relatively long time. This will cause a phase delay and lower the efficiency of our locking signal. To get around this we can modulate the phase of our laser. This will add side bands to the left and right of our frequency

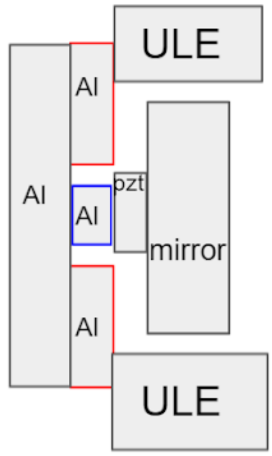

FIG. 7: Diagram mirror mounting. We see an outer aluminum ring that connects to the ULE block. Inside of this ring is another aluminum ring, and these two both connect to the aluminum block on the left. If the outer aluminum ring (red) expands then the mirror would be pushed to the left. However, if the inner ring (blue) expands then the mirror assembly would be pushed to the left. Thus the difference between these can be tuned to compensate for the thermal expansion of the pzt and mirror. diagram

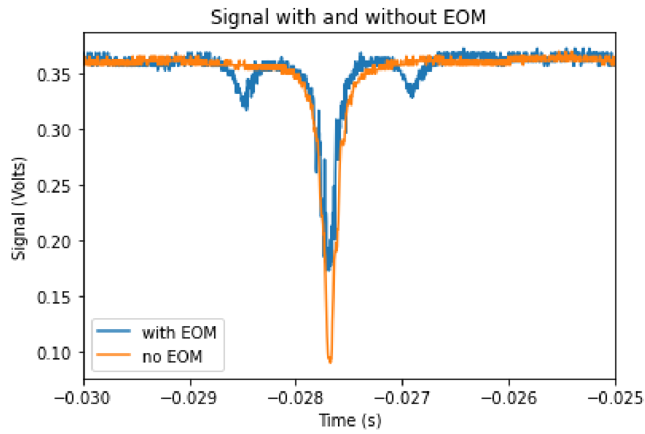

FIG. 8: Data obtained from using the PZT to change the cavity length. The orange plot includes the effects of the EOM and the blue plot does not

displaced by the frequency we are modulating the phase at, with the two peaks having opposite phase. Now if we send this light into our cavity, then on resonance the frequency modulated components will be reflected back. Since these two have opposite phase, if we demodulate the main frequency such that we are only measuring the side peaks we obtain an error signal. This method is called the Pound-Drever-Hall lock and allows for a laser to be locked to a high finesse cavity.

By implementing an Electric Acoustic Modulator, we were able to modulate the phase of the laser light and introduce sidebands. This is shown in figure 8.

VI. CONCLUSION

During this project a saturation absorption spectroscopy setup was created for locking a laser to a rubidium transition, to allow for the calibration of a wavemeter. In addition, A linewidth measurement set up was made to allow for ease of recording a laser's linewidth using a self-heterodyne technique. Lastly, a stable cavity was created and the necessary optics for creating a PDH lock were created and set up. All of these experiments play a very important role in a AMO lab and are vital to many of the experiments in the future.

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[2] Steck, Daniel. (2003). Rubidium 87 D Line Data.

[3] A. L. Schawlow and C. H. Townes, "Infrared and optical masers", Phys. Rev. 112 (6), 1940 (1958)