# Constructing a Saturated Absorption Spectroscopy System for laser locking

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Physics REU 2018, University of Washington

**Abstract**

Having a stable laser at a precise frequency is important to many areas of physics, and there are many techniques to achieve a stable laser. This paper describes the theory and construction of a saturated absorption spectroscopy system and its implementation into an ultra cold atom experiment. This experiment uses Ytterbium Bose-Einstein Condensates (BECs) to create an atomic interferometer for a precision measurement of the fine structure constant $\alpha$. The contribution of a stable laser, and success of this project are discussed.

## Motivation

The fine structure constant, $\alpha$, is a fundamental constant that characterizes interactions between light and matter. $\alpha$ is dimensionless, so its value, which is approximately $\frac{1}{137}$, is the same in all unit systems. It is an important figure in both quantum field theory and atomic physics. The current best measurements of $\alpha$ are within 0.25 parts per billion (ppb) found using an electron $g_e - 2$ technique in combination with quantum electrodynamic (QED) theory and, more recently, 0.2ppb using an atomic recoil technique.[1, 2, 3] The lab this paper focuses on, run by Deep Gupta, attempts to use the latter technique to achieve a measurement of $\alpha$ with a precision of 0.1ppb or better. Using the recoil method provides a check on QED theory by comparing the two values measured with different techniques.

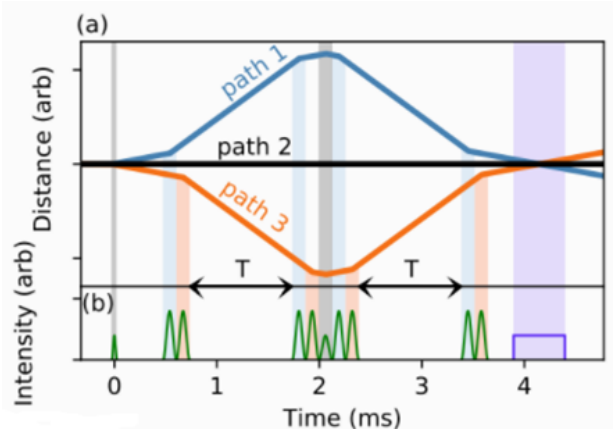


Figure 1: Space-time diagram demonstrating the different paths taken by atoms in a contrast interferometer. The peaks at the bottom represent acceleration Bragg Pluses used to give atoms momentum and the square pulse represents the readout beam.[4]

In order to get this precision, the group uses a contrast interferometer [Fig 1,[4]] to measure the recoil frequency of the atoms (Equation [2]). This is done by splitting a BEC into three separate momentum paths, allowing parts of the wave function to evolve before bringing them back together as shown in figure 1. A readout pulse is then fired, which measures the diffraction grating created by the different parts of the wave function interfering with each other.

$$\Phi(2T) = \frac{1}{2} n^2 \omega_{recoil} T + \phi_{offset} \tag{1}$$

From the total phase of this grating, and the time allowed for evolution of wave functions, the recoil frequency of the atoms can be calculated using equation 1, where $n$ is the measurement of momentum separation $\Delta P = n\hbar k$ and $k = \frac{2\pi}{\lambda}$.

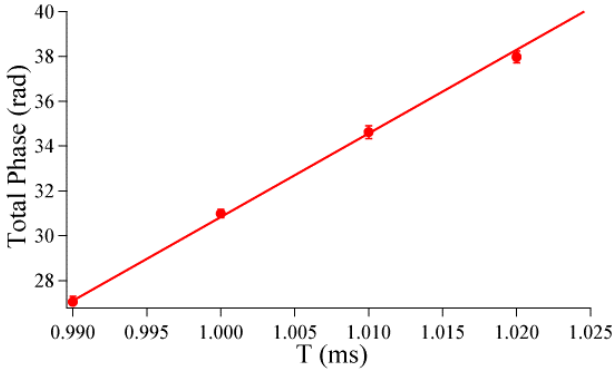


Figure 2: Plot of the total phase found from the readout pulse against the evolution time given to the atoms. The slope of this graph is used to find $\omega_{recoil}$ [5].

The evolution time, $T$, from multiple runs is plotted against the total phase of the atom grating, shown in figure 2. The slope of this plot is equal to $\frac{1}{2} n^2 \omega_{recoil}$. Knowing the momentum separation of the different paths allows for the calculation of $\omega_{recoil}$.

$$\omega_{recoil} = \frac{\hbar k_{laser}^2}{2m} \tag{2}$$

$$\alpha^2 = \frac{4\pi R_\infty}{c}\frac{m}{m_e}\frac{\hbar}{m} \tag{3}$$

Once $\omega_{recoil}$ is known, it is related to $\alpha$ through equation 2 and 3. Knowing the recoil frequency gives the value $\frac{\hbar}{m}$, which can then be used to find $\alpha$. Through this relation, the more precisely $\omega_{recoil}$ and $k_{laser}$ are known the more precise the measurement of $\alpha$ is. Increasing the momentum separation is a main focus of the lab because $\omega_{recoil}$'s precision improves the higher the separation.

In order for this experiment to run, having a stable and precise laser lock is key. With a stable laser set up, the experiment is prone to less issues concerning laser locking and frequency drifting. At the beginning of the summer the ${}^1S_0 \rightarrow {}^3P_1$, 556nm, transition for Ytterbium (Yb) was locked using a beat note set up connecting to a lab down the hall. This system contained difficulties that hindered the experiment. If the fiber transporting the light was bumped, the lock could be undone causing delays. It also prevented the two labs from working with different atomic isotopes of Yb, which the other lab planned to do.

Due to these complications, the decision was made to build a saturated absorption spectroscopy set up. This system would provide the lab with a laser lock less prone to unlocking problems, and independence from the other labs atom choice.

### Background

Atoms at temperature $T$ have an average velocity determined by equation 4, which results in the Doppler effect, $\omega = \omega_L - \vec{k}\cdot\vec{v}$, where $\omega_L$ is the frequency in the lab frame. When using a laser to excite an atom from one energy level to another, the frequency seen by the atom will depend on its velocity. This causes different atoms to interact with different frequencies, broadening the absorption spectrum.

$$u = \sqrt{\frac{2k_bT}{M}} \tag{4}$$

The Doppler effect generated a huge problem in experimental physics because it creates a limit for laser precision. Without the ability to keep a laser within a very small frequency range, atoms will not be able to be laser cooled. In order to surpass this barrier a few techniques have been invented, including saturated absorption spectroscopy.

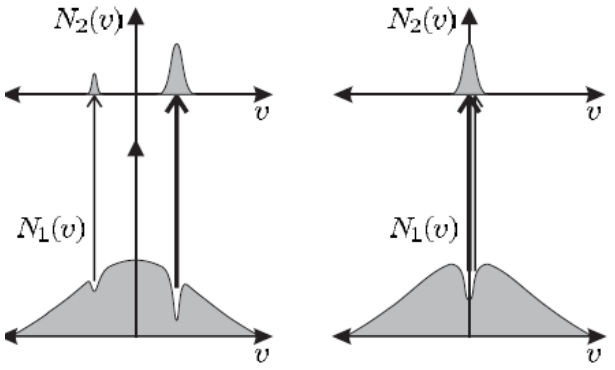


Figure 3: Depiction of the absorption spectrum with both the pump and probe dips shown. On the left, the beams are interacting with different velocity classes. On the right, they are interacting with the zero velocity class.[6]

If a probe beam, swept over a range of frequencies, is sent through an atomic vapor cell into a photo detector, the information collected will show a Doppler broadened absorption spectrum. When the probe beam is at one frequency it will only interact with the atoms traveling at a certain velocity. If another beam, called the pump beam, with the same frequency is shown through the cell in the opposite direction it will be absorbed by atoms traveling with the opposite velocity, as demonstrated on the left side of figure 3. These beams will act on separate atoms, having no effect on each other, unless the frequency of the lasers is in resonance with the zero velocity atoms, as shown on the right side of figure 3.

When this happens the beams affect how much the other will absorb. The pump is given enough power to saturate the atomic vapor, meaning up to 50% of the atoms in the vapor are in the excited state at any given time. This causes the probe beam, which has less power, to interact with as little as half as many atoms. This causes a narrow dip in the absorption spectrum of the probe beam, shown in figure 3.[6] This dip covers a much smaller range than the approximately 1GHz Doppler broadened zone. This narrow signal, which is on the order of 1MHz, allows the laser to be locked at a much more precise frequency than the Doppler broadened range.

This technique gives a reference for when the frequency is at resonance, and allows a lock to a narrow frequency range for sub-Doppler cooling. This stable reference point makes saturated absorption spectroscopy a valuable tool in laser cooling experiments, and one of the reasons it was chosen for this atomic interferometer experiment.

## Construction

For this set up, a dual-axis vapor cell, diagram shown in figure 4, was used. This was designed by previous members of the lab group to accommodate both the 556nm and 399nm transitions in Yb.[7]

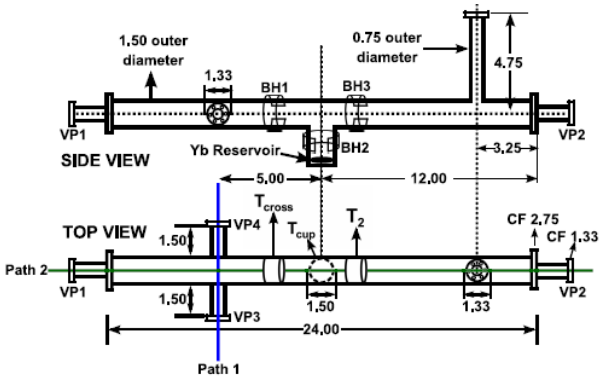


Figure 4: Schematic of the vapor cell used in this experiment.[7]

The vapor cell was placed on a separate optics table from the rest of the experiment. The cell was pumped down below 1mTorr by first using a roughing pump and then, once the pressure was low enough, a turbo pump, checking for leaks along the way. Once the cell was at this pressure, band heaters and heater tape were added before wrapping the system in aluminum foil. The temperature of the cell was raised at a rate of one degree Celsius per minute, to protect the view ports from any damage from a sudden temperature difference.This baking was done to get rid of water vapor or any other undesired particles.

The temperature of the Ytterbium cup was raised to 400°C, view ports to 250°C, and the tube to 200°C. The tube was kept at a lower temperature to allow Ytterbium vapor to stick to the sides in an attempt to prevent any from sticking to the view ports, blocking the optical path. These temperatures were held overnight before sealing off the vapor cell from the pumps. The cell was then back filled with Argon to 30mTorr to extend the time before the Ytterbium vapor stuck to the walls, preserving the Ytterbium source in the cell for as long as possible.

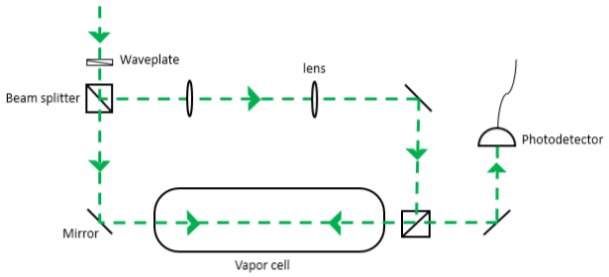


Figure 5: Diagram of the initial optical set up, to make sure the cell was ready for this method.

During the bake out of the vapor cell, the optics were also set up, as shown in figure 5. The pump and probe beams originate from the same source, a fiber carrying laser beam from the main experiment, and separate using a polarizing beam splitter. A half wave plate is placed directly in front of the beam splitter to control the ratio of power sent to the pump and probe beams. Lenses, creating a telescope, were placed in the path of the probe beam to increase the diameter of the pump beam. This allows the probe beam to pass only through saturated atoms, giving the best signal. Making the diameter of the pump beam larger allows for this alignment process to be easier. The probe beam going through the vapor cell is reflected off a mirror and into the photo detector to make alignment for the optimum signal less time consuming.

Optimizing the absorption signal for the best lock involves a few different components. To ensure there is enough power to read a clear signal there is 100$\mu$W in the probe right before the photo detector, and to ensure saturation of the vapor there is 1.3mW in the pump right before the vapor cell. The temperature of the cell is also monitored to optimize the absorption peak. The temperature, measured at the Ytterbium cup, is between 560°C and 570°C to create a dense enough vapor in the cell but not cause too much signal loss. The view ports are kept at 230°C to minimize collection of Ytterbium vapor so the laser light is not blocked. The tube temperature, measured at the T-cross shown on figure 4, is held at 160°C. The tube needs to be heated using the heater tape as well as wrapped in foil. This allows the Ytterbium vapor to remain dense for a greater length in the tube, which has an sizable positive effect on the signal size.

The temperature of the cell is controlled by three Variac power sources. One going to the cup at 125V, one to the heater tape at 60V, and one for both the view ports in parallel at 35V. The relationship between the voltage output and the temperature is not

linear. It resembles a more quadratic relationship so controlling high temperatures requires only small voltage changes, but no systematic study was done with this equipment. These settings produce the optimum temperature distribution for this system.

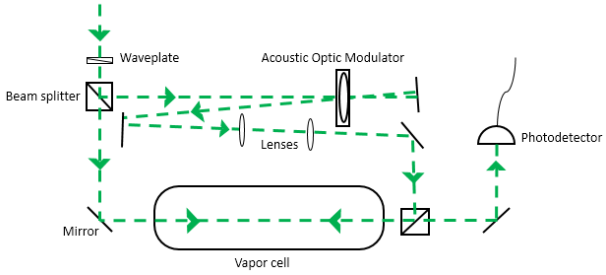


Figure 6: Optical set up diagram including the double passed AOM for frequency shifting and modulation.

Once the set up showed a peak in the absorption spectrum, indicating the set up was working, an acoustic optical modulator (AOM) was installed on the pump beam, as shown in figure 6. AOMs' use a crystal and a radio frequency to shift a laser's frequency by a controlled amount, about 450MHz in this case. They transform a radio frequency into a sound wave in the crystal which can exchange energy with the photons.[8] By placing an AOM on the pump beam, the beam's frequency is offset from the probe's. The beams no longer interact with the zero velocity atoms at the same time, but instead have a specific, controlled, velocity class where the dip in absorption occurs, shown in figure 7. There is another AOM controlled on the laser that is directly used in the experiment. This allows the main experiment to shift the frequency back and control where on the frequency spectrum the laser is locked.

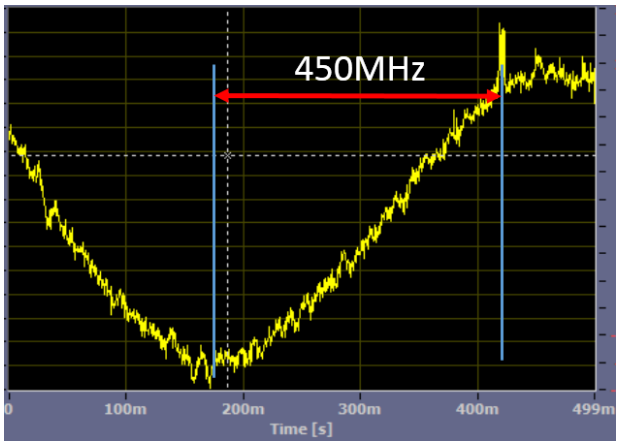


Figure 7: Image taken form the computer software showing the transmission level on the y-axis, as the frequency is swept over time on the x-axis. The absorption peak is shown on the top right of the curve.

The frequency of the AOM offset is also modulated to sample the frequencies as the laser frequency is linearly sweeping. This modulation samples the signal ahead and behind the linear sweep. The transmission signal is then mixed with the original modulation signal. When this is done an error signal, shown in figure 8, appears because of the sharp slope on the absorption peak.

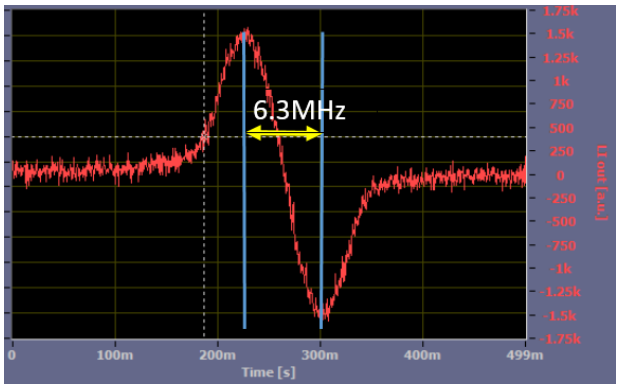


Figure 8: Plot showing the error signal that the program uses to lock the laser.

Looking at figure 8, the signal goes from positive to negative while its slope goes from positive to negative to positive. Digilock, the laser locking program used, is then set to lock to where the negative slope crosses the time axis. If the laser drifts one way or the other the program will see the y-value change. Based on the sign of this drifted y-value the program provides the correct feedback, bringing the laser back to the right frequency.

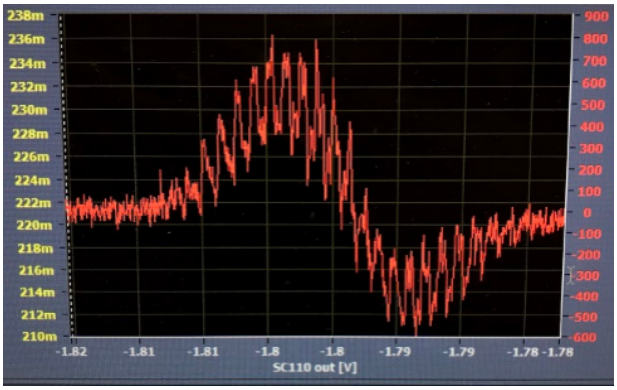


Figure 9: Plot of the error signal containing a 60Hz noise, making the signal harder to lock to.

The quality of the error signal is the determining factor for how precise and stable the laser frequency is. The higher the signal to noise for the error signal, the better the laser lock will be. It is also important to keep the error signal itself free of as much noise as possible. During the construction of this set up, a 60Hz noise appeared on the error signal, shown in figure 9, that required correction. This noise was first due to the AC current flowing through the heater tape from the Variac, creating an alternating magnetic field affecting the energy levels of the atoms in the vapor, through the Zeeman effect, as the current alternated. This caused the absorption spectrum to have a 60Hz effect that eventually led to the noise on the error signal. This was fixed by folding the heater tape on itself so the magnetic fields canceled out. A similar $60Hz$ noise appeared twice more and was traced back to a grounding issue in the AOM driver box. Once the grounding issues were fixed the signal became clear again and the lock precise enough to continue the main experiment.

## Conclusion

In this project, the Doppler effect and atomic theory allowed for the construction of a laser locking system in an experimental lab.The frequency width of the error signal is 6.3MHz with a signal to noise ratio of $10:1$. With this newly implemented saturated absorption spectroscopy system, the Gupta lab group is able to trap cold atoms and create a BEC. From this, the group is continuing to develop the contrast interferometer to measure $\alpha$ more precisely.

With this new system implemented, the laser has been much more stable, than compared to the beat note system used previously. This allows for data to be collected more with less interruptions than before. A longer term goal for this spectroscopy system is to move it to the same optics table the experiment is conducted on. This would save space to allow for further developments in the lab. For this to happen the vapor cell and optics would be moved onto a $3x1$ foot optical breadboard and placed above the main experiment. Ideally this spectroscopy set up will continue its function for the duration of the experiment.

## Acknowledgements

This work was made possible by funding from the National Science Foundation, as well as faculty and facilities from the department of physics at the University of Washington. A special thanks to the graduate students in the lab, Dan Gochnauer and Katie McAlpine for answering constant questions. Final thanks to Dr. Subhadeep Gupta for being an outstanding advisor throughout the summer.

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