Steps Toward a Prototype Atomic Clock

Nathan Belcher *College of William and Mary*
Irina Novikova *College of William and Mary, Physics Department*

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Abstract

Work continues on a prototype atomic clock. With an Ulm vertical-cavity surface-emitting laser (VCSEL), the desired modulation characteristics and lasing at 794.7 nm was achieved. A dichroic atomic vapor laser locking (DAVLL) system was installed and tested, and works reasonably well. Electromagnetically induced transparency (EIT) was achieved, and phase modulation with two different devices was also seen.

1 Introduction

In the last decade, advances have been made in creating miniature (sub-cubic centimeter) atomic clocks, based on laser probing of a vapor. The laser employed in these clocks is a vertical-cavity surface-emitting laser (VCSEL), which has useful characteristics for this application. The overall goal of my project is to create a prototype atomic clock, and previous work from the summer and this semester have pushed our group closer to achieving this goal. This paper will describe the theories underlying the atomic clock, the hardware necessary to temperature stabilize the laser and measure properties of the laser and rubidium cell interaction, and the data and results seen in the work performed this semester.

2 Theory

The atomic clocks contain three parts: a transition in an alkali metal atom (that has free valence electrons), a frequency modulator with counter, and a laser. The element of use in this atomic clock is rubidium, which has one free valence electron. The frequency modulator provides phase modulation, creating two electro-magnetic fields at different frequencies out of one physical laser. A counter matches the frequency driven by the modulator to give a reference for time, and the laser drives the entire process. To keep the laser at a set frequency determined by the modulator, another part called a dichroic atomic vapor laser locking (DAVLL) system is needed. The DAVLL uses an error signal determined by the difference of signal in two photodetectors to keep the laser's frequency on a rubidium resonance.

2.1 Transitions in Rubidium

In the rubidium electron energy levels, the transition wavelength used in this atomic clock is 794.7 nm. This matches the transition from $5S_{1/2}$ to $5P_{1/2}$, and the hyperfine splitting at 6.834 GHz is contained in the $5S_{1/2}$ energy level. Hyperfine splitting is a correction to the energy levels due to the difference in the spin orientation of the nucleus with the spin of the electrons, and is a small correction with respect to the total energy level. The three level system comprised of two $5S_{1/2}$ hyperfine states and the $5P_{1/2}$ level forms what is known as a lambda system (figure 1). It is called a lambda system because of the resemblence to the Greek capital Λ. ω_c is the carrier frequency the laser must match to raise the electrons into the excited state, while ω_p (probe frequency) is the carrier frequency plus the hyperfine splitting frequency.

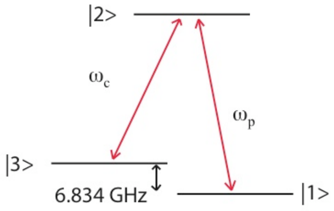

Figure 1: A lambda system. Levels 1 and 3 are states in $5S_{1/2}$ seperated by the hyperfine splitting (6.834 GHz), and level 2 is 794.7 nm away from the $5S_{1/2}$ state.

When the laser drives the electrons into the excited state, some will decay into the hyperfine split level denoted by state 1 in the figure. In a process called electromagnetically induced transparency (EIT), all of the electrons will be driven to the quantum superposition of states 1 and 3 (a “dark” state), which does not interact with either electromagnetic field causing the atomic sample to become transparent. This transparency happens only if a frequency difference between ω_c and ω_p is very close to the hyperfine splitting between states 1 and 3 (clock transition), and allows the locking of a frequency modulator to the counter at the clock frequency.

2.2 Phase Modulation

Because the lambda system needs two different frequencies of laser light, a few problems exist. The first problem is the laser will move around a set frequency in a random way (”jump”), regardless of the quality of the laser. If two physically seperate lasers are used at two different frequencies, they will both jump randomly and not have any correlation. To alleviate this problem, phase modulation is used to create two lasers out of one physical laser. Even through there will still be jumps around the set frequency, both lasers will jump in the same way. The relative frequency of the two lasers can be set by an external generator, and this creates a carrier with sideband comb.

The mathematics behind phase modulation are useful, so I will explain them. A generic wave is created with the form

$$E = E_0 e^{ikx - i\omega t + i\varphi(t)} \tag{1}$$

where E_0 is the amplitude of the wave and ω is the phase. φ(t) is the modulation wave in the form

$$\varphi(t) = \varepsilon sin(\omega_m t) \tag{2}$$

where ε is the amplitude of modulation and ω_m is the modulation frequency. Combining the two equations gives

$$E = E_0 e^{ikx - i\omega t + i\varepsilon sin(\omega_m t)} \tag{3}$$

To decompose this equation into amplitude and frequency parts, Bessel functions must be used. From the generic Bessel function equation

$$e^{insin(\varphi m)} = \sum_{n=0}^{\infty} J_n(\varepsilon) e^{im\varphi} \tag{4}$$

the iεsin(ω_mt) of equation 3 can be broken into

$$e^{in\varepsilon sin(\omega_m t)} = \sum_{n=0}^{\infty} J_n(\varepsilon) e^{i\omega_m nt} \tag{5}$$

Substituting equation 5 into equation 3 gives

$$E = \sum_{n=0}^{\infty} E_0 J_n(\varepsilon) e^{ikx - i\omega t + i\omega_m nt} \tag{6}$$

and rearranging shows the final form

$$E = \sum_{n=0}^{\infty} E_0 J_n(\varepsilon) e^{ikx - i(\omega - n\omega_m)t} \tag{7}$$

This equation is the basis for the carrier and sideband comb, because the frequency difference between the carrier and each nth sideband is determined by ω-nω_m.

An advantage of using the VCSELs is that their output can be phase-modulated by direct current modulation. This allows matching of the hyperfine splitting in the rubidium vapor, because the frequency difference can be chosen. In additon, the amplitude of the sidebands and carrier are determined by the nth-order Bessel function and can be calculated.

2.3 DAVLL

The DAVLL system plays an important role in the prototype atomic clock because it allows locking of the frequency of the VCSEL to a specific resonance of rubidium. In a one laser system with the atoms being excited from the ground state to an excited state, the absoprtion spectrum looks like an inverted gaussian curve. But, in a two laser system with the ground state hyperfine shifted (creating the lambda system in figure 1), the relative position of each absorption spectra are also shifted. The DAVLL electronics compares the signals received in two photodetectors perpendicular to each other, and subtracts one from the other. The resulting signal resembles a negative sine wave, having a relatively steep negative line through the zero point. From the difference of the two absorption spectra, an error signal is read by the electronics and used to correct the frequency of the laser until the error signal reaches zero. This process continues to adjust the laser's frequency to keep the laser locked with a rubidium resonance.

3 Hardware

3.1 Temperature Stability

Because the project started from the beginning, we had complete control over the design and fabrication of the hardware for the laser system. Using ideas from Sergey Zibrov at Lebedev Physics Institute in Russia, who had designed a temperature controlled diode laser system, a system was created that would be robust yet easily assembled and disassembled when changing laser diodes. The laser needed to be held at a fixed temperature to achieve stability in wavelength, so the system was designed to keep the laser at a given temperature.

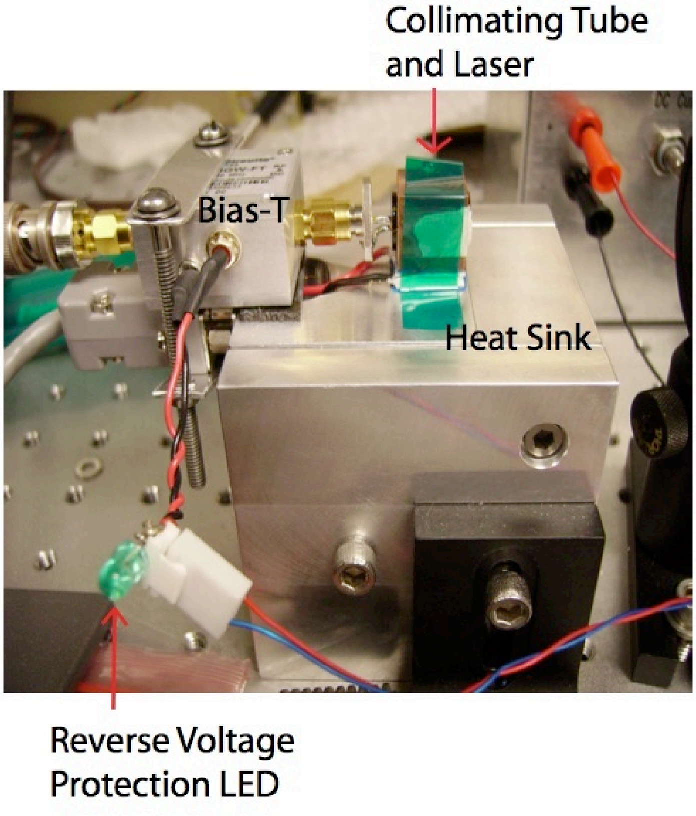

Figure 2: The laser system.

Figure 2 shows the laser system designed by our group. The system

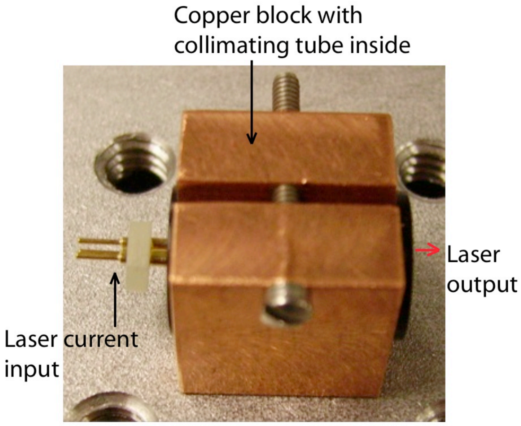

Figure 3: Collimating tube holder for the lasers.

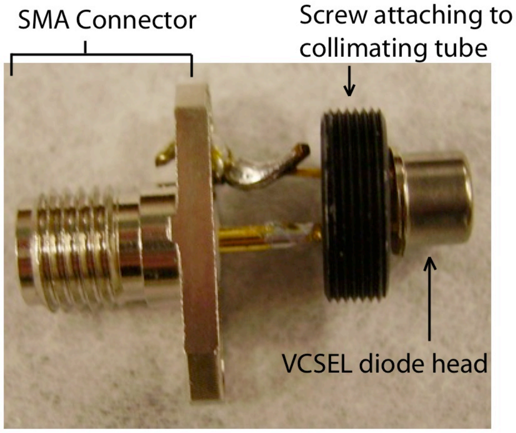

Figure 4: VCSEL diode with SMA connector.

provides the laser with a stable temperature and modulation of the laser's current, which are both necessary in the prototype atomic clock. The basis for the laser system is the heat sink, which doubles as the holding block for the system. The temperature controller uses a peltier that heats or cools depending on the direction of current flow, and the peltier needs a large piece of metal from which to draw or give heat. This large piece of aluminum was also designed with a piece to be raised or lowered, allowing a changing beam height.

Using a temperature conducting epoxy, a copper block containing the collimating lens and diode holder for the laser (figure 3) was placed on the peltier. This block was made from copper because it can change temperature relatively quickly and gives the laser a stable basis from which to heat or cool. The laser is installed on the left side of the picture (with the three pin connector) and lases towards the right of the picture. There were difficulties with the collimating lens, because the size of the diode cap did not allow the collimating lens to reach its focal point. Another lens had to be ordered with a longer focal length, and this lens was able to collimate the beam.

The temperature contoller drives the peltier, and was purchased from Wavelength Electronics, Inc. (model number WTC3293-14000). The temperature can be set using a potentiometer from 0 to 70 degrees Celsius, but it has been found that the peltier can only drive the temperature to about 37 degrees Celsius due to a current limit of 0.5 A. The controller is stored in a box with a cutout for a D-sub connector and LED screen, and is connected to the peltier and thermistor through another D-sub connector mounted on the heat sink.

The SMA on the laser (figure 4) is connected to a Bias-T, which mixes rf modulation and dc current and outputs to the laser. The rf signal is input to the Bias-T by a digital synthesizer, which produces rf power at very accurate frequencies, and the dc current is provided by a constant current source.

In addition to the pieces shown, there is also a metal box with a hole for the laser that is placed on top of the heat sink and around the collimating tube holder. This stabilizes the air around the laser, because the small airflow in the laboratory is enough to cause temperature fluctuations large enough to affect the wavelength of the laser. The temperature fluctuations are especially noticable when operating at temperatures above 35 degrees Celsius.

3.2 Laser Power Supply

Much of the research done this summer was to find a power supply for the lasers that could operate at very low currents with little noise added to the signal. The laser's ability to maintain a constant frequency in the range needed to remain on a rubidium resonance is very much determined by the ability of the power supply to maintain a constant current. After trying one commercial power supply and two designs of power supplies of our own, one design was found to operate with stable constant current and little noise. Using four D-cell batteries to power the constant current source and the circuit in figure 5 to maintain a constant current, a power supply was fabricated that suits the needs of the laser. For a further analysis of the issues associated with the power supplies, see refer to [1].

3.3 Measuring Setups

After the laser was installed in the laser system, measurements were taken to see modulation of the laser and resonances in rubidium. Two different setups were used to obtain the data, and will be explained below.

To see signal that has meaning for phase modulation, an interferometer (Fabry-Perot cavity) must be used. A Fabry-Perot cavity is a set of two mirrors with 99 percent reflectivity aligned such that the mirrors are parallel with each other and perpindicular with the beam (see figure 6). When this alignment is achieved, the waves reflecting off the mirrors constructively

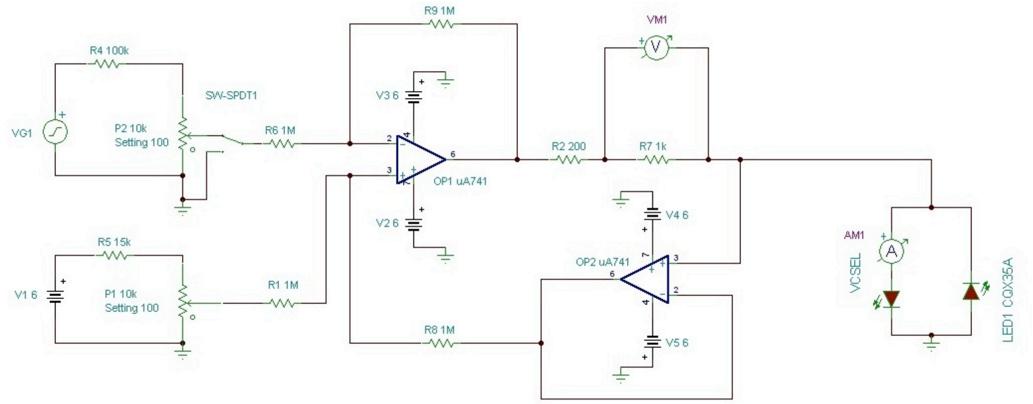

Figure 5: The schematic for the battery-powered constant current supply of the laser.

interfere to create transmission through the mirrors. For the early measurements of VCSEL modulation, a purchased Fabry-Perot cavity with length of 5 cm and a free spectral range (FSR) of 1.5 GHz was used. This FSR was not enough to see the full effect of rf modulation, so a cavity with a length of approximately 5 mm was created from two mirrors. We achieved an FSR of approximately 40 GHz and a finesse of approximately 100, which allowed resolution of second and third sidebands.

This Fabry-Perot cavity was fabricated by epoxying two piezoelectric crystals on a lens mount (see figure 6; the piezos are the green pieces on the top mirror) and connecting their wires to a BNC connector. Piezoelectric crystals work by changing the length of the crystaline structure in one plane based on the input voltage, and the BNC connector was attached to a piezo scanner (made by ThorLabs) which provided an input voltage. The piezo scanner was modulated with a function generator to provide scanning of the length of the cavity, providing transmission of the wave through the cavity and giving a signal on the oscilloscope.

Alignment of the Fabry-Perot cavity has proven difficult with the low powered lasers, because of the decrease in signal after the cavity. To align the cavity, an iris is placed after the optical isolator (see figure 7) to indicate the position of the reflection. The mirror with the piezoelectric crystals (see figure 6) is installed on the optical table, and its reflection is moved with screws on the optical mount to be directly back into the iris. The front mirror is then installed, and its reflection is also moved back into the iris.

Both mirrors reflections are moved into the iris to crudely align the mirror to each other and to the incident beam, and fine-tuned to each other and the photodetector with the screws on the mirror mounts.

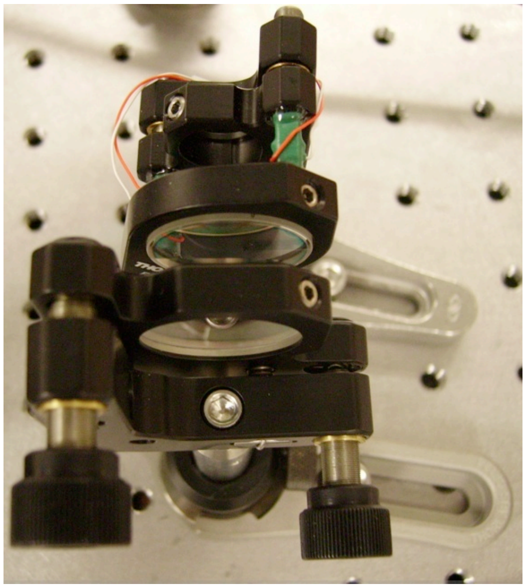

Figure 6: The Fabry-Perot cavity with length of approximately 5 mm.

For the modulation measurement, either the Fabry-Perot cavity or the current into the laser could be scanned. Using the optical setup in figure 7, the modulation figures for both the Modulation Synthesizer and the Stellex Mini-YIG in the Data and Results section were taken by scanning the Fabry-Perot cavity.

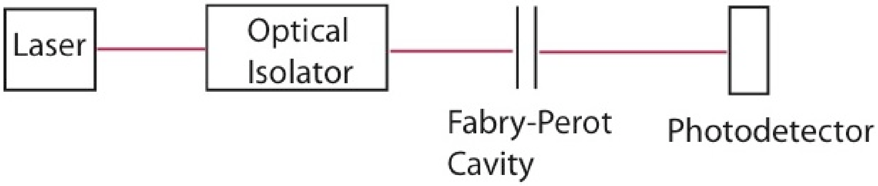

Figure 7: Visual schematic of optical setup for measurement of phase modulation.

To measure the rubidium resonances in a rubidium vapor cell, the optical setup in figure 8 was used. The input current of the laser was modulated by a function generator, and the output measured by the oscilloscope. When we first saw the resonances, they just looked like noise at the top of the triangle wave. But, as the current was increased, we saw the "noise" (resonances) move down the triangle wave. When the vapor cell was taken out, the input triangle wave was seen without noise, causing us to understand that the noise seen on the triangle wave was in fact the resonances of rubidium.

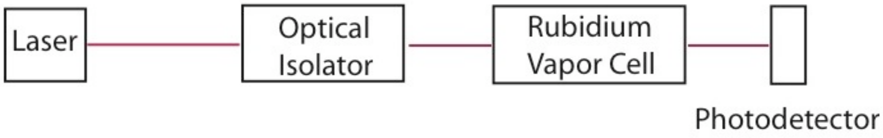

Figure 8: Visual schematic of optical setup for measurement of rubidium resonances.

When measuring resonances in rubidium, two different vapor cells can be used. One cell, which is usually used as a reference cell, has the two different species of rubidium (85 and 87) mixed with an inert buffer gas. Because both species of rubidium are present in the cell, there are more absorption resonances than the single species cell. The single species cell (containing rubidium-87) is inside a set of three shields that limit external magnetic fields and is used in the clock experiment. As seen in figure 15, the single species cell contains four absorption resonances, while the mixed cell contains five absorption resonances (figure 16).

3.4 DAVLL

As explained in the theory section, DAVLL is used to lock the laser's frequency to match an absorption resonance of rubidium. There are two parts of hardware that comprise the DAVLL system: one is the optics (shown in figure 9) that contains the photodetectors and mixed rubidium cell; the other is the electronics that has a circuit with proportional and integral parts to provide current to the laser. The optical and electronic parts are connected via BNC connectors, and the output of the electronics is connected to an input of the laser circuit.

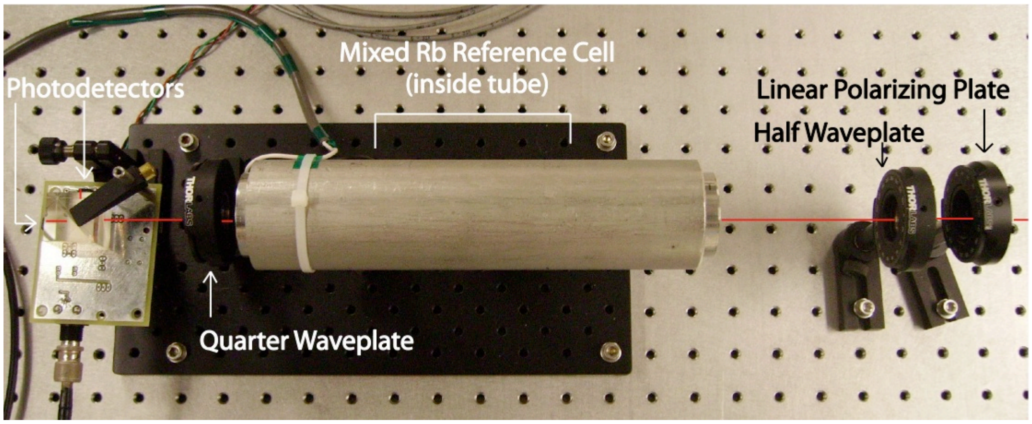

Figure 9: The optical hardware of the DAVLL system. The full hardware include the optical hardware plus a circuit that provide the feedback to the laser.

3.5 Modulators

To create the carrier and sideband comb needed in the experiment, the laser must be modulated. There are two methods of modulation: one using a commercial digital synthesizer (Agilent E8257D); and the other using a Stellex Mini-YIG Oscillator. The commercial digital synthesizer produces modulation at very precise frequencies up to 14 dBm, and figures 10 through 12 were taken with this modulator. In an attempt to use different pieces of hardware in the experiment, a Stellex was purchased. This modulator uses a crystal to generate modulation between 5.95 and 7.15 GHz at approximately 10 dBm of power. The modulation frequency can be changed by increasing or decreasing the current in a coil, which changes the magnetic field strength the crystal feels. The group has had some issues with the Stellex, because the current in the coil a reactive load. The Stellex had been calibrated using a function generator's offset voltage to provide the current, but we learned that the coil will provide a large backward current into the function generator if the voltage increases or decreases in a large increment. This caused two function generators to break, and the group to adopt a constant current source loosely based on the constant current source for the laser. When the circuit is completed, recalibration with current will give the amount of current needed to drive the oscillator at 6.8 GHz. Figures 13 and 14 were taken with the Stellex modulation.

4 Data and Results

To be used in the prototype atomic clock, each laser must meet three qualifications. First, the laser must operate on a single mode; second, the laser must have strong phase modulation (close to one-to-one sideband to carrier ratio at 6.834 GHz); and third, the laser must tune to an atomic transition in rubidium. During the summer, four lasers were tested and one laser passed all three requirements. The laser that passed all requirements is an Ulm VCSEL, and been in use since the middle of the summer. It has been modulated by both the commercial digital synthesizer and the Stellex, and figures will be shown in the VCSEL Modulation section. In addition, the work on the DAVLL system and the achievement of EIT will be discussed.

4.1 VCSEL Modulation

After constructing the laser hardware and installing the VCSEL, the laser was connected to the digital synthesizer. We observed various sideband-to-carrier ratios according to the input power, and achieved very close to a 1-to-1 sideband-to-carrier ratio at 14 dBm (figures 10-12). When connected to the Stellex, we achieved sidebands greater than the carrier for maximum input power and approximately .5 for decreased input power (figures 13, 14). The data was taken with the short Fabry-Perot cavity (figure 6) while sweeping the piezoelectrics.

One interesting result found centered on the "saturation" of the signal on the oscilloscope based on the modulation power and current. Saturation of the signal occurred when there were too many sidebands with not enough energy in each, causing a drop of the signal from sharp, high peaks to wide, low peaks barely above the noise on the scope. We found that the saturation depended on the input current, meaning low current with high modulation power gave saturation of the sideband-carrier comb. We also found that the VCSEL could modulate at higher powers when lasing with higher currents, so the current was increased.

There are two factors that influence the laser's frequency, both of which are in our control. One is the temperature, controlled by the peltier and driven by a temperature controller, and the other is input current, controlled by the constant current source. Increasing either the temperature or the current increases the laser's frequency, so there is a balancing game with these two to keep the laser at an absorption resonance frequency. Because

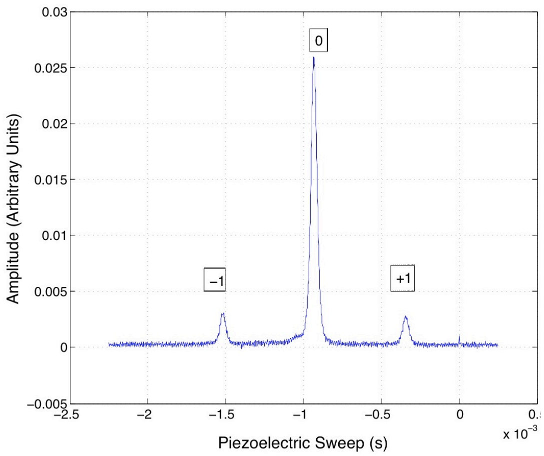

Figure 10: Modulation of the Roithner VCSEL at 6.8 GHz and 5 dBm of power.

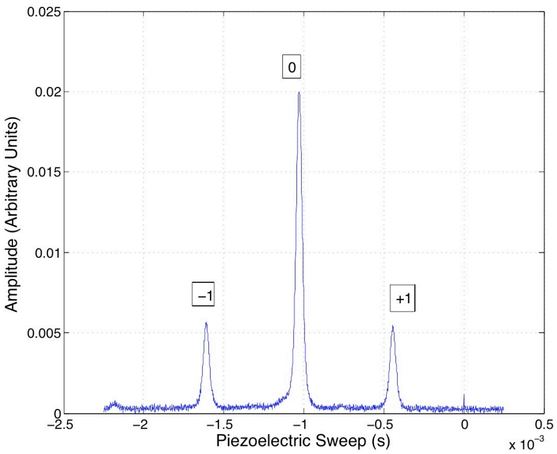

Figure 11: Modulation of the Roithner VCSEL at 6.8 GHz and 9 dBm of power.

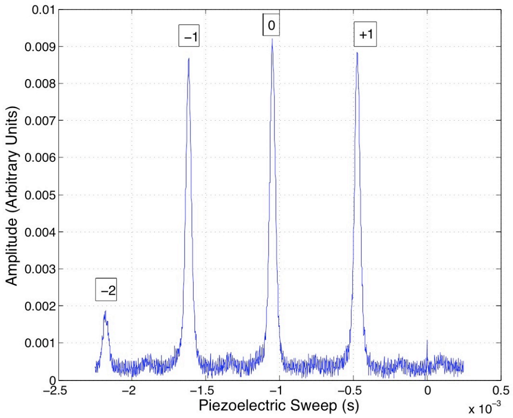

Figure 12: Modulation of the Roithner VCSEL at 6.8 GHz and 14 dBm of power.

there was incentive to increase the laser's current (more modulation power), the temperature had to be lowered to keep the laser on resonance. After finding the resonances at higher current and lower temperature, figures 15 and 16 were taken. Figure 15 is the pure vapor cell in the shields, and figure 16 is the mixed vapor cell in the DAVLL system.

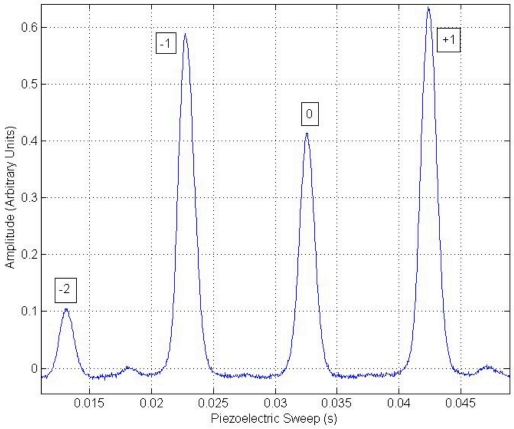

Figure 13: Modulation with the Stellex with maximum input power.

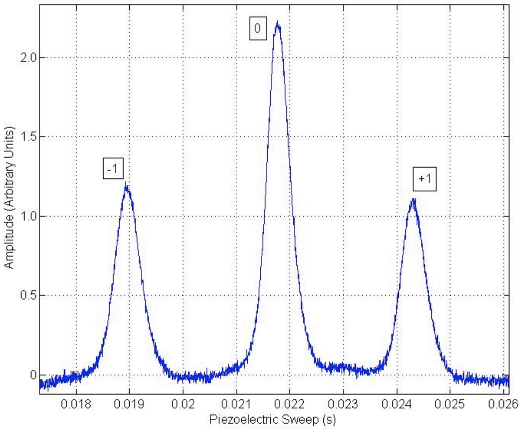

Figure 14: Modulation with the Stellex with decreased input power.

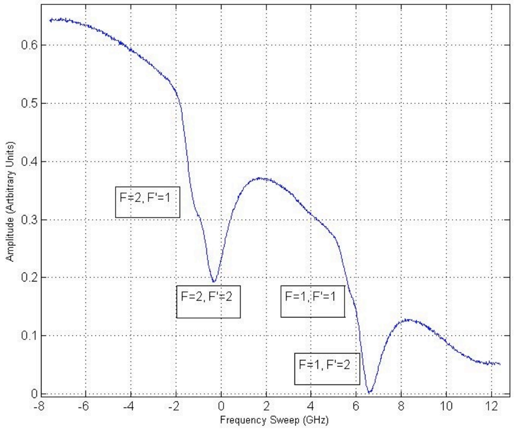

Figure 15: Rubidium resonances seen in a pure rubidium-87 cell.

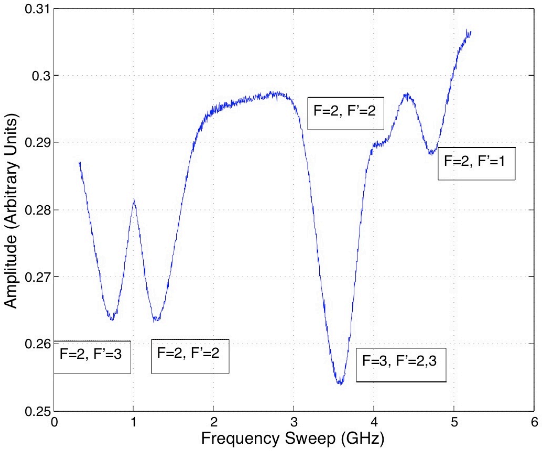

Figure 16: Rubidium resonances seen in a mixed rubidium-85 and -87 cell.

4.2 DAVLL Locking

The DAVLL is an important part in the creation of a prototype atomic clock, so to have the system working properly is ideal. The group has had some issues with the electronic part of the locking system, but it works mostly as it should. There are two inputs to the electronics (Raw and Aux), and four potentiometers (pre, post, cap and no cap) that contol feedback to operational amplifiers. The Raw input is the raw signal from the optical part of the DAVLL, and the Aux input is signal from an external function generator. These two signals are on very different voltage scales; Raw about 100 mV and Aux variable from 100 mV to 20 V. When the system was first tested, there seemed to be proper locking in a specific rubidium resonance, as seen by resonances in a Fabry-Perot cavity and the DAVLL error signal on an oscilloscope. But, to understand which rubidium resonance the laser was locking required the voltages of the Raw and Aux to be roughly the same. The Aux signal amplitude is controlled by the post potentiometer and the ratio of a resistor to the post potentiometer, and the amplitude of the function generator should range from approximately 1/4 of maximum amplitude to about 3/4 of maximum amplitude. After changing the values of the resistor (0 to 10kΩ) and the post potentiometer (10 kΩ to 30 kΩ), this allowed varying the signal strength of the function generator in the desired range. These changes set the signal amplitude of the Raw and Aux signals to be on the same voltage scale, and give a better understanding of which rubidium resonance the signal locked on.

The other issue the group has with the DAVLL electronics is an offset in the error signal. When the laser is locked on a rubidium resonance, the error signal should fluctuate around the zero point. The fluctuation up or down causes the electronics to increase or decrease the laser's current, matching the laser's frequency with the rubidium resonance frequency. But, this offset in the error signal causes the laser to have tension between the error signal and the correction signal (output signal to the laser). The correction signal should have small continual fluctuations around the zero point also, but the offset in the error signal drives the correction signal to fluctuate around a non-zero point. This causes us to question whether the laser is locked on resonance or if the two signals are not physically representative of the locking. Also, the circuit design may be too dependent on the proportional part of the circuit, with not enough emphasis on the integral part. This could be the cause of the error signal offset, and increasing the integral part of the circuit could with the error signal offset.

4.3 EIT

As discussed in the theory section, EIT occurs when all of the electrons are driven to a dark state that does not interact with either electromagnetic field, causing the laser to have near 100 percent transmission. The Ulm VCSEL and pure rubidium-87 cell were used to achieve EIT, and can be seen in figure 17. Figure 17 shows a single EIT peak (blue signal), while the green signal is the single peak Zeeman split into three peaks. To see this effect, an external magnetic field was applied to the vapor cell, causing the ground state to split into three levels. This split corresponds to the three peaks.

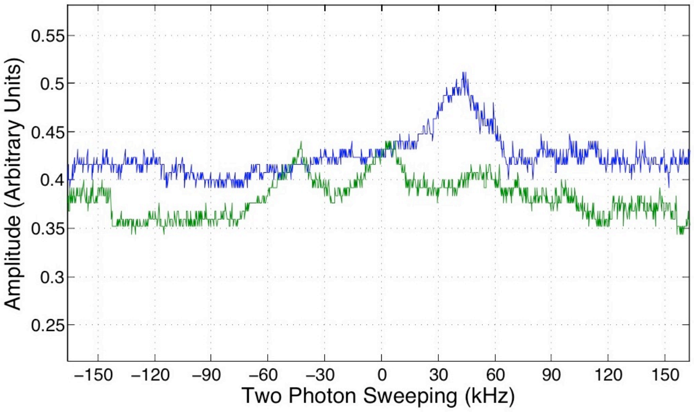

Figure 17: EIT and triple EIT as seen with Ulm VCSEL and pure rubidium-87 cell.

5 Conclusion

While the work discussed in this paper has been productive in working toward a prototype atomic clock, much must still be done. The Stellex Mini-YIG oscillator must be calibrated to understand the relationship between input current and frequency shift, and constant current source to the Stellex fabricated. True DAVLL locking on a rubidium resonance must be established, so we can understand the frequency the clock at which the clock operates. A counter must be added to the system to set a basis for time, so that the system will truly become a prototype atomic clock. Much work has been done on this prototype atomic clock, but as usual, there is much work still do be done.

6 Acknowledgements

I would like to thank Euginiy Mikhailov for his electronic help, Nate Philips for answering general lab questions, and Chris Carlin for his great work on the DAVLL system.

7 Bibliography

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