

**Construction of a Tunable External  
Cavity Diode Laser and a Far Off-  
Resonant Optical Dipole Trap for  
Ultracold Atoms**

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## Introduction:

This summer, I have been working in the research group of Carl Wieman at the University of Colorado, Boulder. Graduate student Scott Papp has directly observed my work. During my time at CU, I have been working on two different projects. First, I constructed an external cavity diode laser. After completing this, I then began assembling an optical trap. Each of these projects will contribute to the group's research of Bose-Einstein Condensates.

## Motivation for my projects:

The laser that I built will be used for Bragg spectroscopy. Bragg spectroscopy is used to have a greater understanding of Bose-Einstein Condensates. By exposing the condensates to two off-resonant laser beams with a frequency difference  $\omega$ , a moving interference pattern from which atoms can scatter is formed. This occurs only when the Bragg condition is fulfilled (energy and momentum are conserved). The Bragg scattering process can be thought of as the absorption of a photon from one laser beam and stimulated scattering into the second laser beam. Bragg spectroscopy can be used to measure properties of the Bose-Einstein Condensates [1].

External cavity diode lasers have many advantages. They tend to be cheaper and easier to build than other types of lasers. Also, it is easy to tune the laser to a specific frequency, which, in our case, is the frequency for the transitions of Rubidium 87.

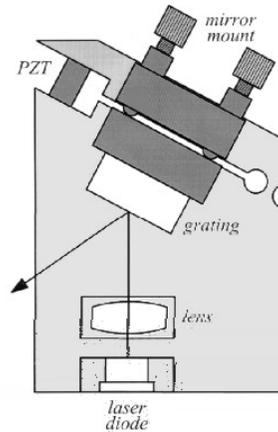
The second project that I worked on was constructing an optical trap. The oscillating electric field of a laser in an optic trap induces an oscillating atomic electric dipole moment. A potential is produced that corresponds to the intensity of the laser beam. If the laser frequency is tuned below the atomic resonance, the atoms are attracted to the most intense regions of the beam. Alternatively, if the laser frequency is tuned above the atomic resonance, the atoms are attracted to the regions of least intensity [2]. In our case, we use a laser tuned to a frequency lower than the atomic resonance causing the atoms to seek the highest beam intensity.

Currently, the research group is investigating Bose-Einstein Condensates of the Rubidium 85 and Rubidium 87 isotopes. Previously, Rubidium 87 has been studied, but Rubidium 85 has some important differences. In order to cool Rubidium 85 to the needed level, we use a mixture of the 85 and 87 isotopes. Rubidium 87 is then used to sympathetically cool Rubidium 85. However, the optical trap that is being used in the experimental setup at the present time is too strongly confining, which causes many collisions between the Rubidium 85 and Rubidium 87 atoms. Therefore, we need an optical trap that is bigger and, consequently, weaker. The optical trap that I began assembling will be large enough for the Rubidium 85 atoms.

#### External Cavity Diode Laser:

An external cavity diode laser consists of a “box” that houses the laser diode. This box contains a laser diode holder and a main block. Within the main block is a cavity. A diffraction grating is on the side of the cavity opposite of the laser diode. The

diffraction grating refracts the beam out of the laser. Figure 1 gives provides an illustration for such a box.



*Figure 1*

Laser "box" layout

There are many steps in constructing a laser. The first of these was to solder connections in the laser box. These connections included cables for the temperature control and current control.

Next, I had to optimize the temperature control feedback. Two pieces of the external laser cavity are independently controlled: the laser diode holder and the main cavity block. To stabilize the temperature, I used a temperature control that consists of a thermistor, a servo, and a thermoelectric cooler (TEC). The thermistor gathers the information about the temperature that the laser is at. It sends the information to the

servo, which accordingly adjusts the amount of current that is sent to the TEC. The TEC is then what cools the laser.

After setting the temperature controls, the next step in building the laser was to setup the laser diode. I first inserted the laser diode into the holder. Then, I put the diffraction grating in the laser cavity. The diffraction grating was mounted such that a Piezoelectric Transducer (PZT) could vary the size of the cavity. This variation in the size caused the frequency of the laser to be modified. When adding the diffraction grating, I had to make sure that the beam from the diode was hitting the grating such that the entire beam was landing on the grating and that it was also centered on the grating. In addition, the beam had to exit the laser box through the glass portion.

Next, the beam from the laser diode had to be collimated. In order to collimate a beam, the point source has to be at the focus of the lens. Therefore, if the beam is focusing, the lens needs to be moved closer to the source. On the other hand, if the beam is diverging, the lens needs to be moved away from the source. The holder for the laser diode had a lens at one end. That was the lens that was adjusted to collimate the beam.

Then, the feedback of the beam had to be aligned. The “ghost beam” (a reflection off of the front facet of the diode) needed to be reflected back into the diode causing additional lasing. When the ghost beam was overlapping the original beam and reflecting back into the diode, I was able to notice a significant increase in the power of the laser. To have the diode aligned to the highest extent, I adjusted the positioning of the grating until the power of the laser was maximized. This is all done slightly below the threshold current (discussed below).



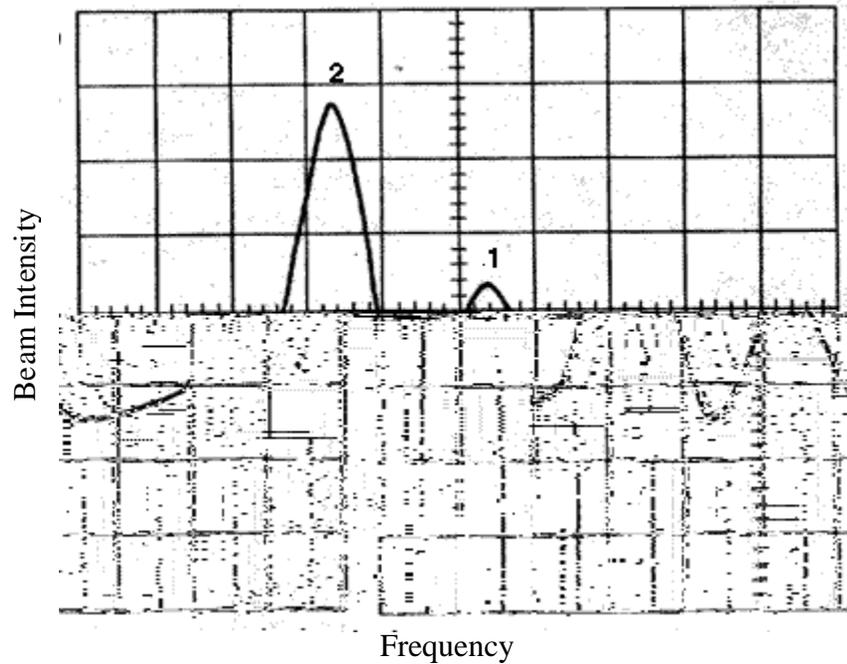


Figure 3

Doppler broadened Rubidium spectrum: Peak 2 is due to Rubidium 85

Peak 1 is due to Rubidium 87

One horizontal division=534 MHz

Frequency increases to the left

Source: see Reference 3

However, looking at this signal, you can see that the absorption lines are broad and overlap. This is because of the fact that the atoms are moving due to being at room temperature. The Doppler effect of these moving atoms therefore causes different atoms to absorb photons at different frequencies. Atoms moving towards the laser will absorb photons at a frequency that, when measured in the lab frame of reference, is lower than their actual resonant frequency. On the other hand, atoms moving away from the laser will absorb at a frequency that is higher than their actual resonant frequency. In order to remove this Doppler effect, I needed to use saturated absorption spectroscopy.

When using saturated absorption, there are three beams passing through the cell of vapor: two probe beams and one pump beam. Each probe beams passes through the cell landing on its own photodiode detector. However, one of the probe beams is overlapped by the pump beam, which propagates in the opposite direction. Figure 4 shows a possible layout for saturated absorption.

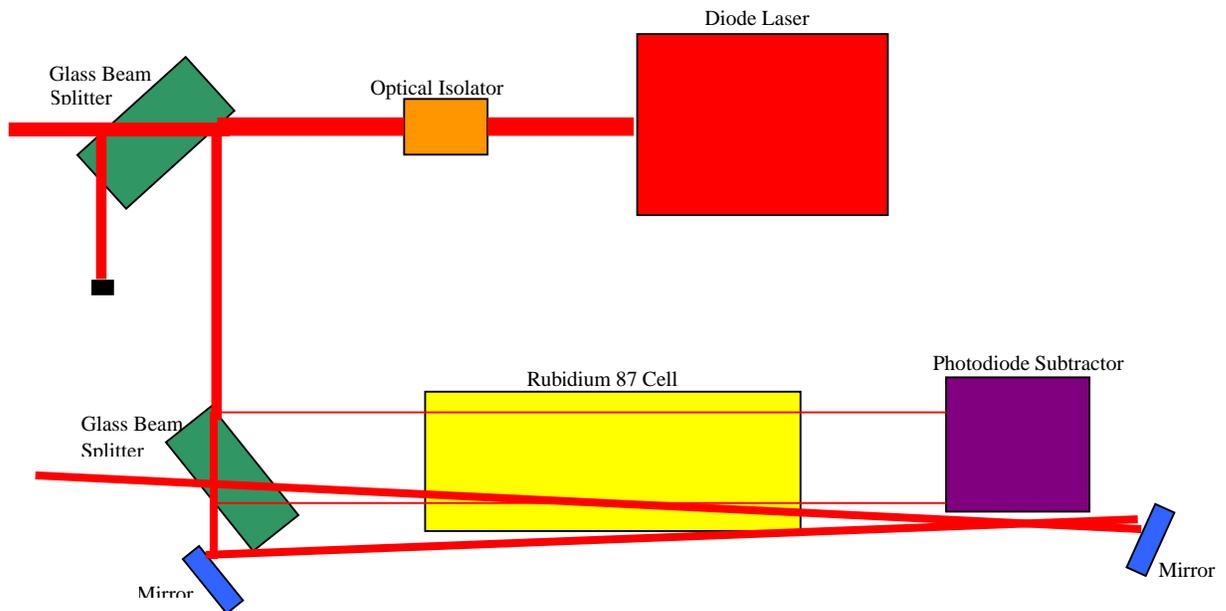


Figure 4

Saturated absorption layout

Two beams passing through cell to photodiodes are “probe” beams

Beam reflected back through cell is “pump” beam

“Photodiode Subtractor” takes the difference of the two probe beam signals

But how does saturated absorption work? The pump beam is strong enough to excite all the atoms that are in resonance with the transition, “saturating” the transition by removing all the atoms from the transition state. First, consider the case of the atoms that are at rest. For them, there is no Doppler shift, and the depletion of a state occurs when the laser frequency exactly matches the frequency of the transition. The probe beam coming in the opposite direction at this frequency would normally be absorbed by the resonant transition, but because the pump beam already depleted the state, this absorption is removed, and the intensity of the light hitting the photodiode increases.

For any atoms moving so that they are Doppler shifted to be in resonance, the pump beam would still deplete the state. However, since the probe beam is going the other way, they are Doppler shifted in the opposite direction, so they are not affected by the probe beam. Therefore, the depletion has no effect on the absorption of the probe beam except for those atoms that are at rest. The resultant signal for the probe beam overlapped by the pump beam is the same as that shown in Figure 3, except for the “dips” where the atoms with zero velocity would be. Figure 5 shows the signal from the probe that is overlapped by the pump beam.

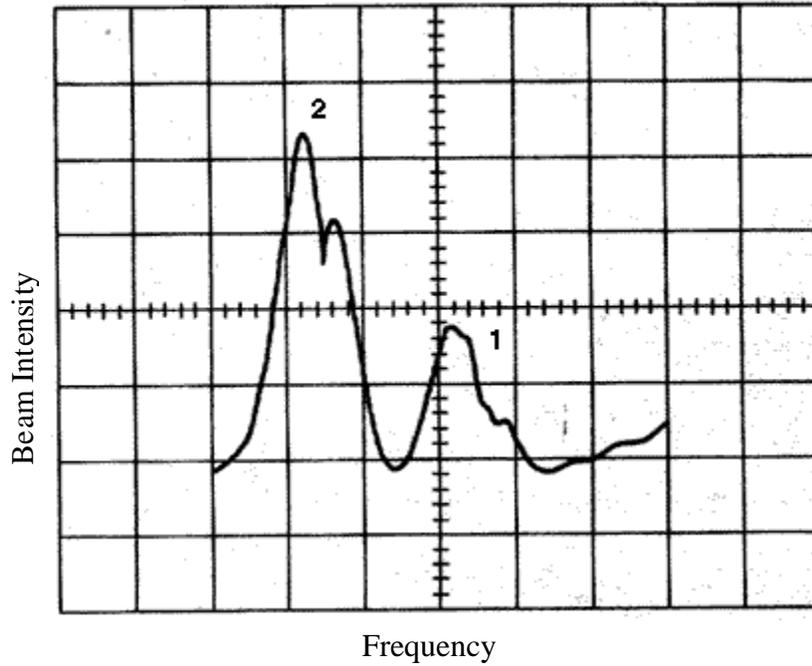


Figure 5

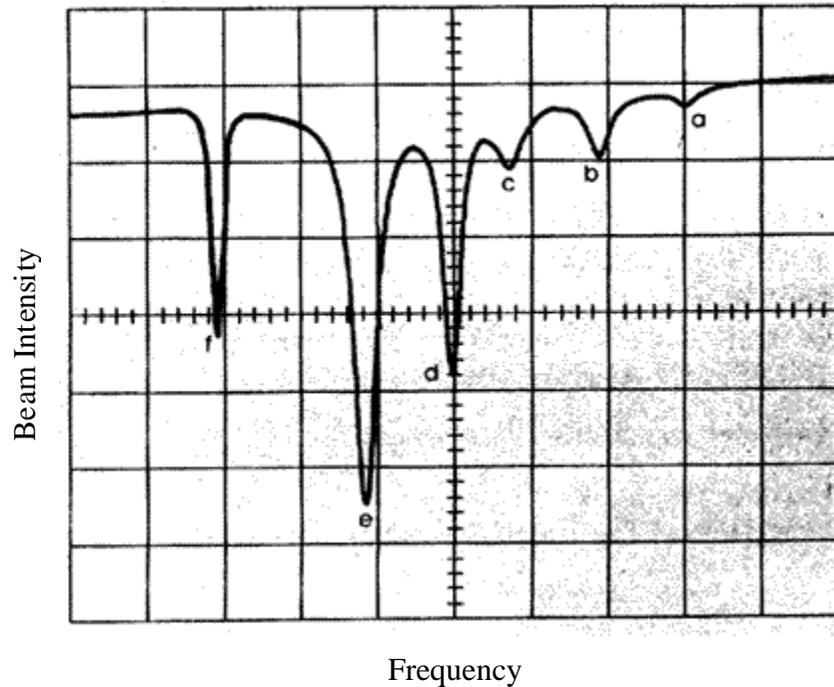
Doppler broadened spectrum with “dips”

One horizontal division=534 MHz

Frequency increases to the left

Source: see Reference 3

By taking the difference of the absorption of the two probe beams (one being affected by the pump beam and the other not), only the saturated absorption features remain in the spectrum, with high resolution since the effect has now pre-selected the atoms at rest and eliminated the Doppler broadening [4]. Figure 6 shows a saturated absorption signal.



*Figure 6*  
Saturated absorption lines in higher resolution  
One horizontal division=69 MHz  
Frequency increases to the left

Figure 6 shows Peak 1 of the spectra above (Figure 3) in higher resolution

Source: see Reference 3

The absorption lines show the hyperfine splitting of the upper  $5^2P_{3/2}$  states. Peak “a” corresponds to the transition of  $F=2$  to  $F'=1$ . Peak “c” corresponds to the transition of  $F=2$  to  $F'=2$ , and peak “f” corresponds to the transition of  $F=2$  to  $F'=3$ .

However, it is obvious that there are three extra signals: peaks “b”, “d”, and “e”. These absorption lines are known as “crossover” peaks. Crossover peaks occur because the Doppler shift allows certain moving atoms to be in resonance with both the pump beam and the probe beam. At a frequency half way between transitions, those atoms which are moving toward the pump beam so as to be in resonance with the lower

frequency are also moving away from the probe beam and are Doppler shifted to the higher frequency (and vice-versa). Therefore, the probed atoms are again depleted from the initial state.

I can now compare the signal of Figure 6 with the known transitions of Rubidium 87. It is possible to know the frequency between each of the transition peaks. Figure 7 gives the transitions of Rubidium 87 for the  $5^2S_{1/2}$  state to the  $5^2P_{3/2}$  state.

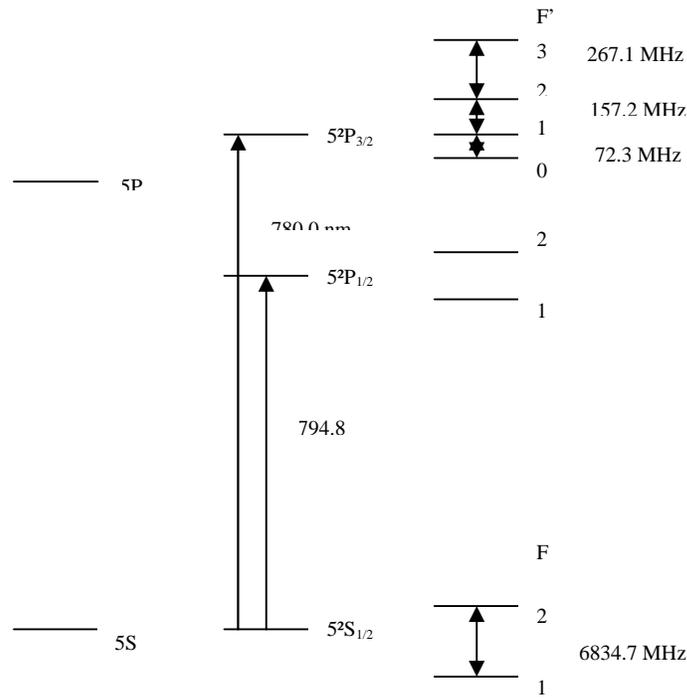


Figure 7

Energy levels and hyperfine levels for Rubidium 87

Energy level spacings are not to scale

Source: see Reference 5

Looking at Figure 6 and comparing it to Figure 7, the frequency between peaks “a” and “c” is 157.2 MHz. The frequency between peaks “c” and “f” is 267.1 MHz. It is also possible to calculate the frequency between the crossover peaks by remembering that they occur at the halfway point between any two transitions.

When the laser is set at the transition of Rubidium 87, it is operating at a wavelength of 780 nm. This frequency corresponds to the transition between  $5^2S_{1/2}$  and  $5^2P_{3/2}$  states. For the laser I constructed, this frequency requires a current of about 90.6 mA.

After the external cavity diode laser was constructed, the only thing that needed to be done was to set the lock-in amplifier. The lock-in ensures that the laser stays at a constant frequency, specifically, the frequency of the transition of the atoms. With the laser now locked, I was able to calculate the frequency noise of the laser by measuring how much the locked signal varied. I found the frequency noise of the laser to be about 10 kHz.

### Optical Trap:

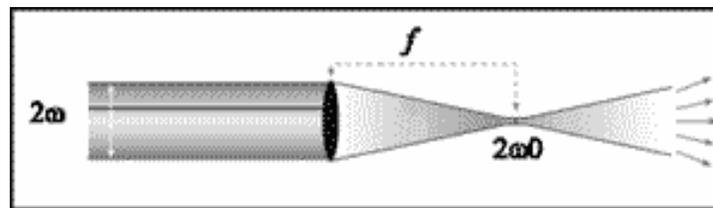
The first thing that I did to construct the optical trap was to collimate the beam from the optical fiber. The process that I used to do this was similar to that described earlier with the laser diode. However, this time the lens used to collimate the beam was separate from the source and therefore required slightly more adjusting.

After the beam was collimated, I used a Charge-Coupled Device (CCD) camera to view the beam. The program that ran the CCD camera gave me measurements of the

size of the beam. If I then focused the beam, I was able to calculate the expected value for the focused beam's waist size by using the equation

$$w_0 = wf / \lambda \quad [6]$$

where " $w_0$ " is the waist size of the beam, " $w$ " is the size of the beam when it enters the lens, " $f$ " is the focal length of the lens, and " $\lambda$ " is the wavelength of the laser. Figure 8 provides an illustration of this equation.



*Figure 8*

Illustration of collimated beam with radius " $w$ " being focused to a beam waist of " $w_0$ " by a lens with focal length  $f$

I then checked this calculated value with the measured value. I was able to look at the size of the beam close to the focus by slightly moving the position of the CCD camera with respect to the lens. The CCD camera's program enabled me to measure the size of the beam at different distances. Figure 9 shows an example of such data close to the beam waist.

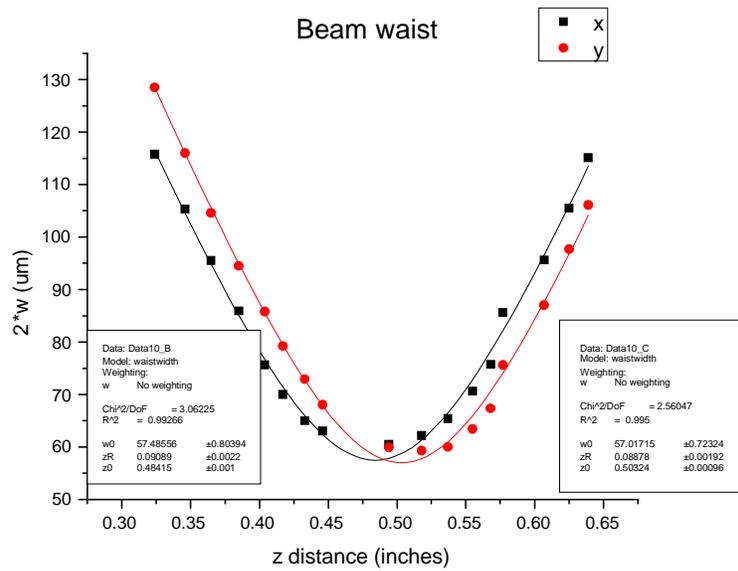


Figure 9

Waist beam using lens of focal length=20 cm

and beam with wavelength=1064 nm

Black curve represents diameter of beam in x direction

Red curve represents diameter of beam in y direction

From this graph, it is possible to see that the beam is focusing at different places in the x and y directions. This is referred to as astigmatism in the focusing of the beams. For the Figure 9, the astigmatism in the focused beam is about 485  $\mu\text{m}$ . The astigmatism in the optical trap could be due to a number of different things. One possible cause is if one of the lenses was not centered with respect to the beam. Also, if one of the lenses was not parallel to the beam, it could result in astigmatism.

## Conclusion:

For the project of assembling an external cavity diode laser, I first stabilized the temperature control. Next, I collimated and aligned the beam. The laser then had to be set up in a saturated absorption layout. I was able to successfully tune the laser to the resonant frequency of Rubidium 87. The frequency noise of the laser is considerably low, which is a good characteristic. This laser should satisfactorily meet the requirements to perform Bragg Spectroscopy.

When building the optical trap, there were a couple of problems that I came across. The first was that the measured waist beam was smaller than the calculated value. Second, there was a fairly large astigmatism. Both of these could be due to a variety of different things such as the beam not passing through the center of one of the lenses or the lenses not being parallel. As more optics are added to the optical trap, these issues could be minimized.

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