Photoassociative Spectroscopy of Strontium Along the $^1S_0$-$^3P_1$ Transition using a Littman/Metcalf Laser

By

Andrew Traverso

Advisor:

T.C. Killian

Abstract

We present the design and implementation of an extended cavity diode laser (ECDL) system for use in photoassociation spectroscopy of the $^1S_0$-$^3P_1$ transition in atomic strontium. By driving this transition we will be able to tune to the least bound vibrational level of the strontium dimer, which gives us the greatest control of the scattering length. Controlling the scattering length will facilitate our pursuit of Bose-Einstein Condensation.

I. Introduction

A. Atomic Cooling and Trapping Overview

In general, atomic cooling and trapping is accomplished via a system of three pairs of orthogonal counter-propagating lasers and an inhomogeneous magnetic field. The counter-propagating lasers are red-detuned from an atomic transition so that if the atom is moving against the flow of the beam, the frequency of the laser is Doppler-shifted and thus driving the atomic transition. By doing so, the laser imparts a force on the atom lessening it’s momentum in the direction of beam propagation. Thus the lasers act as a velocity dependent force that lessens the average momentum of all atoms in the chamber.

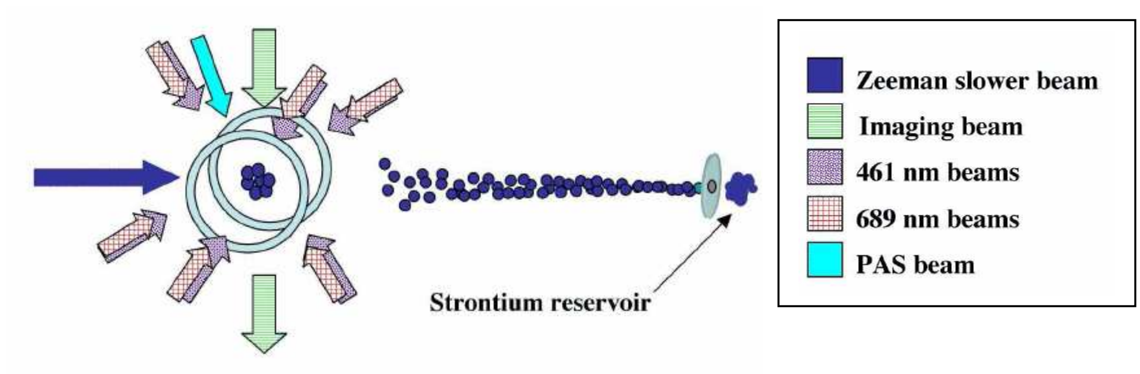

Fig. 1:

Unfortunately, this does not actually trap the atoms since there is no position-dependent force, but merely achieves what is called “optical molasses”. To achieve actual trapping of the atoms, an in-homogeneous magnetic field is placed around the chamber such that the magnetic field is equal to zero at the center of the trap. The magnetic field induces energy level splitting within the atoms due to the Zeeman Effect which in turn shifts the frequency of light that they absorb between certain transitions. This shift is entirely dependent upon the strength of the magnetic field. Thus as an atom moves from the center of the chamber (where the magnetic field is zero), the field increases, which in turn changes the transition bringing it more in resonance with the lasers. By this method the force on the atoms due to the lasers increases as they move farther away from the center of the chamber thus creating the trap.

B. Photoassociation

Photoassociation is the process by which free ultra cold atoms form a bound molecular state when exposed to a photon. In this case, two free strontium atoms form a bound molecular state when exposed to a photon detuned from 688 nm to one of the bound state resonances. Through photoassociation one can determine the S-wave scattering length of the atoms as well as all of the bound molecular states. All atomic interaction is governed by C_n/R^n forces where at large distances the interaction is governed by R^6 which is the Van Der Waals force while at closer distances the potential is described by the R^3 term, a dipole moment. Once the metastable molecule is formed, it can decay either by radiative escape or via state-changes. In radiative escape, the molecule breaks apart at a smaller internuclear separation than it had first formed at. By dissociating at smaller separation, each atom has a high kinetic energy, which ejects them out of the trap. When the molecule undergoes state-changes, it transitions down to lower bound energy levels of the ground state molecule.

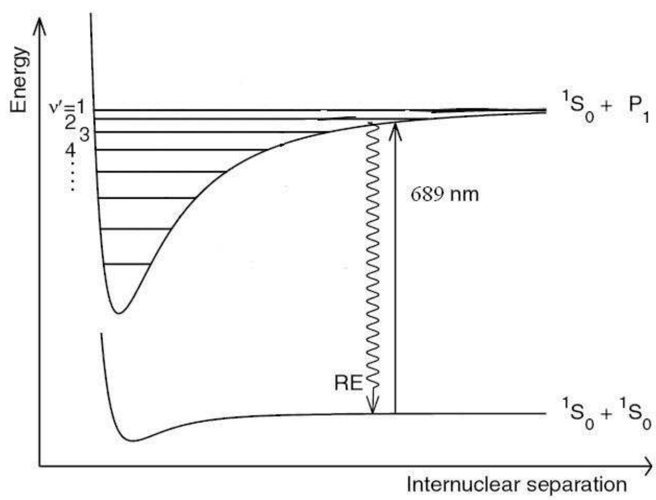

Fig. 2:

C. Purposes for Photoassociation

The immediate goal for this line of experimentation is to not only confirm previous found bound states of the photoassociative molecule, but also scan through the full frequency range and detect new ones. Knowing the different energy levels of the diamer help characterize such parameters of the experiment like the ground state potential and the strength of the atomic interaction.

Our end goal for the PAS laser is to manipulate the S-wave scattering length of ^{88}Sr so that BEC can be achieved. This is accomplished by inducing a bound molecular state which changes the wavefunction and thus the scattering length of the strontium. As is evident from the equations, the scattering length, *a*, is dependent primarily upon the one-body loss rates as well as the detuning from resonance. Strontium 88 is a much better choice for manipulating its scattering length, since its a_{bg} is much smaller than ^{86}Sr.

$$a = a_{\rm bg} + \frac{1}{2k_i}\ \frac{\Gamma_{\rm stim}\ \Delta}{\Delta^2 + (\Gamma_{\rm spon}/2)^2}$$

$$K_{\rm inel} = \frac{2\pi\hbar}{m}\ \frac{1}{k_i}\ \frac{\Gamma_{\rm stim}\ \Gamma_{\rm spon}}{\Delta^2 + (\Gamma_{\rm spon}/2)^2}$$

- Γ = One body loss rates
- Δ = Detuning
- a_{bg}= scattering length without light
- m = atomic mass

II. <u>Experimental Setup</u>

A. Extended Cavity Diode Lasers

For the purposes of the experiment, a single longitudinal mode laser with a wide range of tuning is desired. In this case, a diode laser is the best option since they are made at a wide variety of wavelengths, provide enough power, and are relatively cheap due to their wide commercialization. The wavelength that a diode lasers outputs is determined by the type of semiconductor material and structure. However, the output wavelength can be manipulated since the diode is sensitive to changes in both current and temperature. Unfortunately, these two features only provide a limited amount of tuning and do not provide a narrower linewidth. Thus to accomplish a better range of tuning and a narrower laser linewidth, an extended cavity must be implemented.

All extended cavity diode lasers (ECDLs) have three features in common that determines which wavelength is selected. These are the gain curve of the laser diode, the cavity length, and the optical feedback. Having already discussed the laser diode, it suffices to say that gain curve of the laser diode is the most static feature that can only be changed drastically by changing the diode. What is important to remember is that the laser cannot tune to a wavelength that does not fall within the range of the gain curve.

The ECDL takes advantage of the principle of optical feedback where any wavelength that is sent straight back into the diode causes all subsequent light emitted by the diode to be at the same wavelength as the light that was used as feedback (i.e. stimulated emission). So, the ECDL's only task is to select a wavelength from the light initially emitted from the diode and send it back into the diode as feedback. The selected wavelength defines the feature of optical feedback.

Similarly, the total optical distance that the feedback travels from emission to reentry into the diode defines the cavity length. This is a significant feature because only wavelengths that can fit an integer number of times will constructively interfere. Thus, this feature can be tuned by varying the length of the cavity which changes the wavelengths that will constructively interfere within it.

The product of these three features determines the output frequency of the laser as is evident in Fig. 3. The point where the product is maximized will be the output frequency of the laser. It should also be noted that the product will also have a much narrower gain curve than the laser diode's and thus supply more power only at the desired frequency. Of the three, the optical feedback holds primary importance since it offers the widest range of tuning.

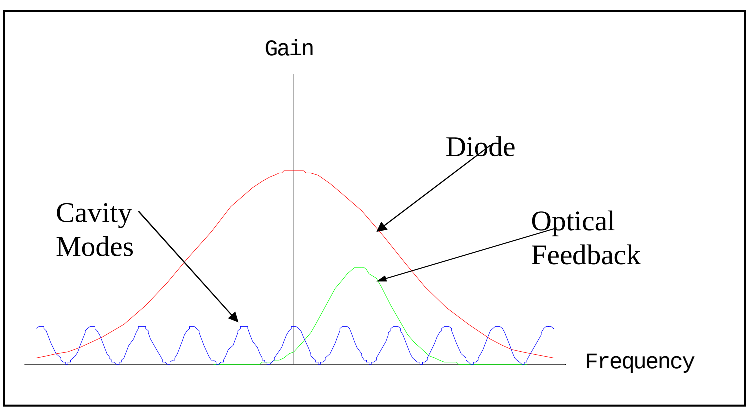

Fig. 3:

B. General Overview of the Littman/Metcalf Extended Cavity Laser

For the purposes of PAS, we chose to design a Littman/ Metcalf extended cavity diode laser. The LM cavity holds many advantages including a longer cavity length, a narrower linewidth and higher stability from the twice diffracted feedback, less sensitivity to changes in current, and a static output beam path.

In concept, the LM cavity is very simple. The main components are merely a laser diode, collimating lens, diffraction grating, and a plane mirror. These components are oriented according to Fig. 4.

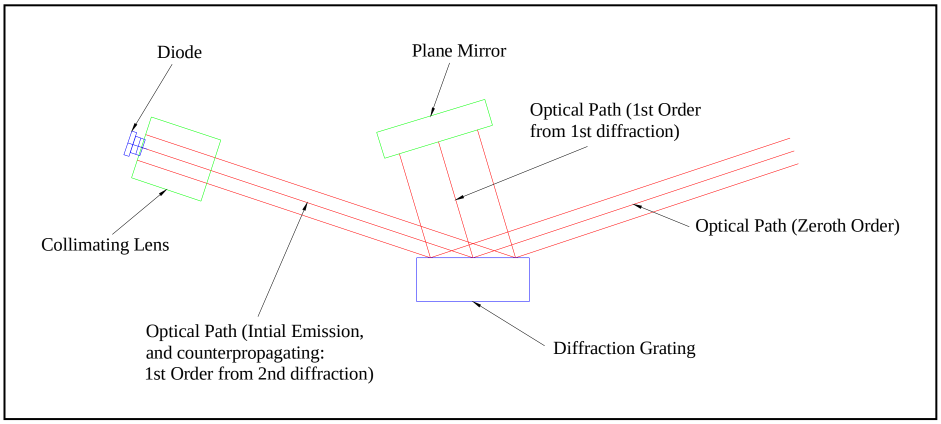

Fig. 4: General Configuration of a Littman Metcalf Laser

The laser diode emits a spray of coherent light which is first collimated before it is incident with the diffraction grating. After the incident beam is diffracted, the first order maximum of the diffracted beam is retroreflected by the plane mirror back onto diffraction grating. Here, the retroreflected beam is again diffracted and its first order diffraction is sent back onto the diode as feedback. At this point, the diode should begin to emit photons only at the wavelength of the feedback.

At this point optical feedback is achieved and now it is possible to tune the laser to the desired frequency. At the diffraction grating, the specific frequency of feedback can be selected, since different frequencies will diffract off of the grating at slightly different angles. The LM can choose which frequency to send as feedback by changing the angle of the plane mirror relative to the diffraction grating.

Most LM cavities are designed so that the cavity length modes and the frequency of the optical feedback are adjusted simultaneously by moving the mirror. This is accomplished by rotating the mirror around the point where the plane of the grating intersects the perceived optical path emission plane from the diode. This arrangement allows for changing the cavity length and sweeping through different frequencies diffracted by the grating simultaneously and ideally maintain the optical feedback peaks in line with one of the cavity length modes. The next section will address the design concerns and specifications of the specific LM cavity built for the experiment.

C. Design Specifications for the Littman/Metcalf Diode Laser

The driving thought for the design of this laser was to make all the components as small and as robust as possible while allowing for a wide range of control for many parameters.

The first step in the design is to choose the length of cavity and the wavelength region that the laser needs to tune through. These two pieces of information are all that is needed to specify a general configuration of all the optical components, as seen in Fig. 4. In this case a cavity length of approx. 13 cm was chosen for higher stability and given that the laser was intended for for use in either PAS or the Red MOT, it was centered at 689 nm.

At this point, despite having a very fundamental design for the laser, it becomes necessary to start addressing the more practical concerns of how each component is going to be held firmly in place so as to minimize any environmental disturbances and yet still allow for controlled tuning of the component. Thus each was made either out of brass, copper, or aluminum and made as large as the space constraints would allow to achieve the stability desired. A schematic of the design can be seen in Fig. 5.

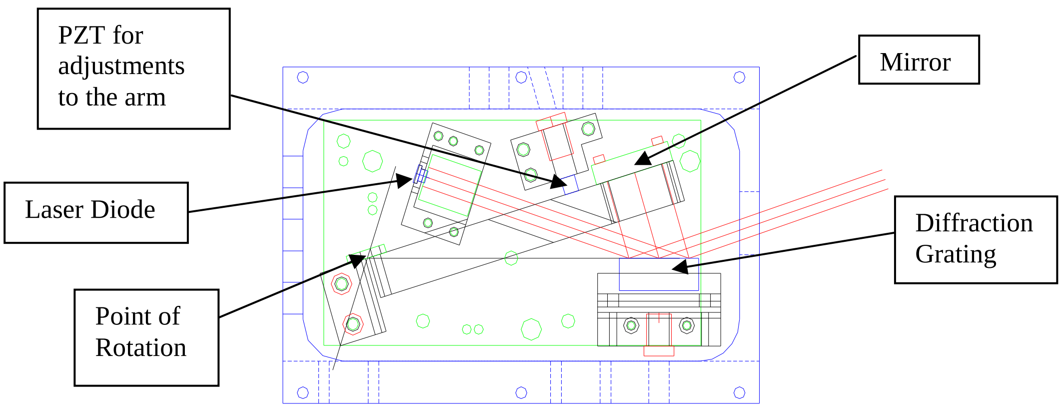

Fig. 5: Schematic of the Extended Cavity with all mechanical components.

In particular the mounts for the mirror and the diffraction grating provide the tuning necessary for achieving optical feedback. In the case of the mirror, it is attached to an aluminum beam that can be pivoted around the desired point of rotation as discussed earlier for LM lasers. It is rotated by pushing it with a fine adjustment screw, or by pushing it with a Piezoelectric Transducer (PZT) for finer adjustments. This allows for control of the optical feedback in the x-y plane. On the other hand, the diffraction grating mount controls the vertical component of the optical feedback and can be adjusted using both a fine adjustment screw and a PZT.

With mechanical control established, the last two major parameters for controlling the laser are the laser diode's temperature and the current supplied to it. For the case of the temperature, thermoelectric coolers (TECs) were added. One was placed beneath the diode mount itself to finely control the temperature of the diode, while two more were placed under the brass plate that holds the entire system, to provide further stability and temperature control of all components. As for the controlling the current, a prefabricated circuit accomplishes this task. Both of these factors need to be controlled since they affect the gain curve of the diode and in fact are used as other parameters to help tune the Extended Cavity.

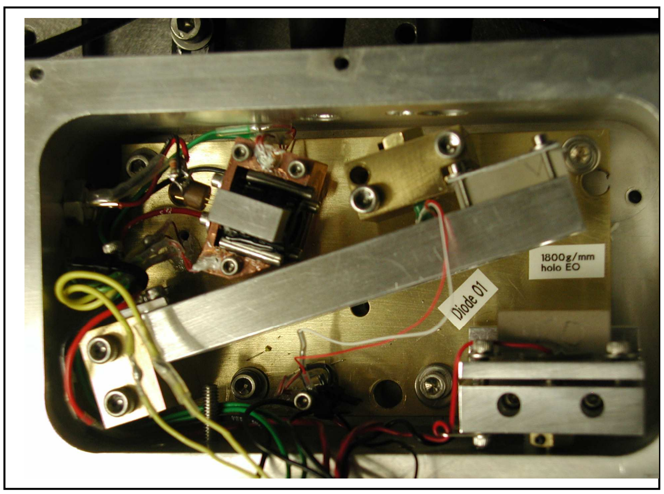

Fig. 6: Picture of the Littman-Metcalf Extended Cavity.

D. Collimating the laser

The first optical alignment process is the collimation of the laser diode. For a beam to be properly collimated the laser diode's point of emission should ideally be placed at the focal length of the collimating lens. In our case a temporary holding mount had to be fabricated to hold the collimating lens at the correct position until it was permanently sealed in place using dental glue (heliobond).

The beam profile should be as symmetric and uniform as possible. Ideally, there should be a very bright, symmetric circle/oval at the very center of the beam and the overall beam should also be circular to slightly elliptical. If there are any waists in the beam path (points where the beam is focused down), then the collimating lens is too far away from the emission plane. On the other hand, if the beam profile is just expanding along the beam path, then the collimating lens is too close.

E. Achieving Optical Feedback

Once all of the components are installed and the beam is properly collimated, optical feedback must be achieved. The first step is to find the actual feedback beam and ensure that it is in fact going back into the collimating lens using the tuning screws on the diffraction grating and the mirror to move it if necessary. Ideally, the feedback beam should be centered on the collimating lens as much as possible.

At this point there is definitely some sort of feedback getting back into the diode, but it is far from ideal. To improve the feedback, current supplied to the diode must be dropped to the diode’s threshold (i.e. it is just barely lasing). By adjusting the tuning screw for the diffraction grating and watching the beam profile, there will come a point when the beam profile has gotten brighter and is lasing more strongly. At this point the process is repeated, where the current is dropped down to the new threshold and further smaller adjustments are made to the diffraction grating tuning to achieve better and better feedback. For this process only a slight adjustment needs to be made to the tuning for the mirror to ensure that the beam is on a constructive cavity mode. All of the tuning to achieve optical feedback is accomplished by adjusting the diffraction grating. Once it is achieved there is no need to make any further adjustments to the diffraction grating since all wavelength tuning is accomplished by adjusting the mirror.

F. Tuning the Laser

At this point the laser is almost ready for experimentation and it is necessary to couple the laser to both a wavemeter and a Fabry-Perot cavity. These two tools provide useful information to characterize the beam. The wavemeter allows us to know what wavelength the laser is currently emitting at, while the Fabry-Perot cavity, when oscillating around a given cavity length, allows us to know if the laser is single mode. With these tools, it is possible to tune the laser to any wavelength within the gain curve of the laser diode.

There are actually 3 parameters that can be used to tune the laser to the desired wavelength: the temperature, the current, and the adjustment of the mirror. For the most part, most tuning will be accomplished through the adjustment of the mirror since it offers the greatest degree of control, but it is necessary to use the other two parameters on occasion to find ideal regions to lase at. For instance, at a specific temperature T, a given wavelength may not be within one of the nice single mode regions of the laser, but if the temperature is adjusted, that region has now changed and now with a slight amount of adjustment to the mirror, it is possible to find that wavelength in one of the single mode regions and lase at it.

For instance, if the laser needs to be at 689 nm, the fine screw for the mirror is adjusted so that the feedback is now roughly in that region. From here, the PZT is used as a finer adjustment to start scanning for the desired frequency. If the region that 689 nm exists at is not single mode, then adjustments need to be made to the temperature and/or the current to move one of the nice single mode regions towards 689 nm. At this point, further adjustments need to be made for the mirror to correctly find 689 nm in the new region. Below is a list of specifications for the laser designed and built for the experiment.

Laser Specifications

- Diode: Eudyna FLD6A2TK single mode centered at 690 nm
- Grating: 1800g/cm Holographic
- Threshold Current with Feedback: 18.72 mA
- MHF tuning range: 7 GHz
- Operating Current: ~50 mA
- Arm PZT Tuning: 0.23 V per 500 MHz
- Diode Current Tuning: 5 GHz per 1 mA

III. Preliminary Data

To test the functionality of the laser, it was tuned to 688 nm, the transition of Sr that all the future photoassociation experiments will be using. Then while its wavelength was being slightly oscillated around 688 nm it was sent through Sr atoms held in the red MOT. In principle, the laser should eject the Sr atoms out of the trap when on resonance. Fortunately, the datasets demonstrate that this actually occurred.

Three data sets were taken for various timescales and intensities. All three datasets show that there was a drop in the number of atoms in the trap as the laser was swept through the wavelengths centered on 688 nm. The first two sets, Fig. 7 and 8, both had an intensity of 4.5 μW but different timescales. Interestingly enough, it is evident that power broadening is occurring even at this low of intensity as the linewidth changes so drastically. The last data set, Fig. 9, was taken with the power attenuated to 0.15 μW. Again, the linewidth for this plot is almost an order of magnitude smaller than that of the first two sets.

All these results indicate that the laser is in fact on resonance with the 688 nm transition and easily has enough power to drive this transition. It will be quite useful in the experiments to come.

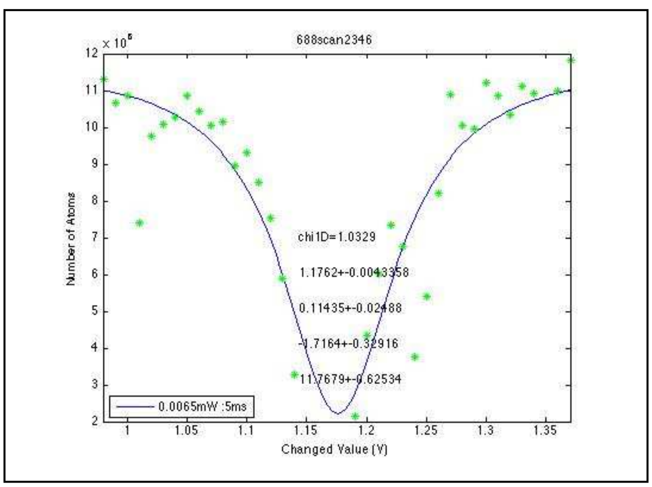

Fig. 7: 200 ms timescale, 4.5μW
Linewidth: 248.5 MHz

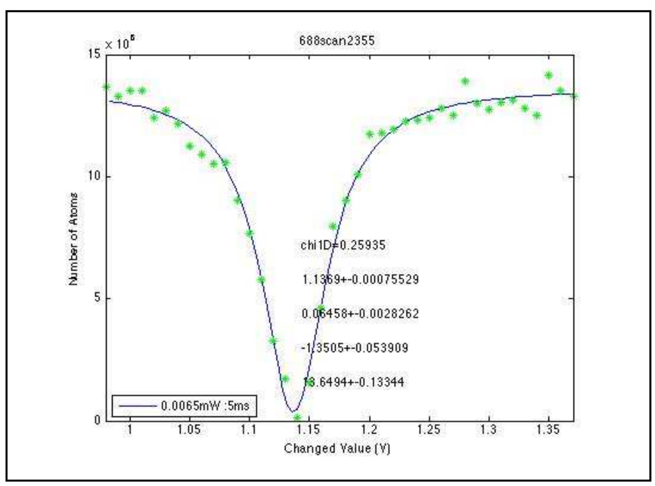

Fig. 7: 100 ms timescale, 4.5μW
Linewidth: 140.4 MHz

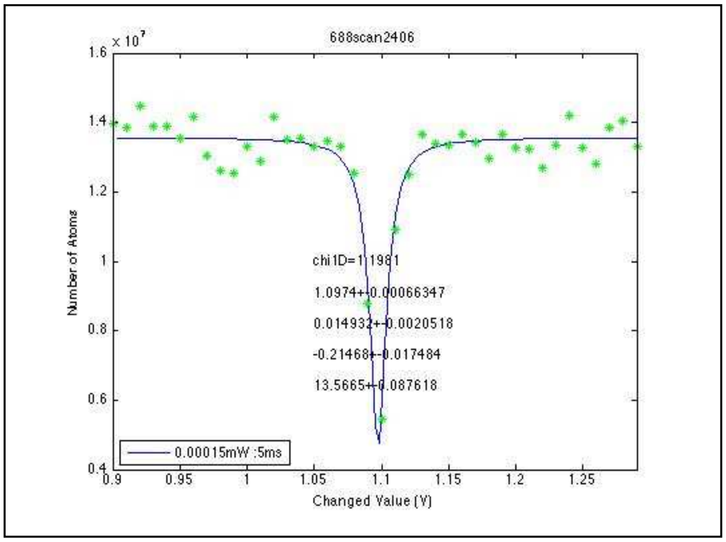

Fig. 9: 100 ms timescale, 0.15μW
Linewidth: 32.5 MHz

IV. <u>Conclusion</u>

This thesis presented the design, construction, and successful implementation of a Littman-Metcalf extended cavity diode laser for the purpose of photoassociation. It also examines many considerations for the purpose of this laser in the current experiment. This laser will be used in the far future for further experiments in photoassociation as well as aiding in the creation of a Bose-Einstein Condensate. It performs quite well, barring a diode burnout.

V. References

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