# Doppler-Free Saturated Absorption Spectroscopy of Rubidium
## Using a Tunable Diode Laser

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August 7, 2009

## Abstract

By performing Doppler-free saturated absorption spectroscopy using a tunable diode laser, we were able to observe the $^{87}$Rb transitions between the $5^2S_{1/2}$ and $5^2P_{3/2}$ P P = The tunable diode laser beam has been amplified using slave laser injection, and is now ready to be locked, seed a new tapered amplifier, and used as a source of light for a magneto-optical trap to cool and trap Rb atoms.

## Introduction and Theory

reliable sources of narrow-band light [1]. By using a diode laser with a high reflectivity coating on its back facet and a reduced reflectivity on the output facet, along with a diffraction grating with a higher reflectivity, the back of the diode laser chip and the grating will form the new laser cavity of a tunable diode laser.

The frequency of the tunable diode laser can then be changed by changing the cavity length. This is done in a controlled manner by changing the voltage applied to piezoelectric transducer disks (PZT), which move the grating in response to the applied voltage. However, since changing the cavity length changes the frequency of the laser, one has to be careful to avoid changes in cavity length due to thermal expansion or mechanical vibrations. This can be done by controlling the temperatures of the

baseplate and the diode laser using temperature controllers, enclosing the laser in an insulated metal box to avoid air currents, and mounting the cavity on rubber cushions to reduce the movement due to vibrations [1].

linewidth makes them particularly useful for high resolution spectroscopy. Recall, atomic spectral lines are due to transitions in an atom between energy levels. To make a transition to a higher level, an atom will absorb radiation at a frequency corresponding to the energy difference between those two energy levels. The decrease in radiation passing through the sample of atoms can then be detected, and an atomic absorption line can be observed on an oscilloscope.

Even though atoms can only absorb at specific frequencies, their spectral lines do have some width. One source of linewidth broadening is natural broadening. The natural linewidth can be determined using the Heisenberg uncertainty principle, as shown below in equation 1 [2].

$$\Delta v \geq \frac{1}{2\pi\tau}$$ (Eqn. 1)

where $\Delta v$ is the natural linewidth and $\tau$ is the lifetime of the excited state. Another source of linewidth broadening is Doppler broadening. This is due to the random thermal motion of individual atoms in the gas, which causes a Doppler shift in their absorbed radiation. The moving atoms will then absorb a range of different frequencies of radiation, and the spectral lines will be broadened. The full-width at half maximum amplitude $\Delta v_{\frac{1}{2}}$ of the Doppler-broadened line is given by the following equation [2].

$$\Delta v_{\frac{1}{2}} = \frac{2v_0}{c}\sqrt{\frac{2kT \ln 2}{M}}$$ (Eqn. 2)

where $v_0$ is the resonance frequency when the atom is at rest with respect to the source of radiation, M is the mass of the atom, and T is the temperature. For a low pressure gas at room temperature, Doppler broadening is the main source of linewidth broadening.

In the Bohr model of the atom, electrons orbit the positively-charged nucleus and can only occupy certain discrete energy levels. These orbits are specified by quantum numbers, and the higher the principle quantum number n, the larger the orbit and the higher the energy. However, these energy levels are then further split according to different interactions. A very small splitting of the energy levels, hyperfine structure, results from the interactions between the magnetic moments of the electron and nucleus. These interactions couple the electron angular momentum **J** and the nuclear angular momentum **I** to form the total angular momentum **F**. $\nu_{J,F}$ of the hyperfine levels of Rb are calculated using the following equation [2].

$$\nu_{J,F} = \nu_J + \frac{AC}{2} + \frac{B\left[\frac{3}{4}C(C+1) - I(I+1)J(J+1)\right]}{2I(2I-1)J(2J-1)}$$

(Eqn. 3)

where $\nu_J$ is the frequency corresponding to the energy of the $n^{2S+1}L_J$ state, I is the nuclear angular momentum quantum number, J is the electron total angular momentum quantum number, A and B are constants for a particular state, and C defined by the following equation

$$C = F(F+1) - J(J+1) - I(I+1)$$

(Eqn. 4)

where F is the total angular momentum quantum number, and I and J are the quantum numbers as noted above. For the $5^2P_{3/2}$ state of $^{87}$Rb, the accepted values for A and B are 84.85 MHz and 12.52 MHz respectively [2]. Using these values, along with equations 3 and 4, the difference in frequency between two particular hyperfine levels can be calculated.

Considering that the Doppler-broadened width of the 780 nm spectral line of Rb at 297 K is 513 MHz, and the frequency spacing between the F=1 and F=2 hyperfine levels of the $5^2P_{3/2}$ state of $^{87}$Rb is 157.2MHz, it is clear that Doppler-broadening obscures these hyperfine energy levels. To overcome

this Doppler broadening in order to observe hyperfine structure in Rb, one can use saturated absorption spectroscopy.

In this paper we describe how get the tunable diode laser system running, amplify the beam with slave laser injection, and use the tunable diode laser to perform Doppler-free saturated absorption spectroscopy on Rb. We also describe a method used to lock to the side of an absorption peak, but note that another method may be used later to lock the laser to the maximum, rather than the side, of an absorption peak. The laser will then be ready to seed a new tapered amplifier (NewFocus TA-7600 series). Once amplified, the laser will be used to make a better magneto-optical trap (MOT) to trap and cool Rb atoms used in experiments studying the cold collisions of these atoms with polar molecules.

**Experimental Apparatus**

Since the home-built tunable diode laser was constructed before I began the project, it will not be described it in great detail. In general, the tunable diode laser consisted of a Sanyo high power laser diode (DL-7140-201) and collimating lens mounted on a baseplate, along with a diffraction grating mounted to a mirror mount also attached to the baseplate. The system was enclosed in an aluminum box to isolate it from air currents. The diffraction grating was mounted in a Littrow configuration, such that the $1^{st}$ order diffracted light returned to the laser diode, and the $0^{th}$ order exited out a small window in the aluminum box. The frequency of the tunable diode laser could be adjusted in a controlled manner by applying a voltage to the PZT, which moved the diffraction grating in response to the applied voltage. The general arrangement of the components of the tunable diode laser is shown below in Figure 1.
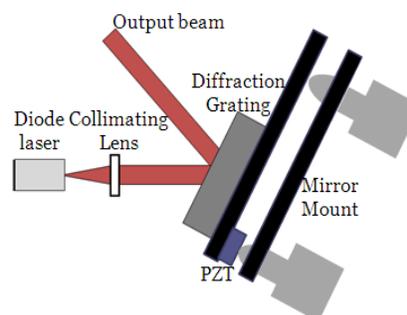
Figure 1. This figure shows the arrangement of the components of the tunable diode laser. These components are mounted on a baseplate, and then enclosed in an aluminum box.

The slave laser used was a diode laser, consisting of a Sanyo high power laser diode (DL-7140-201) and

collimating lens, all contained in an aluminum box.

The arrangement of the apparatus used for saturated absorption spectroscopy, slave laser

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breadboard, which was placed on rubber cushions on the lab table to prevent vibrations of the optical
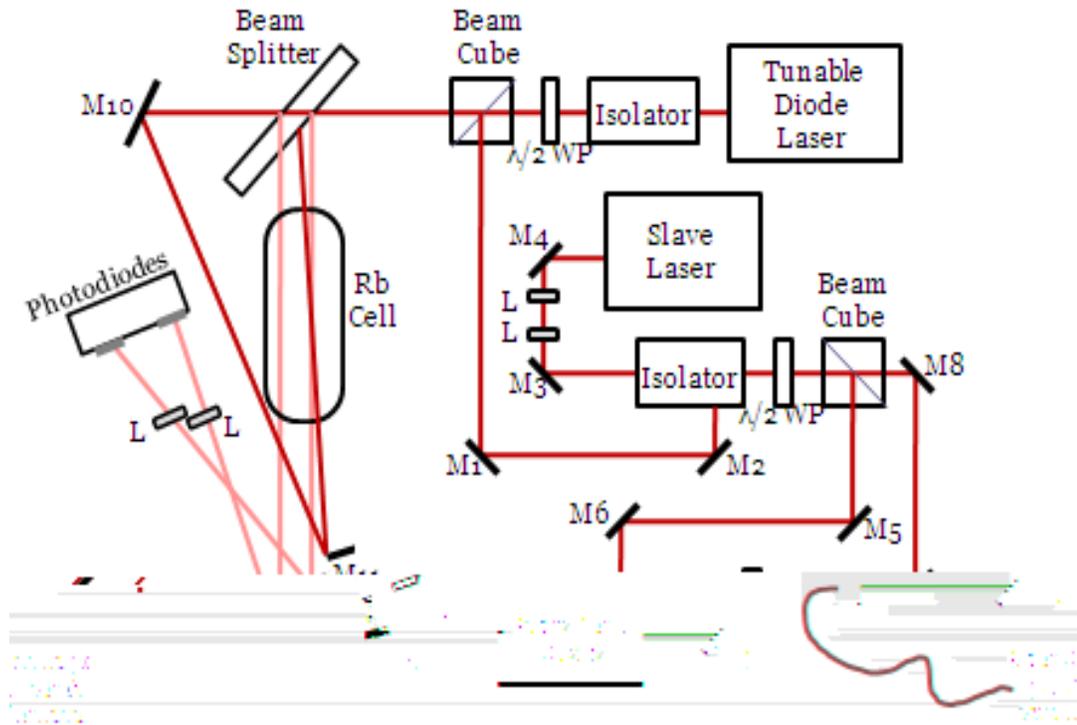
breadboard.



Figure 2. This shows the arrangement of the apparatus used for saturated absorption spectroscopy, slave laser injection, and fiber coupling. In general, the setup on the left-hand side of the diagram is for saturated absorption spectroscopy, and the setup on the right-hand side is for slave laser injection and fiber coupling.

As is shown above in Figure 2, for the final optical setup, light coming from the tunable diode

laser passes through an optical isolator and half-wave plate and is split at a beam cube. The light

passing straight through the beam cube is used for saturated absorption spectroscopy. It is split into

three beams at a beam splitter  two less intense probe beams and one more intense pump beam.  The two probe beams (which are reflected off the beam splitter) pass through the Rb vapor cell, are reflected by mirrors M12 and M13, and focused by lenses (Newport KBX 058, focal length of 75.6 mm) onto two photodiodes in a photodiode amplifier circuit (JILA  ND025AX).  The more intense pump beam passes through the beam splitter and is reflected by mirrors M10 and M11 such that it also passes through the Rb cell, but in the opposite direction.  The pump beam is aligned such that it overlaps with one of the probe beams in the Rb cell.

For the slave laser injection, the light split off by the beam cube is reflected by mirrors M1 and M2 and enters the side port of an optical isolator.  The light then goes through the isolator, is reflected by mirror M3, focused by two lenses, and reflected by mirror M4 to inject the slave laser.  The beam then passes back out of the slave laser, is again reflected by mirrors M4 and M3, goes through the optical isolator and half-wave plate, and is split at another beam cube.  A small portion of the light is reflected by mirrors M5, M6, and M7 into a Fabry-Perot interferometer (Tropel Model 240 Spectrum Analyzer, 1.5GHz FSR).  The rest of the light is reflected by mirrors M8 and M9 and is then fiber-coupled.  This fiber-coupled beam will eventually go to seed a new tapered amplifier.

The final arrangement of the electrical equipment needed to run the tunable diode laser, perform saturated absorption spectroscopy, and lock to the side of an absorption peak is shown in Figure 3 below.
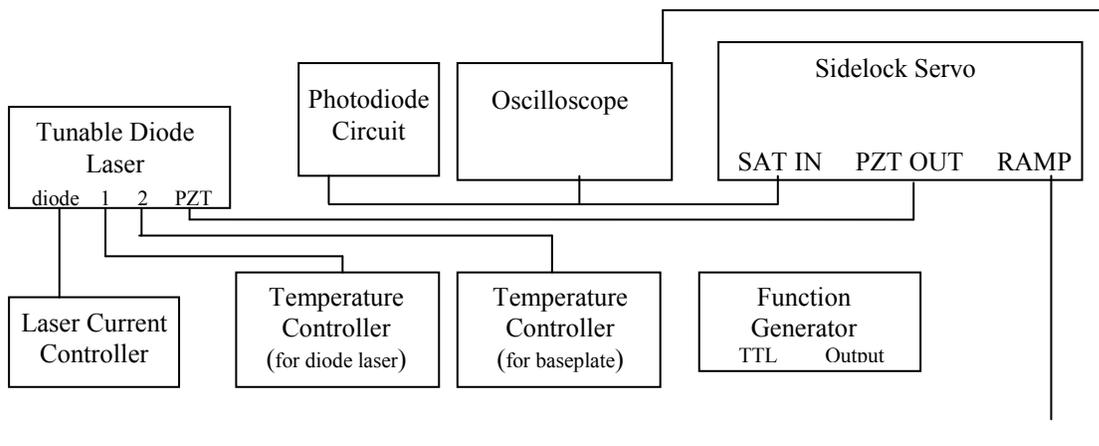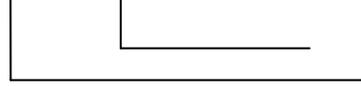
Figure 3.  This shows the final arrangement of the electrical equipment needed for the tunable diode laser, saturated absorption spectroscopy, and locking to the side of an absorption peak.  Note that the power and current supplies needed to run the equipment are not shown.

## Procedure

### I.   Getting the tunable diode laser system running

To get the diode laser system running, two temperature controllers (JILA  QQ035AX) were obtained and modified as needed to work as Peltier thermoelectric coolers so that they could heat or cool as needed.  The Ziegler-Nichols tuning process was used for two controllers, temporarily turning off the integral and derivative components of the proportional-integral-derivative (PID) control, increasing the proportional gain until the error monitor signal began to oscillate, and from that, calculating the values for the needed integrating and differentiating capacitors.

After tuning the temperature controllers, one for the baseplate and one for the diode laser, they were both set to a temperature of 17 C and connected to the laser.  A current supply was connected to the laser.  Using a power meter, the output power of the laser was measured as a function of laser current.

The beam was viewed using an infrared card and the collimating lens was rotated slightly until the beam was well collimated.  A small mirror on an optical post was temporarily placed inside the aluminum box containing the laser, directly in front of the diffraction grating.  An optical spectrum analyzer was used to measure the free running wavelength of

A

laser fine temperature to reach a wavelength close to 779.5 nm.  The mirror was then

removed, and the diffraction grating was realigned, first checking to make sure that the 1st

order beam diffracted from the grating returned to the center of the lens, re-adjusting the tilt

of the diffraction grating about the vertical axis until the laser wavelength was at 779.5 nm,

and then finely adjusting the vertical alignment of the beam to maximize the intensity of the

output beam.

## II. Injecting the slave laser

30 mW of power would be needed to seed the tapered amplifier. Since the tunable diode

laser would be run at currents of 75 mA or less, around 85% of the power would be

transmitted through an optical isolator, 1to 2 mW of power would go to the saturated

absorption spectroscopy setup, and roughly 50% of the remaining beam would be fiber-

coupled to go to the tapered amplifier,

power to seed the tapered amplifier.

To solve this problem, the output of the tunable diode laser was amplified by injecting a

slave diode laser. The optical equipment needed for this was arranged as shown in Figure 2.

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diode laser, the slave laser would be able to lock to the master

laser used in this setup simply consisted of a diode laser and collimating lens (without a

diffraction grating), so the slave laser would be able to output more usable power than the

master tunable diode laser and would therefore amplify the beam. A Fabry-Perot

interferometer (Tropel Model 240 Spectrum Analyzer) was used to check that the slave laser

matched the frequency of the master diode laser.

## III. Performing saturated absorption spectroscopy

A double photodiode amplifier circuit (JILA ND025AX) was built, set for manual gain adjusting, and tested. The optical equipment needed for saturated absorption spectroscopy was arranged as shown in Figure 2. The optical isolator was aligned to maximize transmission, and the half-wave plate was adjusted such that one to two mW of power was going into the saturated absorption spectroscopy setup. A function generator (Simpson 420)

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roughly 15V at a frequency of 3Hz. The laser current was then adjusted until the rubidium cell could be seen to fluoresce when viewed with a handheld IR viewer. The saturated absorption spectrum of Rb was observed on an oscilloscope. The PZT ramp frequency was increased to 25 Hz, and the ramp amplitude and offset were adjusted as needed to zoom in on a particular set of spectral lines. The mirrors in the saturated absorption spectroscopy setup were slightly adjusted to maximize the absorption peaks. The gain in the photodiode circuit was adjusted manually to adjust the DC offset of the signal. To further help with the offset, the vertical tilt of the beam splitter was adjusted and the beams were re-aligned in an iterative process, until the DC offset of the subtraction signal was as close to zero as possible.

## IV. Locking to the side of a peak

After obtaining a stable saturated absorption spectrum signal, a sidelock servo lock box was obtained and the electrical equipment was arranged as shown in Figure 3. The sidelock servo was then used to lock to the side of an absorption peak using the following procedure: Starting with the ramp switch on and the PZT lock switch off, the ramp and PZT bias were increased as needed until the saturated absorption signal was seen. The ramp gain was slowly decreased and the PZT bias was adjusted as needed to zoom in on a peak. To then lock to the side of the peak, the ramp was turned off, and the PZT loop was turned on.

## Results and Discussion

   A plot of gain vs. current was made for the tunable diode laser, as shown in Figure 4.  Looking at

this plot, one can see that the threshold current for the laser is around 30 mA.  From this point on, the

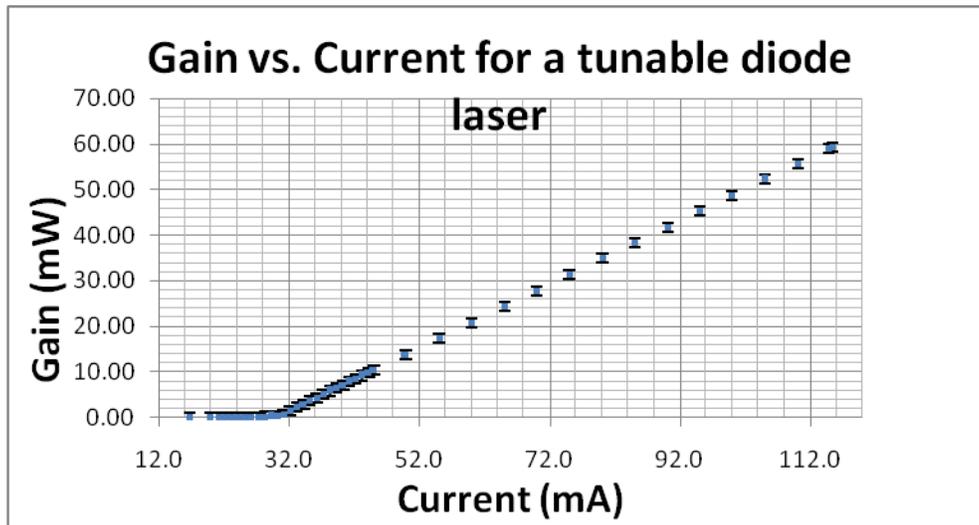laser gain is directly proportional to the laser current.



Figure 4.  This shows a plot of gain vs. current for a tunable diode laser.

   By using Doppler-free saturated absorption spectroscopy, with the tunable diode laser current set

at 74.6 mA, we observed the $^{87}$Rb transitions between the $5^2S_{1/2}$ and $5^2P_{3/2}$          P       P

and 3.  The difference signal of the two probe beams, showing these transitions, is shown below in

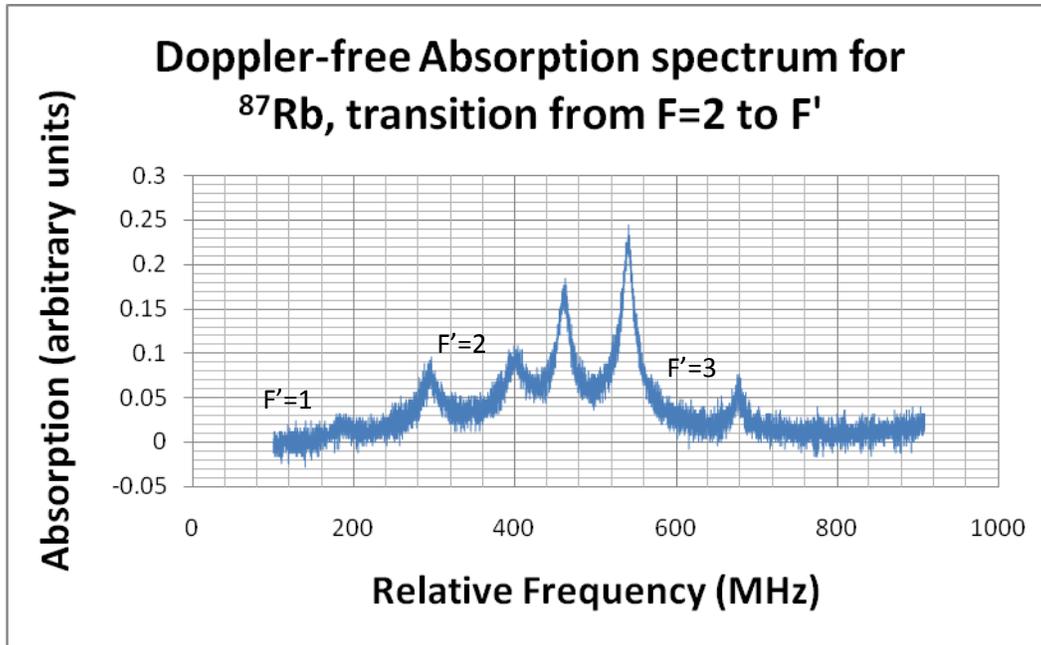Figure 5.

## Doppler-free Absorption spectrum for $^{87}$Rb, transition from F=2 to F'

Figure 5.  This shows the Doppler-free absorption spectrum of the $^{87}$Rb transition between the $5^2S_{1/2}$ and $5^2P_{3/2}$ states from

P        P            =

Since the spectrum of Rb is so well known, the spacing between hyperfine levels was calculated

according to theory and used to calibrate the horizontal axis of the graph.  Note that the 3 transitions,

    P        P                =                                                                         -way

between each pair of true resonances.  The absorption peaks appeared to have full width at half

maximum (FWHM) linewidths of roughly 30 MHz.  While this is certainly much less than what the

Doppler-broadened linewidth would be, it is more than the mere natural linewidth.  Possible sources of

power broadening.

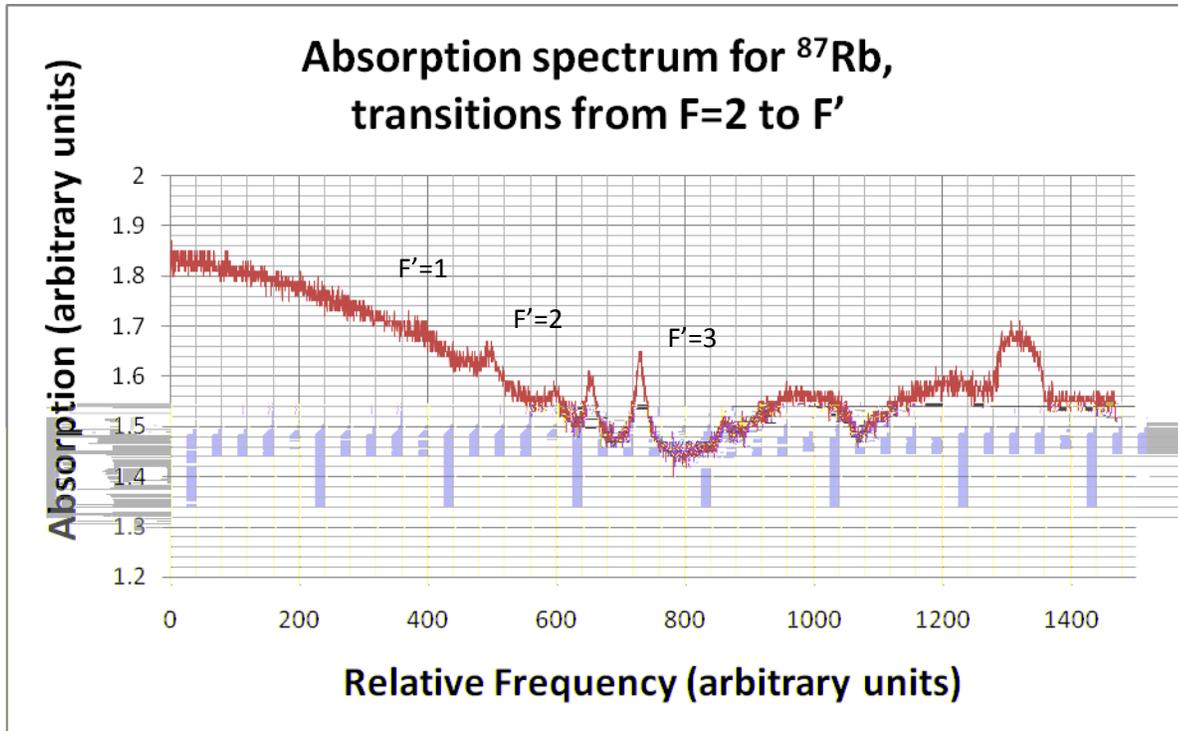    The signal from the one overlapped probe beam is shown below in Figure 6.

Figure 6.  This shows the signal from the overlapped probe beam.

In this figure, one can see the hyperfine structure from the [87]Rb P        P

Doppler-broadened profile, as expected.  The two jumps in the spectrum occurring around 1000 and

1300 on the relative frequency scale are due to mode hops in the laser.  Unfortunately, because of mode

hops, only one set of transitions                                                                        Z

continuous tuning range is small.  However, by re-adjusting the laser current, the other sets of transitions

                                                    small co

problem.

After first observing the saturated absorption spectrum of [87]Rb, the procedure for locking to the

side of a peak was performed successfully.  However, after unlocking the laser in order to take data of

the Rb spectrum, this locking process was not repeated, because it would be a while before the new

tapered amplifier would come, and when the laser will actually be used for MOT light, a better method

for locking the laser than locking to the side of a peak may be used instead.

**Conclusion**

We were able to get a tunable diode laser running, inject a slave laser to amplify the beam, and use Doppler-free saturated absorption spectroscopy to observe the Doppler-free saturated absorption spectrum of $^{87}$Rb for the transitions from F=2 to F'.  Now that we've found a temperature and laser current at which we can observe a stable saturated absorption spectrum, the laser can be locked to a particular frequency.  The output of the slave laser has been fiber-coupled, so it is ready to go to the input of the new tapered amplifier upon its arrival and be used to make a better MOT to trap and cool Rb atoms.

**References**

[1] K. B. MacAdam, A. Steinbach, and C. Wieman, "A narrow-band tunable diode laser system with grating feedback and a saturated absorption spectrometer for Cs and Rb," Am. J. Phys. 60 (12), 1098-1111 (1992).

[2] Doppler-Free Saturated Absorption Spectroscopy: Laser Spectroscopy.  Advanced Laboratory Lab Manual write-up.  Spring 2001.