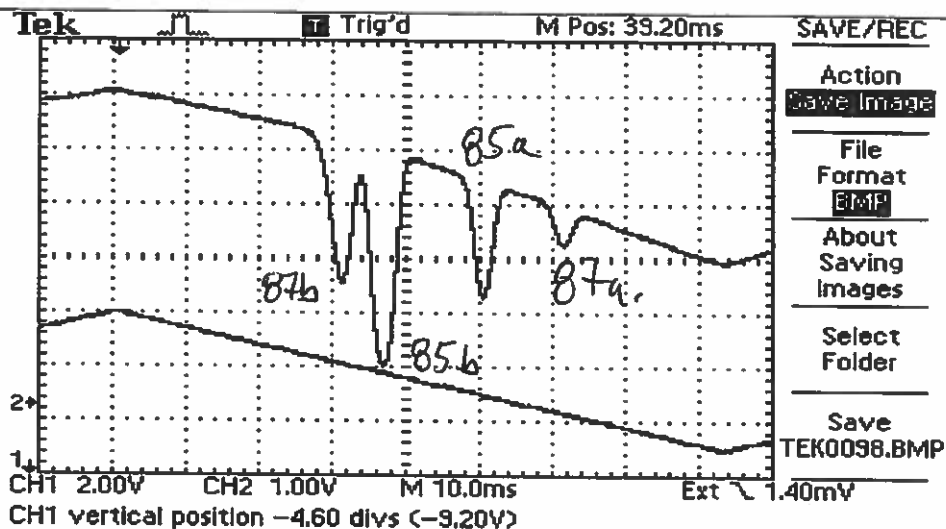
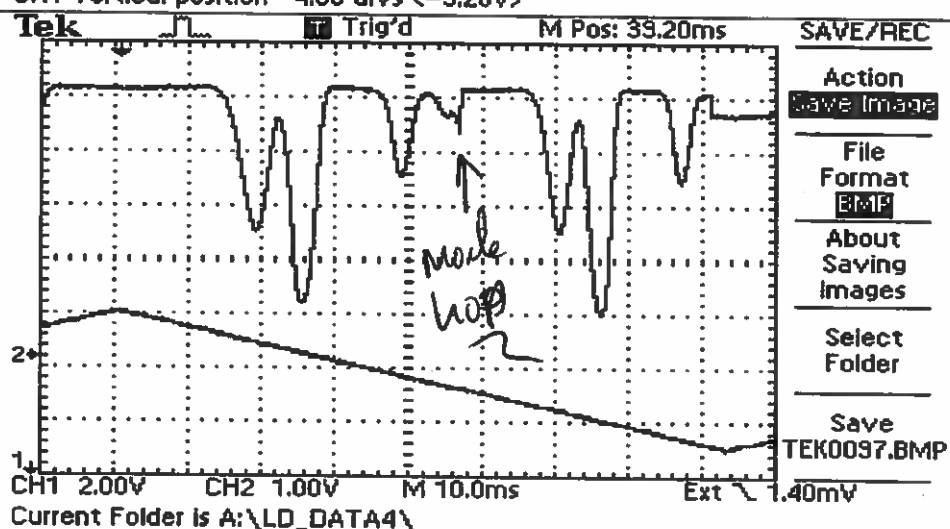


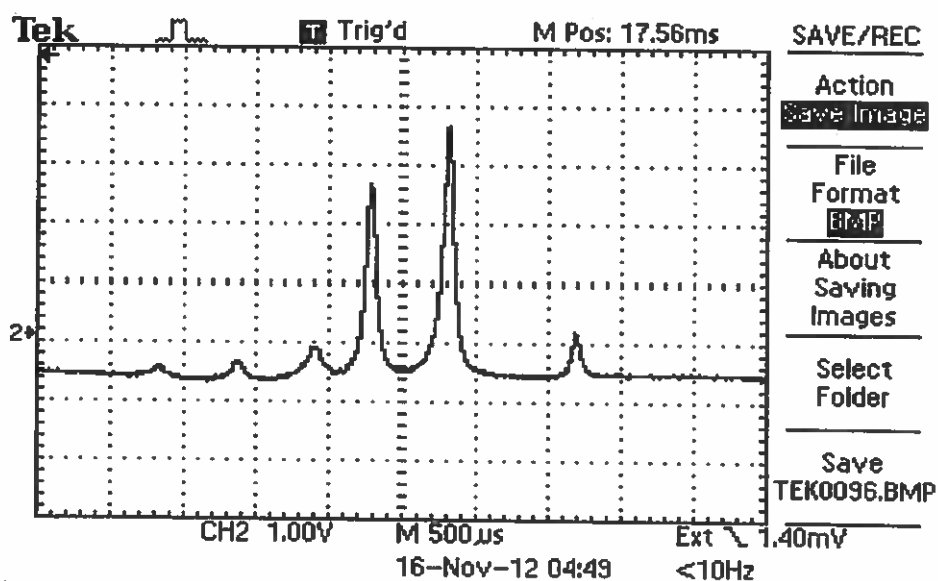
Piezo and Current Scan  
 Chan. 2 = Detector  
 Chan. 1 = Piezo monitor  
 Photodiode Gain = 1M  $\Omega$   
 Cell Temp = 45  $^{\circ}$ C  
 LD Temp = 2.719V  
 LD current = 47.85 mA  
 Current Mod. Attn. = 0.6



Piezo only Scan  
 Chan. 2 = Detector  
 Chan. 1 = Piezo monitor  
 Photodiode Gain = 1M  $\Omega$   
 Cell Temp = 45  $^{\circ}$ C  
 LD Temp = 2.719 V  
 LD current = 49.80 mA



Doppler Free Spectrum  
 $^{87}\text{Rb}$  F=2 (87b)  
 Chan. 2 = Detector  
 Chan. 1 = OFF  
 Photodiode Gain = 1M  $\Omega$   
 Cell Temp = 45  $^{\circ}$ C  
 LD Temp = 2.719 V  
 LD current = 49.80 mA  
 Detector Gain = 5



DL228-1b

I threshold = 30.9 mA

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November 19, 2012

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College of Sciences

Physics department

Laboratory Manual  
on  
**DIODE LASER EXPERIMENT**  
**PHYS 403LAB**



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# Diode Laser Spectroscopy

*"Spectroscopy and Much More, Using Modern Optics"*

## DLS1-A USER'S MANUAL

A PRODUCT OF TEACHSPIN, INC.

Designed in collaboration with  
Professor Kenneth Libbrecht of the California Institute of Technology

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# DIODE LASER SPECTROSCOPY

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# **DIODE LASER SPECTROSCOPY**

## Diode Laser Physics

### I. LASER BASICS

Beginning in the mid 1960's, before the development of semiconductor diode lasers, physicists mostly used tunable "dye" lasers in pioneering atomic physics experiments needing tunable laser light. Dye lasers use a chemical dye as the active medium, *i.e.* the material which produces the laser emission. A population inversion in the dye is created, typically, with a fixed-frequency "pump" laser. An individual dye will lase over a limited wavelength range, and different dyes are available to make tunable lasers at essentially all visible and near-infrared wavelengths. Unfortunately dye lasers are large, cumbersome instruments that are both very expensive to purchase (~\$100,000.00) and expensive to operate and maintain. Some of the solid-state lasers used as dye laser replacements, such as the popular Ti:sapphire crystal (titanium-doped sapphire), work better than dyes, and other techniques using non-linear crystals exist to generate tunable laser light (Yariv 1991). However, while these may be less difficult to use than dye lasers they are still very expensive options.

The recent development of tunable, narrow-bandwidth, semiconductor diode lasers dramatically changed this picture. These lasers are inexpensive, easy to operate, and produce high-power, tunable, narrow-bandwidth radiation ( $\Delta\nu < 1$  MHz,  $\Delta\lambda < 1.5 \times 10^{-6}$  nm). For these reasons, tunable diode lasers have rapidly become commonplace in modern research laboratories.

Interior Diagram of TOLD9200 Series

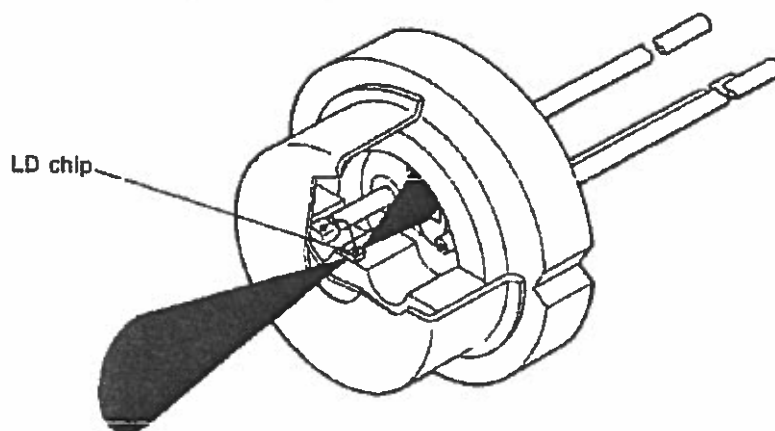


Figure 1: Cut-away view of a typical laser diode can, like those used in the TeachSpin laser

The basic physics of diode lasers is presented in several review articles and books, such as Wieman and Hollberg (1991) and Camparo (1985). Figure 1 shows a cut-away view of a typical diode laser, similar to the ones used in this experiment. The actual semiconductor device is a small chip (LD chip in Figure 1), bonded to a heat-sink. Tiny wires connect the

chip to the outside world. Most of the light emitted by the laser comes out the front facet, and a small amount also comes out the back facet. (The two facets are constructed to have different reflectivities). Often, a photodiode is placed at the back of the can, to monitor the laser output power. The main laser beam, which is elliptical and strongly diverging, comes out a window in the front of the laser diode can.

Figure 2 shows a more detailed view of a typical laser diode chip. Current is driven from the top to the bottom of the chip (see arrow in Figure 2), creating electron-hole pairs that recombine in the active layer, emitting light in the process. The light is confined to a narrow channel in the chip,  $\sim 2$  microns high,  $\sim 10$  microns wide, and about 400 microns long (wavy line in Figure 2). The facets of the chip, at the ends of the channel, act as partially reflecting mirrors enclosing the laser cavity.

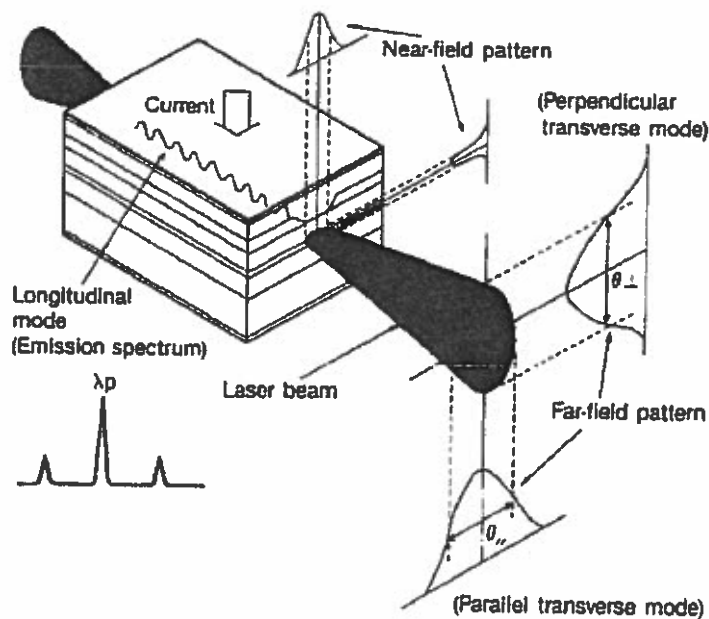
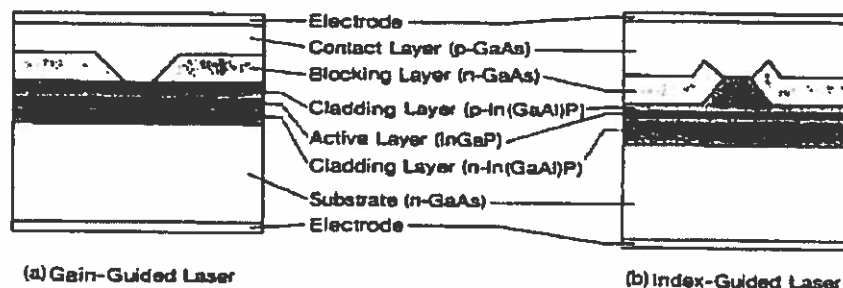


Figure 2: Schematic view of a laser diode chip

Figure 3 shows a schematic picture of the actual semiconductor layer structure in a diode laser. How all this *really* works, the nitty-gritty semiconductor technology, is not something we will concern ourselves with in this discussion. Since light generation in a diode laser results from the recombination of electron-hole pairs injected into an active layer at the diode's n-p junction, the wavelength of the emitted light is approximately that of the band gap of the material. The electron-hole population inversion is restricted to a narrow strip in the active layer, so the laser's optical gain is spatially localized. Gain is the amount that an optical wave is amplified by stimulated emission as it passes through the laser cavity. The diode heterostructure also serves as an optical waveguide; the active layer has a higher index of refraction than its surroundings, so light is confined to the channel by total internal reflection. The cleaved facets at the end of the chip serve as the cavity mirrors and output couplers. These can be coated to increase or decrease the facet reflectivity.

## SCHEMATIC STRUCTURE OF VISIBLE LASER DIODES



**Figure 3:** Schematic picture of the internal semiconductor structure of some typical laser diodes. This view is looking into one facet of the laser cavity.

By careful construction of the diode cavity, the laser can be made to emit in a single longitudinal cavity mode (*i.e.* a standing wave inside the cavity, with a fixed number of nodes along the cavity axis and no nodes in the transverse direction). A "bare" diode laser has a linewidth of typically  $\Delta\nu \sim 50$  MHz. The spatial mode of the laser, and thus the shape of the output beam, is defined by the narrow channel that confines the light. Since the channel is rectangular, and not much larger than the light wavelength, the output beam is elliptical and strongly diverging (see Wieman and Hollberg 1991).

At low levels of injection current, the optical losses exceed the gain and a population inversion is not achieved. The light output is then broad-band, spontaneous emission, similar to that of an LED. But, above a "threshold" current, the laser emits a coherent beam, which increases in intensity linearly with injection current. The output power in coherent radiation can be as high as 50 percent of the input electrical power, which is very efficient compared with other methods of producing laser light.

Diode lasers have many uses; primary among these are retrieving data stored on optical disks (for instance all compact disk players use diode lasers) and sending light pulses down optical fibers for telecommunications. At present, one can purchase diode lasers that operate at wavelengths from the blue to the infrared; there is a big push in industrial labs to produce shorter wavelength lasers, in order to increase the density of optical disk storage. Power levels for single-mode diode lasers are typically a few mW, but can be as high as 1 Watt.

The TeachSpin diode lasers (Sanyo DL-7140-201S) emit up to 70 mW of output power near 785 nm. The back surface of the tiny semiconductor laser cavity is highly reflecting, while the front surface is often coated with a thin antireflection layer to enhance its transmission. (Only the manufacturer knows exactly how the facets are prepared; such details are often carefully guarded industrial trade secrets.)

\* It is possible to get an approximate measure of the reflection coefficient,  $R = 16.5\% \pm 5\%$ . (See section A4-2 for details.)



## II. LASERS WITH GRATING FEEDBACK or External Cavity Diode Lasers (ECDL)

### A. Introduction

Bare diode lasers have two undesirable properties: 1) their linewidths ( $\Delta\nu \sim 50$  MHz) are large compared to the linewidths of atomic transitions (in our case  $\Gamma \sim 5$  MHz); and 2) they are extremely sensitive to optical feedback – as little as  $10^{-6}$  of the output light scattered back into the laser may affect its frequency stability. As shown in Figure 4, we overcome both these problems by using a diode laser with a small amount of controlled feedback from a diffraction grating.

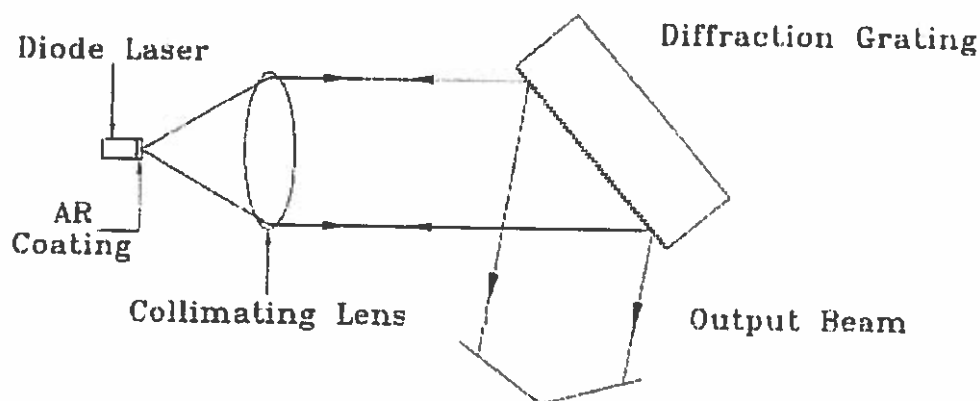


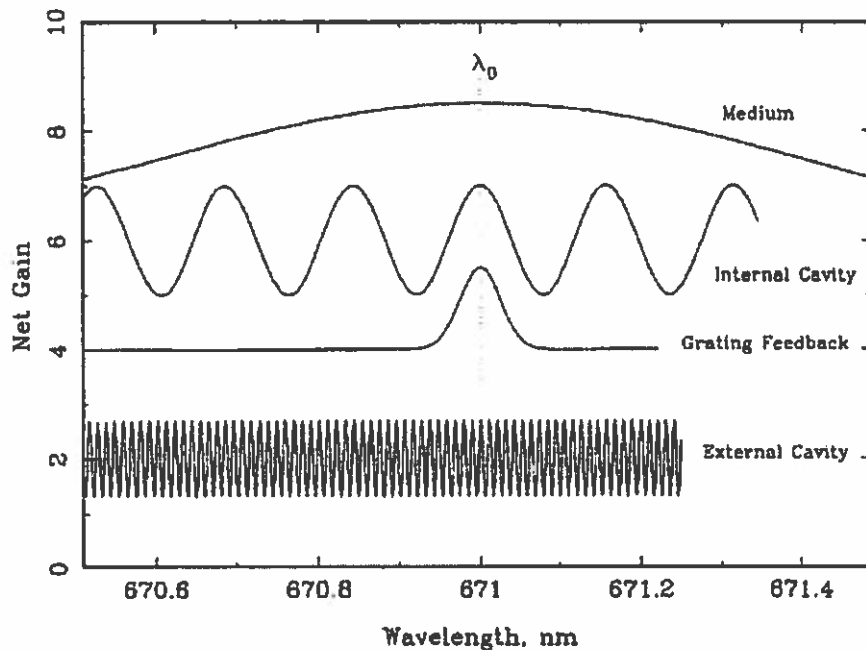
Figure 4: Basic configuration of the diode laser system

A lens in front of the laser collimates the output into a nearly nondiverging elliptical beam. After the lens, the beam strikes a diffraction grating, which is a holographic (no blaze) grating with 1800 lines/mm. Most of the light is directly reflected by the grating ( $m=0$  grating order), but roughly 15 percent is reflected back into the laser ( $m=1$  order). The grating forms an “external cavity” (*i.e.* external to the laser’s own internal semiconductor cavity), which serves to frequency-stabilize and line-narrow the laser output (see Wieman and Hollberg 1991, and references therein, to understand how this happens). With the simple addition of the diffraction grating, the laser is much less sensitive to stray light feedback, and its linewidth will be reduced to  $\Delta\nu < 1$  MHz, much smaller than the atomic transition linewidths we will be observing.

### B. Laser Tuning:

With grating feedback, the frequency of the laser output depends on a number of factors. In order for you to effectively tune the laser to an atomic transition, it is helpful to understand how these factors determine the laser output frequency. The laser will tend to lase at the mode frequency with the greatest net gain (*i.e.* stimulated emission minus optical losses) (see Yariv 1991). Once the laser begins to lase in this mode, stimulated emission limits the number of electron-hole pairs which are available for lasing in other modes, and the result is a laser with a single-mode (*i.e.* single frequency) output beam. (Note: This does not always happen. Our lasers will sometimes lase in two or more modes at the same time, and sometimes the output

frequency will vary rapidly and chaotically over a broad frequency range. While these behavior patterns are interesting, and the subject of some amount of research, we will mainly try to find a place in parameter space where the laser operates in a single mode.) To determine the laser operating frequency (assuming single-mode operation), we need to find the frequency with the highest net gain. Figure 5 shows, schematically, the different contributions to the net gain. These contributions are best explored individually.

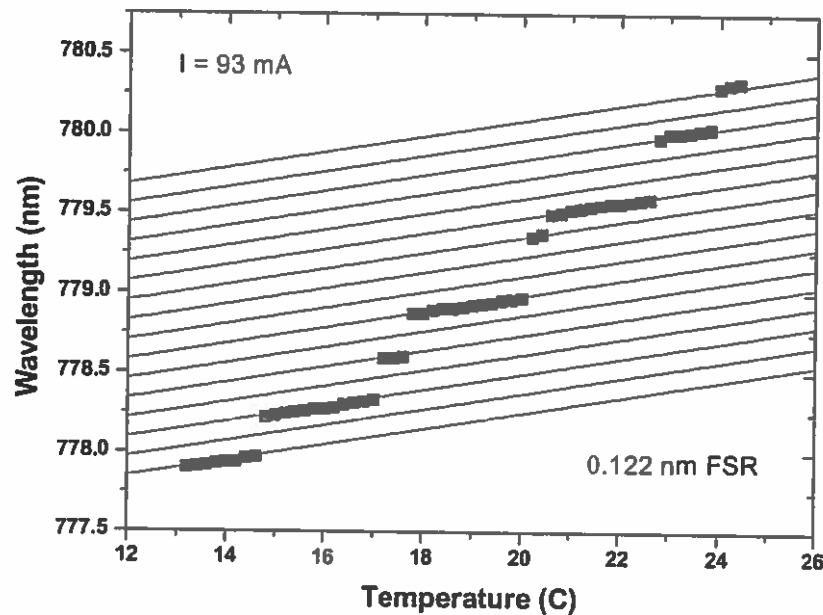


**Figure 5:** Schematic of the different contributions to the net optical gain of an arbitrary laser as a function of frequency. The curves are displaced relative to one another for clarity.

### 1. The medium gain

This depends on the properties of the semiconductor material from which the laser is made, in particular the band gap. The medium gain shows a broad peak in frequency space, whose position depends mainly on laser temperature. Since we are aiming for the rubidium atomic transition, we must set the laser temperature, using the temperature controller, so that it operates near 780 nm, the wavelength of the rubidium resonance lines. This temperature is recorded on the antistatic bag in which each diode is shipped. The temperature for the diode that was shipped in your laser is listed on the data sheet included in your manual.

A plot of Wavelength versus Temperature for a typical laser is shown in Figure 6. The overall slope of this data is about  $0.23 \text{ nm } ^\circ\text{C}^{-1}$ , which should be about equal for all the Sanyo diodes. From this slope and the temperature set point for 780 nm, you can determine an appropriate temperature for any desired wavelength for that specific diode. Once this is done, the medium gain curve is so broad that it is unimportant for determining the precise wavelength of the laser.



**Figure 6:** Output wavelength of a free-running (*i.e.* no external optical feedback) Sanyo DL-7i40-200S diode laser as a function of diode temperature. (The behavior of other diode lasers is similar.)

## 2. The internal cavity

The diode junction forms a small Fabry-Perot etalon, or optical cavity, and like all optical cavities, it has a normal mode structure. This translates to an effective frequency-dependent net gain function which is periodic in frequency, as shown in Figure 5 (see Yariv 1991 or Möller 1988 for a discussion of optical cavities). The period is called the “free spectral range”, and is given by  $\Delta\nu_{\text{FSR}} = c/2Ln$ , where  $c$  is the speed of light,  $n$  is the index of refraction ( $n \approx 3.6$  in the semiconductor), and  $L$  is the cavity length. For this particular laser we have  $\Delta\nu_{\text{FSR}} \approx 60$  GHz ( $\Delta\lambda \approx 0.122$  nm). The internal cavity gain function will shift in frequency with changes in the diode temperature at roughly  $0.05 \text{ nm } ^\circ\text{C}^{-1}$  this is measured from the small scale slope the individual steps in Figure 6. Unfortunately, the temperature of the laser head can not be changed very quickly. The thermal time constant of the laser head can be estimated to be on the order of 10 seconds.\* The internal cavity modes will also change with the diode current. (See Figure 7.)

\* Estimated from the mass ( $\approx 170$  grams), heat capacity and thermal conductivity, assuming the laser head is a solid cube of aluminum with the TEC on one face and the diode and temperature sensor at the center.

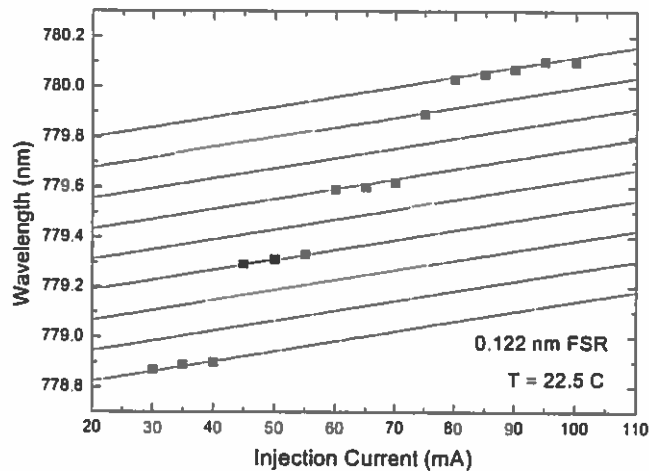


Figure 7: Free-running laser Wavelength versus Injection Current at a fixed temperature

The current affects a diode in two ways. First, increasing the current causes simple heating, which changes the temperature of the diode and thus the wavelength in much the same way as heating the laser head directly. With respect to wavelength, modulating the current can be thought of as a means of rapidly changing the diode temperature. This effect predominates for time scales longer than 1  $\mu$ s and tunes at roughly 2 GHz/mA as shown in Figure 7. The second means by which the current changes the free-running laser wavelength is by changing the carrier concentration in the active region. This modulates the optical path length of the diode, with a tuning rate of about 200 MHz/mA, up to a maximum frequency that is set by the relaxation oscillation frequency of the diode, typically several GHz.

Taken together, Figures 5 - 7 demonstrate the interaction of several influences. Figure 6 shows a plot of the wavelength of a free-running laser as a function of temperature. As the temperature is increased, the maximum gain of both the medium and the internal cavity modes shown in Figure 5 will shift to longer wavelengths. They do not, however, shift at the same rate. This creates laser "mode hops" to different peaks of the cavity gain function. In practice, we would like to set the temperature and injection current so that the laser operates at the rubidium resonance frequency. But, as can be seen from Figure 6, this is not always possible with a free-running laser. With the addition of an external grating, the laser can be made to operate at any wavelength within a reasonably broad range.

### 3. The Grating Feedback

Since a grating disperses light, only light from a narrow wavelength band will be fed back into the laser for a fixed grating left/right (L/R) angle. (The grating up/down (U/D) angle should be set so that the light from the grating reflects back into the laser.) In this apparatus, the grating is used in a Littrow configuration where the first order diffraction is sent back into the diode. In this configuration, the wavelength can be found from  $\lambda = 2 d \sin\theta$ , where  $d$  is

the line spacing of the grating and  $\theta$  is the grating angle (measured from the normal). Assuming an ideal grating, where the resolving power is limited only by diffraction, the spectral width of the first order diffraction,  $\Delta\nu$ , will be given approximately by  $\nu/\Delta\nu=N$ , where  $\nu$  is frequency and  $N$  is the number of grating lines subtended by the laser beam (see Möller 1988 or any general optics book, for a discussion of grating properties). For example, with a 0.3 cm laser beam width, we will find  $N = 5400$  and  $\Delta\nu = 70$  GHz. The position of this peak is determined by the grating L/R angle.

#### 4. The external cavity

This is similar to (2) above, but with the external cavity, one end of which is the grating, and the other is the highly reflective back facet of the diode. Since the external cavity is much larger we have  $\Delta\nu_{\text{FSR}} = c/2L \approx 10$  GHz, for a 15 mm external cavity length. (See Section A.4 and Figure A.4.1 for the relevant dimensions.) This curve shifts by moving the grating position, which we do either with the L/R knob on the laser head or with the piezo-electric transducer (PZT) in the grating mount.

In order to force the laser into single-mode laser operation at a predetermined wavelength  $\lambda_0$  (e.g. an atomic resonance line), the gain from each of the components should peak at  $\lambda_0$  as shown in Figures 5.

To get a more complete understanding of how these contributions interact, how the laser tunes as the grating angle is changed, we have tried to construct an accurate "best guess" picture of the shape of the various cavity modes in the laser. This picture is shown in Figure 8. Referring back to Figure 5, the grating feedback and external cavity gains have been merged into the single solid line of Figure 8. The broad medium gain has been left out of the plot. Figure 8 is a picture of the various cavity modes with all the gains having a maximum at the same frequency.

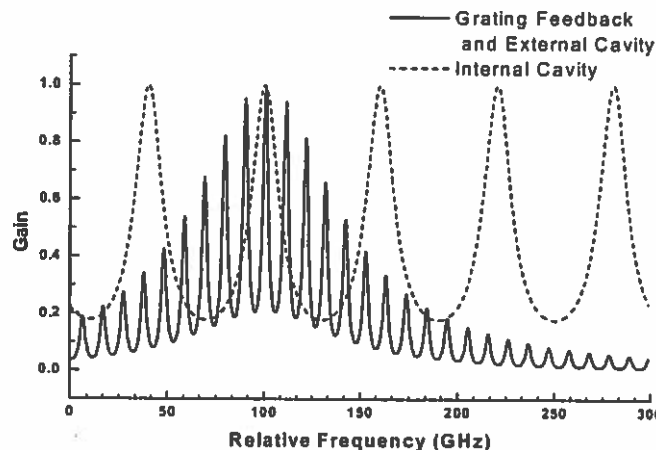
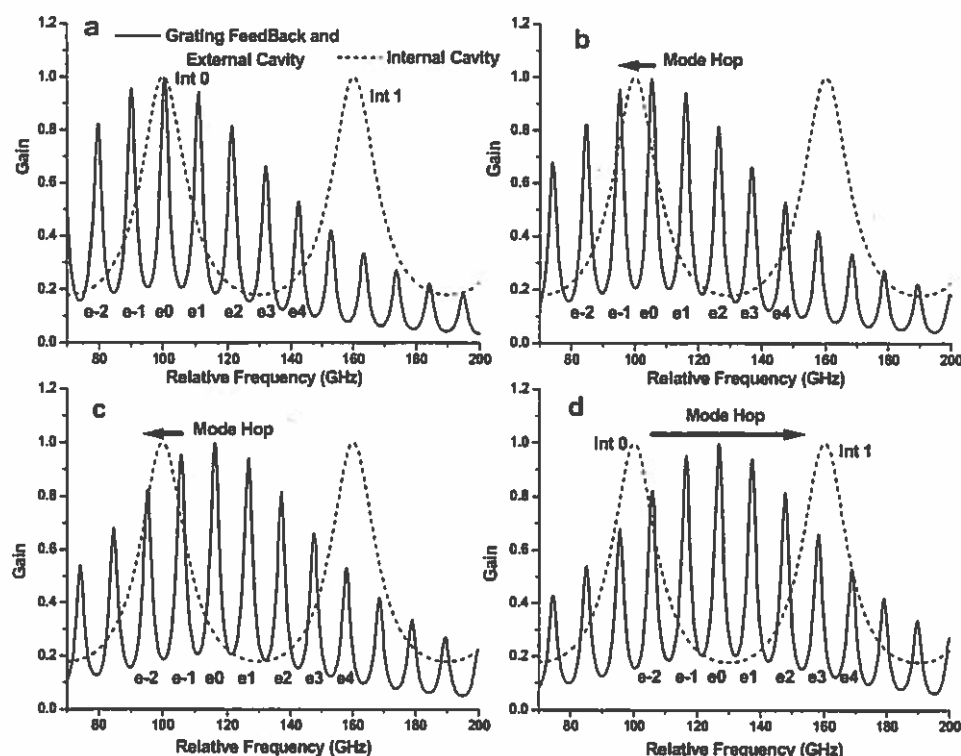


Figure 8: "Best guess" picture internal cavity, grating feed back and external cavity modes in the laser



**Figure 9:** Series of graphs showing how the external and grating feed back mode shifts as the grating angle is changed.

Figure 9 shows a series of pictures of the External and Internal cavity modes as the grating angle is decreased. The pictures show only two of the internal modes labeled Int 0 and Int 1. For reference, we have also labeled some of the external modes e-2, e-1, e0, e1...e4. In Figure 9, Graph a is for the same grating angle shown in Figure 8, where the laser is oscillating in external mode e0. As the grating angle is decreased, mode e0 is shifted to higher frequency, shorter wavelength, until the point shown in graph b. At this point, the overall gain in external mode e-1 is about equal to that in mode e0 and, as the grating continues to move, the laser will jump into mode e-1. As the angle is decreased further, the laser will reach the point shown in graph c and the laser will hop to mode e-2. Finally, in graph d, the maximum of the grating feedback frequency is about half way between internal modes Int0 and Int1. As the angle continues to decrease, the laser will make a relatively larger mode hop and lase in external mode e3 under internal mode Int1.

You should notice that during this change in angle, the laser has swept through the same small frequency range "under" Int0 several times. After these changes, the laser moved to a new frequency defined by Int1 with a rather large gap of frequencies in between. To be able to cover the entire frequency range, we need to be able to change the position of the internal

modes. This is done by changing the laser current. To tune the laser to the correct wavelength for the rubidium transitions, both the correct grating angle and laser current must be found. The procedure for doing this is discussed in the next section. The next section will also describe a clever trick in which both the grating angle and laser current are swept simultaneously at rates such that both the internal mode  $\text{Int0}$  and the maximum of the external modes  $e0$  change in frequency together resulting in long (20 GHz) mode hop free scans. An understanding of the Figures 8 and 9 should help you visualize how this is accomplished.

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## Diode Laser Spectroscopy

### I. BACKGROUND

One of the most important scientific applications of lasers is in the area of precision atomic and molecular spectroscopy. Spectroscopy is used not only to better understand the structure of atoms and molecules, but also to define standards in metrology. For example, the second is defined from atomic clocks using the 9192631770 Hz (exact, by definition) hyperfine transition frequency in atomic cesium, and the meter is (indirectly) defined from the wavelength of lasers locked to atomic reference lines. Furthermore, precision spectroscopy of atomic hydrogen and positronium is currently being pursued as a means of more accurately testing quantum electrodynamics (QED), which so far is in agreement with fundamental measurements to a high level of precision (theory and experiment agree to better than a part in  $10^8$ ). An excellent article describing precision spectroscopy of atomic hydrogen, the simplest atom, is Hänsch *et al.* 1979 (details are in References). Although it is a bit old, the article contains many ideas and techniques in precision spectroscopy that continue to be used and refined to this day.

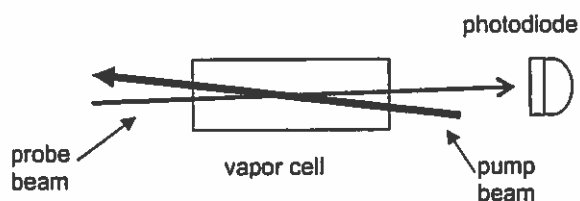


Figure 1: The basic saturated absorption spectroscopy set-up.

### II. QUALITATIVE PICTURE OF SATURATED ABSORPTION SPECTROSCOPY – 2-LEVEL ATOMS.

Saturated absorption spectroscopy is one simple and frequently-used technique for measuring narrow-line atomic spectral features, limited only by the natural linewidth  $\Gamma$  of the transition (for the rubidium D lines  $\Gamma \approx 6$  MHz), from an atomic vapor with large Doppler broadening of  $\Delta\nu_{Dopp} \sim 1$  GHz. To see how saturated absorption spectroscopy works, consider the experimental set-up shown in Figure 1. Two lasers are sent through an atomic vapor cell from opposite directions; one, the “probe” beam, is very weak, while the other, the “pump” beam, is strong. Both beams are derived from the same laser, and therefore have the same frequency. As the laser frequency is scanned, the probe beam intensity is measured by a photodetector.

Figure 2 shows the spectra that might be recorded if 2-level atoms were in the vapor cell. The upper plot gives the probe beam absorption without the pump beam. Here one sees simple Doppler-broadened absorption. In our case, the Doppler width is much larger than the natural linewidth,  $\Delta\nu_{Dopp} \gg \Gamma$ , and the optical depth of the vapor is fairly small  $\tau(\nu) \leq 1$ .



The transmitted fraction of the probe is  $e^{-\tau(\nu)}$ , which defines the optical depth;  $\tau$  is proportional to the atomic vapor density and the path length. As a result, the probe spectrum is essentially a simple Gaussian profile.

The lower plot in Figure 2 shows the spectrum *with* the pump beam. A spike appears right at the atomic resonance frequency. The reason this spike appears is as follows: If the laser frequency is  $\nu_0 - \Delta\nu$ , then the probe beam is absorbed only by atoms moving with longitudinal velocity  $v = c\Delta\nu/\nu_0$ , moving toward the probe beam. These atoms see the probe beam blue-shifted into resonance; other atoms are not in resonance with the probe beam, and so they do not contribute to the probe absorption. Because the pump beam is in the opposite direction, these same atoms see the pump beam red-shifted further from resonance, so they are unaffected by the pump beam. Thus for laser frequencies  $\nu \neq \nu_0$ , the probe absorption is the same with or without the pump beam. However, if  $\nu = \nu_0$ , then atoms with zero velocity,  $v = 0$ , contribute to the probe absorption.

These  $v = 0$  atoms also see an on-resonance pump beam, which is strong enough to keep a significant fraction of the atoms in the excited state, where they do not absorb the probe beam (in fact they increase the probe beam intensity via stimulated emission). Thus at  $\nu = \nu_0$  the probe absorption is *less* than it was without the pump beam. (If the pump beam had infinite intensity, half of the atoms would be in the excited state at any given time, and there would be identically zero probe absorption. One would say these atoms were completely "saturated" by the pump beam, hence the name saturated absorption spectroscopy.) The advantage of this form of spectroscopy should be obvious ... one can measure sharp Doppler-free features in a Doppler-broadened vapor.

### III. QUALITATIVE PICTURE OF SATURATED ABSORPTION SPECTROSCOPY – MULTI-LEVEL ATOMS.

If the atoms in the absorption cell had a single ground state and two excited states (typically an electronic level split by the hyperfine interaction), and the separation of the excited states was less than the Doppler width, then one would see a spectrum like that shown in Figure 3.

The peaks on the left and right are ordinary saturated absorption peaks at  $\nu_1$  and  $\nu_2$ , the two resonance frequencies. The middle peak at  $(\nu_1 + \nu_2)/2$  is called a "cross-over resonance."

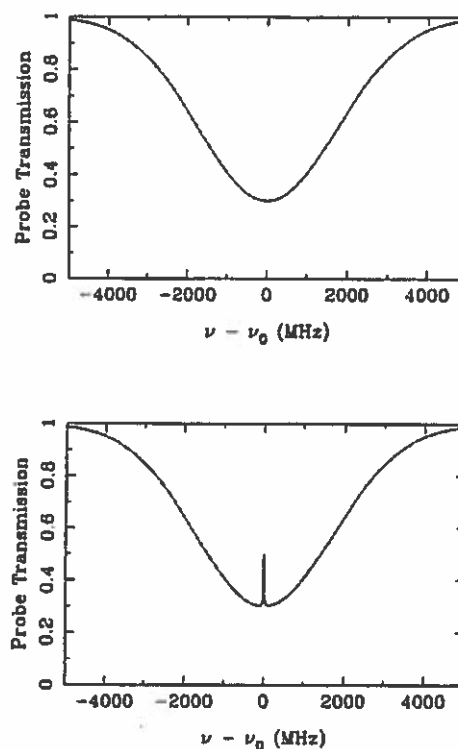


Fig. 2: Absorption spectra for 2-level atoms, both without (upper) and with (lower) the pump beam.

If you think about it for a while you can see where the extra peak comes from. It arises from atoms moving at velocities such that the pump is in resonance with one transition, and the probe is in resonance with the other transition. If you think about it a bit more you will see there are *two* velocity classes of atoms for which this is true – atoms moving toward the pump laser, and away from it.

If the atoms in the vapor cell had a single excited state, but two hyperfine ground states (we call them both “ground” states because neither can decay via an allowed transition), and the separation of the ground states was less than the Doppler width, then one might see a spectrum like in Figure 4. The extra cross-over dip results from a phenomenon called “optical pumping,” which occurs because atoms in the excited state can decay into either of the two stable ground states. Thus, if atoms are initially in ground state  $g_1$ , and one shines in a laser that excites  $g_1 \rightarrow e$ , atoms will get excited from  $g_1 \rightarrow e$ , over and over again until they once spontaneously decay to  $g_2$ , where they will stay. The state  $g_2$  is called a “dark state” in this case, because atoms in  $g_2$  are not affected by the laser. We see that a laser exciting  $g_1 \rightarrow e$ , will eventually optically pump all the atoms into  $g_2$ .

To see how optical pumping produces the extra crossover dip, remember that only the pump laser can optically pump – the probe laser is by definition too weak. Also remember the atoms in the cell are not in steady state. When they hit the walls, they bounce off about equally distributed in both ground states, and the optical pumping only

operates for a short period of time as the atoms travel through the laser beams. If you think about it a while you can see there are two velocity classes of atoms that are responsible for the dip. For one velocity class the pump laser excites  $g_1 \rightarrow e$ , which tends to pump atoms into  $g_2$ . Then the probe laser, which excites  $g_2 \rightarrow e$  for these atoms, sees extra absorption. For the other velocity class the pump laser excites  $g_2 \rightarrow e$ ,  $g_1$  gets overpopulated, and again the probe laser (which now excites  $g_1 \rightarrow e$  for these atoms) sees more absorption.

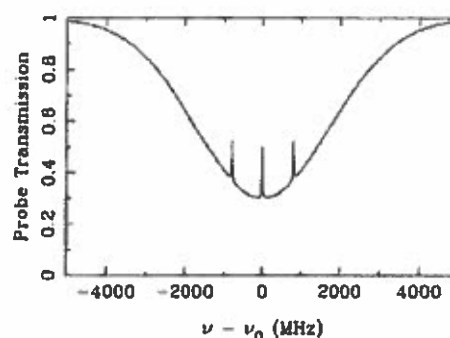


Fig. 3: Saturated absorption spectrum for atoms with a single ground state and two closely spaced excited states.

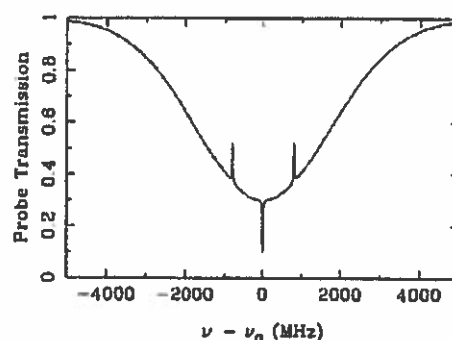


Fig. 4: Saturated absorption spectrum for atoms with a single excited state that can decay into either of two closely spaced excited states.

#### IV QUANTITATIVE PICTURE OF SATURATED ABSORPTION SPECTROSCOPY - 2-LEVEL ATOMS.

One can fairly easily write down the basic ideas needed to calculate a crude saturated absorption spectrum for 2-level atoms, which demonstrates much of the underlying physics. The main features are:

- 1) the transmission of the probe laser beam through the cell is  $e^{-\tau(\nu)}$  and  $\tau(\nu)$  is the optical depth of the vapor;
- 2) the contribution to  $\tau(\nu)$  from one velocity class of atoms is given by

$$d\tau(\nu, v) \sim (P_1 - P_2) F(\nu, v) dn(v)$$

where  $P_1$  is the relative population of the ground state,  $P_2$  is the relative population of the excited state ( $P_1 + P_2 = 1$ ),

$$dn \sim e^{-mv^2/2kT} dv$$

is the Boltzmann distribution (for  $v$  along the beam axis), and

$$F(\nu, v) = \frac{\Gamma/2\pi}{(\nu - \nu_0 + \nu_0 v/c)^2 + \Gamma^2/4}$$

is the normalized Lorentzian absorption profile of an atom with natural linewidth  $\Gamma$ , including the Doppler shift. Putting this together, we have the differential contribution to the optical depth, for laser frequency  $\nu$  and atomic velocity  $v$ :

$$d\tau(\nu, v) = \tau_0 \frac{\nu_0}{c} (P_1 - P_2) F(\nu, v) e^{-mv^2/2kT} dv.$$

The overall normalization comes in with the  $\tau_0$  factor, which is the optical depth at the center of resonance line, *i. e.*  $\tau_0 = \int d\tau(\nu_0, v)$  with no pump laser (the integral is over all velocity classes). 3) The populations of the excited and ground states are given by  $P_1 - P_2 = 1 - 2P_2$ , and

$$P_2 = \frac{s/2}{1 + s + 4\delta^2/\Gamma^2}$$

where  $s = I/I_{sat}$  and  $\delta = \nu - \nu_0 - \nu_0 v/c$ .  $I_{sat}$  is called the saturation intensity (for obvious reasons ... if you consider the above formula for  $P_2$  with  $\delta = 0$ ,  $P_2$  "saturates"  $P_2 \rightarrow 1/2$  as  $I/I_{sat} \rightarrow \infty$ ).

The value of  $I_{sat}$  is given by

$$I_{sat} = 2\pi^2 \hbar c \Gamma / 3\lambda^3.$$

For the case of rubidium,  $\Gamma \approx 6$  MHz, giving  $I_{sat} \approx 2$  mW/cm<sup>2</sup>.

The underlying physics in points (1) and (2) should be recognizable to you. Point (3) results from the competition between spontaneous and stimulated emission. To see roughly how this comes about, write the population rate equations as

$$\begin{aligned}\dot{P}_1 &= \Gamma P_2 - \alpha I (P_1 - P_2) \\ \dot{P}_2 &= -\Gamma P_2 + \alpha I (P_1 - P_2)\end{aligned}$$

where the first term is from spontaneous emission, with  $\Gamma$  equal to the excited state lifetime, and the second term is from stimulated emission, with  $\alpha$  a normalization constant. Note that the stimulated emission is proportional to the intensity  $I$ . In the steady-state  $\dot{P}_1 = \dot{P}_2 = 0$ , giving

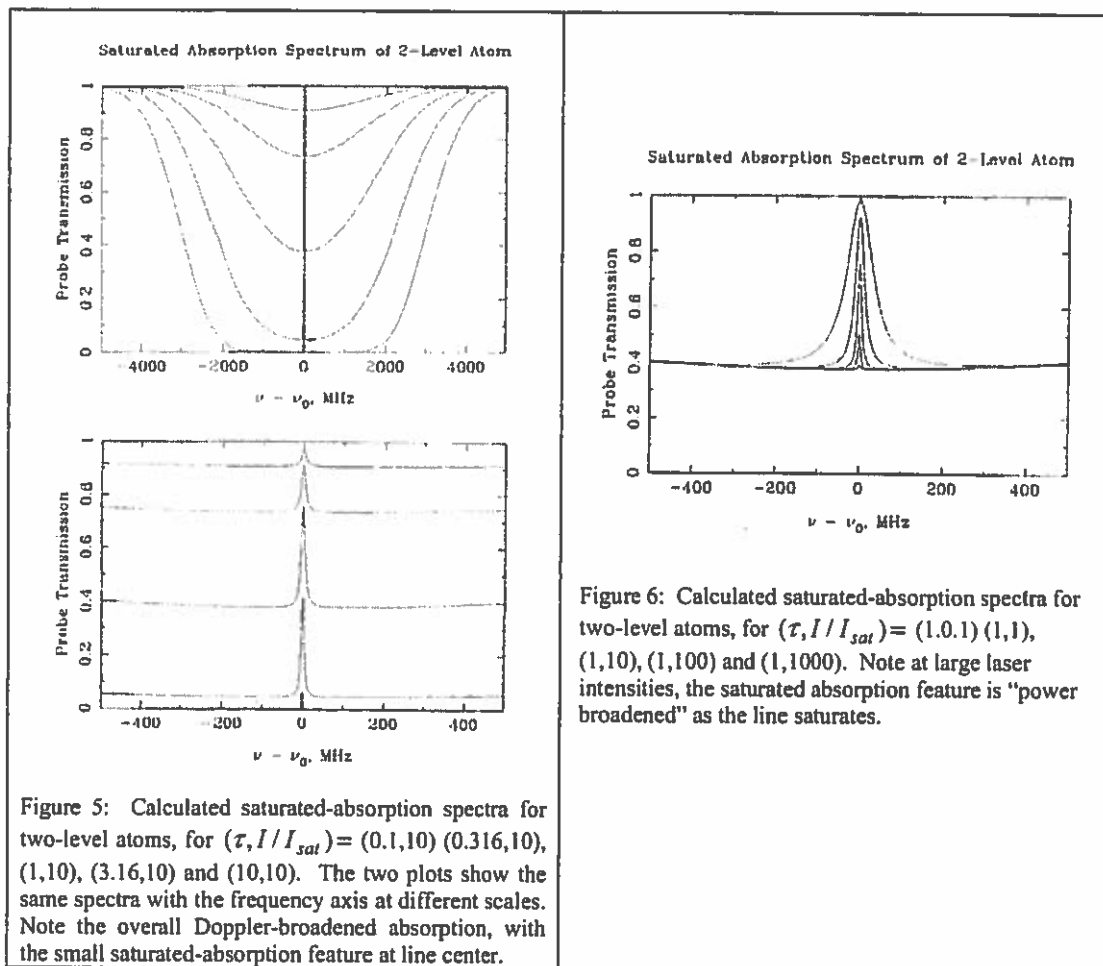
$$P_2 = \frac{\alpha I / \Gamma}{1 + 2\alpha I / \Gamma}$$

The term  $\alpha I / \Gamma$  corresponds to the  $s/2$  term above (note  $I_{sat}$  is proportional to  $\Gamma$ ). A more complete derivation of the result, with all the normalization constants, is given in Milonni and Eberly (1988), and in Cohen-Tannoudji *et al.* (1992), but this gives you the basic idea.

Assuming a fixed vapor temperature, atomic mass, etc., the saturated absorption spectrum is determined by two adjustable external parameters, the pump intensity  $I_{pump}$  and the on-resonance optical depth  $\tau_0$ . The latter is proportional to the vapor density inside the cell. Figure 5 shows calculated spectra at fixed laser intensity for different optical depths, and Figure 6 shows spectra at fixed optical depth for different laser intensities.

In Figure 5 one sees mainly what happens when the vapor density is increased in the cell. At low densities the probe absorption is slight, with a Gaussian profile, and the absorption increases as the vapor density increases. At very high vapor densities the absorption profile gets deeper and broader. It gets broader simply because the absorption is so high near resonance that the probe is almost completely absorbed; for greater vapor densities the probe gets nearly completely absorbed even at frequencies fairly far from resonance; thus the width of the absorption profile appears broader. The saturated-absorption feature in Figure 5 does pretty much what you would expect. The probe absorption is reduced on resonance, due to the action of the pump laser. At very high vapor densities the saturated-absorption feature becomes smaller. This is because while the pump laser reduces the absorption, it doesn't eliminate it; thus at high vapor densities the probe is nearly completely absorbed even with the pump laser. The moral of this story is that the vapor density shouldn't be too low or high if you want to see some saturated-absorption features.

In Figure 6 one sees that if the pump intensity is low, the saturated-absorption feature is small, as one would expect. For larger pump intensities the feature grows in height and width. The width increases because at high laser intensities the effect of the pump laser saturates on resonance, and continues to grow off resonance; thus the width of the feature increases, an effect known as “power broadening.”



Finally, it should be noted that calculating the saturated absorption spectrum for real atoms, which must include optical pumping, many different atomic levels, atomic motion in the vapor cell, and the polarization of the laser beams, is considerably more subtle. A recent paper by Schmidt *et al.* (1994) shows much detailed data and calculations for the case of cesium.

**Problem 1.** Show that  $\tau_0 = \int d\tau(\nu_0, \nu)$  when the pump laser intensity is zero, from the formula above. Hint: the integral is simplified by noting that  $\Gamma \ll \Delta\nu_{Dopp}$ .

**Problem 2.** The above calculations all assume that the pump laser has the same intensity from one end of the cell to another. This is okay for a first approximation, but calculating what really happens is an interesting problem. Consider a simple laser beam (the pump) shining through a vapor cell. If the laser intensity is weak, and the atoms are all pretty much in the ground state, then the laser intensity changes according to the equation  $dI/dx = -\alpha I$ , where  $\alpha = \alpha(\nu)$  depends on the laser frequency, but not on position inside the cell. (In this case,  $\alpha^{-1}$  is called the absorption length.) This equation has the solution  $I(x) = I_{init} e^{-\alpha x}$ , where  $I_{init}$  is the initial laser intensity. The transmission through the cell,  $e^{-\alpha L}$ , where  $L$  is the length of the cell, is what we called  $e^{-\tau}$  above.

Your job in this problem is to work out what happens when the input laser beam is not weak, and thus we cannot assume that the atoms are all in the ground state. In this case  $\alpha = \alpha(\nu, x)$ , which makes the differential equation somewhat more interesting.

Assume the laser is on resonance for simplicity. Then the attenuation coefficient at any position  $x$  is proportional to  $P_1 - P_2$ , which in turn is proportional to  $1/(1+s)$ . Thus we have  $\alpha(\nu_0, x) = \alpha_0/(1+s(x))$ .

In the weak beam limit  $I \ll I_{sat}$  this reduces to our previous expression, so  $\alpha_0 = \tau_0/L$ . Write down an expression which relates the saturation parameter of the laser as it exits the cell  $s_{final}$ , the saturation parameter at the cell entrance  $s_{initial}$ , and the weak-limit optical depth  $\tau_0$ . Check your expression by noting in the limit of finite  $\tau_0$  and small  $s$  you get  $s_{final} = s_{initial} e^{-\tau_0}$ . If  $\tau_0 = 100$ , how large must  $s_{initial}$  be in order to have a transmission of 1/2 (i. e.  $s_{final} = s_{initial}/2$ )?

## V. ATOMIC STRUCTURE OF RUBIDIUM

The ground-state electronic configuration of rubidium consists of closed shells plus a single 5s valence electron. This gives a spectrum which is similar to hydrogen (see attached Scientific American article). For the first excited state the 5s electron is moved up to 5p. Rubidium has two naturally occurring isotopes:  $^{85}\text{Rb}$  (72 percent abundance), with nuclear spin quantum number  $I = 5/2$ , and  $^{87}\text{Rb}$  (28 percent abundance), with  $I = 3/2$ .

The different energy levels are labeled by "term states", with the notation  $^{2S+1}L_J'$ , where  $S$  is the spin quantum number,  $L'$  is the spectroscopic notation for the angular momentum quantum number (i. e. S, P, D, ..., for orbital angular momentum quantum number  $L = 0, 1, 2, \dots$ ), and  $J = L + S$  is the total angular momentum quantum number. For the ground state of rubidium,  $S = 1/2$  (since only a single electron contributes), and  $L = 0$ , giving  $J = 1/2$  and the ground state,  $^2S_{1/2}$ . For the first excited state we have  $S = 1/2$ , and  $L = 1$ , giving  $J = 1/2$  or  $J = 3/2$ , so there are two excited states  $^2P_{1/2}$  and  $^2P_{3/2}$ . Spin-orbit coupling lifts splits the otherwise degenerate  $P_{1/2}$  and  $P_{3/2}$  levels. (See any good quantum mechanics or atomic physics text for a discussion of spin-orbit coupling.)

The dominant term in the interaction between the nuclear spin and the electron gives rise to the magnetic hyperfine splitting (this is described in many quantum mechanics textbooks). The form of the interaction term in the atomic Hamiltonian is  $H_{hyp} \propto \mathbf{J} \cdot \mathbf{I}$ , which results in an energy splitting

$$\Delta E = \frac{C}{2} [F(F+1) - I(I+1) - J(J+1)]$$

where  $F = I + J$  is the total angular momentum quantum number including nuclear spin, and  $C$  is the "hyperfine structure constant." Figures 7 and 8 show the lower S and P energy levels for  $^{85}\text{Rb}$  and  $^{87}\text{Rb}$ , including the hyperfine splitting.

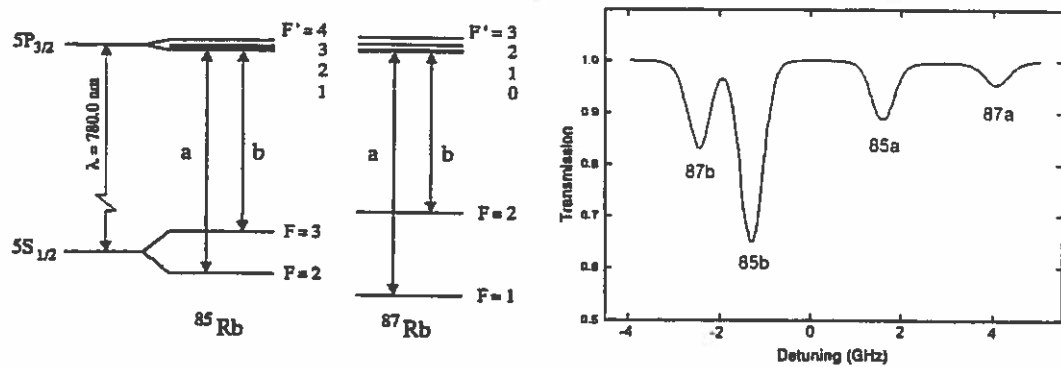


Figure 7: (Left) Level diagrams for the D2 lines of the two stable rubidium isotopes.

(Right) Typical absorption spectrum for a rubidium vapor cell, with the different lines shown.

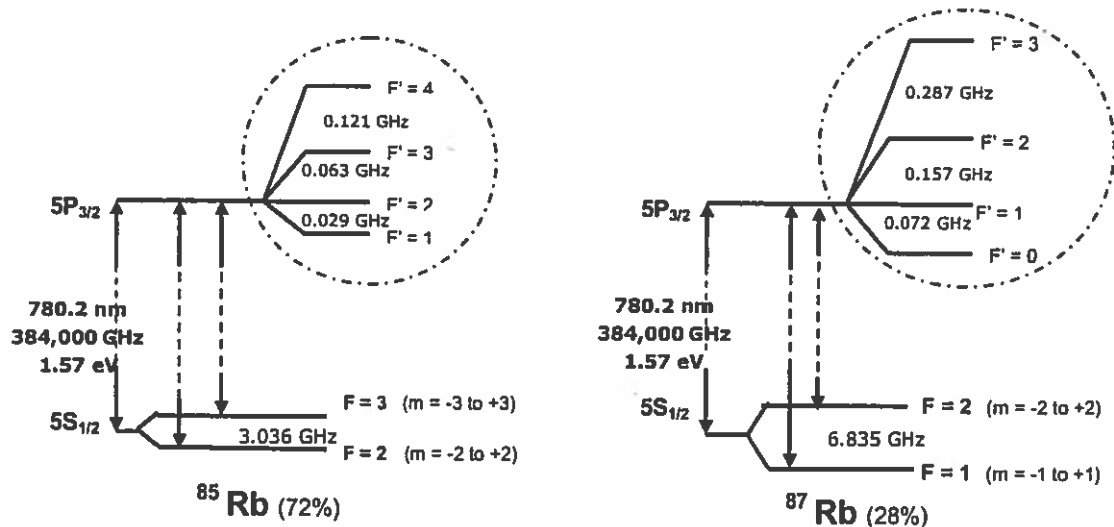


Figure 8: More rubidium level diagrams, showing the hyperfine splittings of the ground and excited states.

## VI. REFERENCES

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Milonni, P., and Eberly, J. 1988, *Lasers*, (Wiley).

Schmidt, O., Knaak, K.-M., Wynands, R., and Meschede, D. 1994, "Cesium Saturation Spectroscopy Revisited: How to Reverse Peaks and Observe Narrow Resonances," *Appl. Phys. B*, 59, 167.



**DIODE LASER SPECTROSCOPY**

# **GETTING STARTED**

**OVERVIEW of the INSTRUMENT  
INITIAL SET UP**

## **I. Overview of the Instrument (See the Apparatus Section 5 for details.)**

### **A. The Laser**

TeachSpin's robust and reliable grating stabilized laser is both temperature and current regulated. When the grating is in place, it provides optical feedback that retroreflects the laser light to create an external cavity that stabilizes the laser to run at a controllable wavelength. A piezo stack, mounted in the grating support, allows the grating position to be modulated by an applied voltage. The laser temperature, laser current and piezo stack modulation are determined by individual modules of the Laser Diode Controller.

A Plexiglas cover over the laser provides isolation from air currents and protects the knobs used to adjust the angle of the grating from accidental changes. There are two holes in the cover to allow the laser beam to exit undisturbed both with and without the diffraction grating in place. (The grating can be removed to study the way the laser behaves without grating stabilization.)

### **B. The Detectors**

Your apparatus is supplied with three photodiode detectors. The detectors contain current to voltage converters. The detector response is linear when the voltage output signal is between 0 and -11.0 Volts so you want to make sure you are nowhere near the -11.0 saturation voltage. A switch on the back of the detector allows you to change the gain setting from 10 M $\Omega$  to 333  $\Omega$  in ten steps. The detectors have separate signal and power cables. Three DETECTOR POWER plugs are on the front panel of the controller. You can send the detector signal directly to an oscilloscope or to the DETECTOR MODULE of the Controller.

### **C. The Absorption Cell Assembly**

The absorption cell assembly consists of an outer glass cylinder, an insulation layer, a heater assembly, a "cold-finger", a thermocouple to monitor the temperature and the gas filled Rb cell itself. The cold-finger is a small piece of metal that fits over a small protrusion on the side of the cell. Because the metal is a good conductor and stays cooler than the cell, any excess rubidium will condense in the protrusion, rather than on the windows of the cell. The heater is both powered by and monitored from the controller.

### **D. The Magnetic Field Coils**

The magnetic field coils are a Helmholtz pair which produces a uniform field at the Rubidium cell. They are used in experiments such as Resonant Faraday Rotation and Zeeman Splitting and must be powered by an external power supply. The Absorption Cell Assembly is mounted at the center, even when they are not in use.

### **E. The Controller**

While almost all functions of the apparatus are controlled by the modules on the front of the Laser Diode Controller, the potentiometer used to set the laser temperature is on the back, to prevent accidental changes. The laser temperature determines the lasing frequency and will be set at the factory. The temperature should be touched only if, for some reason, a check of the Laser Temperature Set Point indicates it has been altered or the diode itself is changed.

The Modules – starting from the right

**DETECTOR/LOW PASS/DC LEVEL:** This module provides power for three detectors and offers two detector inputs and a series of Monitor options. You can look at either detector or a combined signal.

**PIEZO CONTROLLER:** This controls the piezo modulation, which determines the way the angle of the grating is changed and thus the change or “sweep” of the laser frequency. It includes a monitor output.

**RAMP GENERATOR:** This provides a bipolar variable amplitude and frequency triangle wave which can be used, via the RAMP OUTPUT connection, to modulate either or both the piezo stack and the laser current. The resulting changes in the grating angle and current produce the variation or “sweep” of the laser frequency. The RAMP GENERATOR module can supply a wide range of frequencies and amplitudes. The SYNC OUTPUT connection for the oscilloscope is located in this module.

**CELL TEMPERATURE:** The cell temperature is both set and monitored through keys on the LED display. It has been configured by TeachSpin. In case it is accidentally reset, see the Apparatus section for detailed help.

**CURRENT:** The current module controls the current to the laser. It houses a modulation input so that the current can be ramped along with the piezo stack and an attenuator to control the degree of modulation.

**MONITORS:** This set of connectors and indicators, located on the lower part of the cell temperature panel, provides a place to monitor, as a voltage, the set point temperature of the laser as well as the actual temperature and current. The indicator lights indicate the temperature of the laser in reference to the set point.

#### **F. TV and Camera**

The TV and camera will be used to observe both the light coming from the laser and the Rb fluorescence in the vapor cell. While invisible to our eyes, the 780 nm light can be detected by the camera and seen on the TV.

#### **G. The Optics and Connectors**

Your Diode Laser Spectroscopy system comes with a whole collection of bases supports, mirrors, polarizers, neutral density filters and beam splitters which can be combined in a wide variety of ways to do a wide range of experiments that is limited only by your imagination.

## **II. Initial Setup – What to do first** (This may take one or two hours.)

These instructions will help you set up and align your laser for the first time. When you have carried out these detailed steps, your laser will be tuned to the Rubidium resonance lines. Once aligned, it is unlikely that the laser will need any more than minimal tweaking.

#### **A. Unpacking and Setting Up the Laser**

1. The room used for your diode laser should be able to be closed to other users, first so that you can dim the room lights, but most importantly so you can have absolute confidence that no stray laser beams can escape and potentially cause harm to anyone.

2. Unpack the various components from their shipping containers and place everything on a table with plenty of room to work.
3. Place the Controller at one end of the optical breadboard. (we find it easier to put the controller and laser on the right side of the board – the laser connection is behind the left end of the controller.)
4. Mount the laser on one end of the breadboard so that the beam will go across the board. (Before making placing the laser head on the board or making connections to it, ground yourself to remove electrostatic voltages.)
5. Remove the protective plug from the laser head 9-pin D-connector. Connect the laser to the controller using the 9-pin D-cable provided, which plugs into the back of the controller.
6. Make sure the laser power switch (located on the left side of the controller, on the front) is in the **off** position. Then plug in the laser controller power cord and turn on the main power switch (located in the back, near the power cord).

**B. Setting up the Absorption Cell Assembly** – the cell takes a while to get to optimum temperature so you want to have it heating up while you do other things.

1. Slide the Absorption Cell Assembly into the Magnetic Field Coils and secure it.
2. Place the assembly on the breadboard so that the laser beam will go through the cell. Put it eight inches or so away so that you have room to work between it and the laser.
3. Connect both cables from the cell assembly to the back of the controller. You will notice that the polarity of the banana plug heater wires does not matter. The polarity of the blue thermocouple connector, however, does matter. It will only plug into the blue receptacle one way.
4. When the power is turned on, the Cell Temperature controller (LED display on front panel) will first reset and then display the cell temperature. In five or ten minutes the cell temperature will be close to its factory established set-point temperature of 50 °C.\* You may check and/or change the cell temperature set-point as follows:
  - a) Press the leftmost button on the cell temperature controller. It is marked by a circular arrow. The temperature controller will read SP1.
  - b) Press the rightmost button on the cell temperature controller. The cell set-point temperature (in degrees C) will now be displayed.
  - c) You can press the up/down arrow buttons to change the set-point. Start with a temperature of 50 °C.
  - d) Press the rightmost button. The display will read SP2
  - e) Press the leftmost button twice. The display will read RUN momentarily, then it will read the cell temperature.
  - f) The cell temperature should read near the set-point after several minutes. You may proceed with the next step before the final temperature is reached. The Cell Temperature controller is not critical to operation of your diode laser. It merely improves the signal strength by increasing the rubidium density in the cell. See Theory section for a plot of Rb pressure versus temperature.

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\* A starting temperature of 50 °C was chosen to give a nice strong absorption signal (about 90%). Once you become familiar with the system you may want to work at a lower temperature.

Trouble shooting: If the controller is not working as described please refer to the Apparatus section of the manual under Cell Temperature Controller for how to configure and set your controller. It is possible your controller became reset during shipping or by a student (the ever-present scapegoat).

### C. Starting up the Laser

*Operating note: The diode laser frequency depends on temperature. If not set correctly, you may not be able to get your laser to tune to the Rb resonance lines. The optimal temperature was determined at TeachSpin and is recorded on the data sheet.*

#### 1. Check the Diode Laser temperature:

- a) Use a voltmeter to read the TEMPERATURE SET-POINT in the MONITORS section of the controller chassis. This voltage should equal the Temperature Set-point recorded on the data sheet shipped with your laser. If it does not, adjust the 10-turn potentiometer on the back of the chassis to obtain the correct set-point.
  - b) Make sure the LASER TEMPERATURE INDICATOR lights are both off. If either of these is on, then the laser temperature has not yet reached its set-point temperature. With a voltmeter connected to the LASER DIODE TEMPERATURE pin jacks, you may monitor the laser temperature.
2. PUT ON SAFETY GOGGLES. Your laser typically runs with an output optical power of 10-30 mW, all concentrated into a narrow, intense beam. Staring directly at the Sun sends about 1 mW into your eyes, and **this is already enough to cause permanent eye damage**. To make matters worse, the laser light has a wavelength close to 780 nm, which is nearly invisible. Practice proper laser safety – anyone that is in the room and can see the laser, should wear safety goggles when the laser is on.
  3. Set the laser CURRENT potentiometer fully counterclockwise (low current) then turn the LASER POWER switch on.

### D. Aligning the Laser

1. Locate the IR viewing card. The sensitive area of the IR card is a dull orange color. This contains a polymer that absorbs UV light from the ambient lights in the room, especially fluorescent lights. The polymer molecules are then excited into a metastable state, and incident IR light from the laser can induce a transition that emits visible light. (Note the IR card will not work well if the room lights are off for an extended period.) The IR card allows you to “see”(actually locate) the laser beam even when you are wearing your protective goggles, since the goggles do not block the visible light emitted by the polymer.
2. Hold the IR card at the laser output (the hole in the plastic cover of the laser) while you turn up the laser CURRENT knob. You will need to turn the knob 3-4 turns before the beam becomes detectable on the card.

### 3. Set up the TV and Assemble the TV camera:

- Put the TV monitor near the controller and set it up to display camera image.
- Connect the power cable of the camera to the 12V power supply provided, and connect the camera output cable to the TV monitor. You should see an image on the monitor.
- Place the TV camera, mounted on an optical post, into a post holder. Then the camera can conveniently be placed on the optical table with the laser and other optical components.

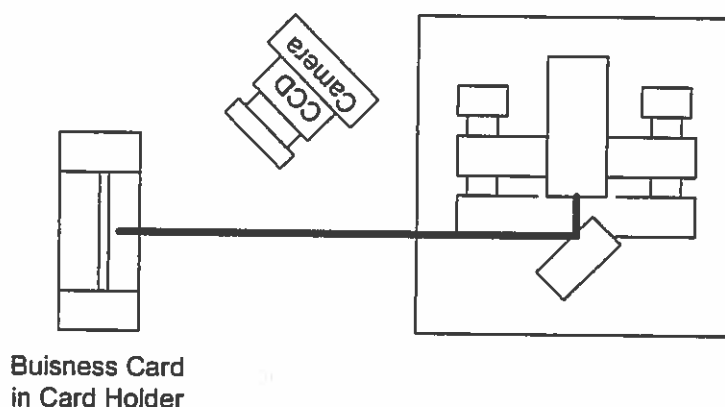


Figure 1. External Cavity Alignment

*Operating note: The camera lens can be focused over a broad range of working distances, from infinity to as close as a few centimeters. The focus is adjusted by turning the lens. Do NOT shine the laser beam directly into the TV camera, for this may damage the CCD sensor.*

- Place a business card in the Neutral Density Filter holder and locate it so that it intercepts the laser beam see Figure 1. Focus the TV camera on the card. Dim the room lights and turn the laser current to zero. Now increase the current while watching the TV monitor. You will see a light spot that becomes slightly brighter as you increase the current. Your diode laser is below threshold, it is not lasing, but only acting as an LED. As you continue to increase the current you will observe a sudden brightening of the beam spot and the appearance of a speckle pattern characteristic of lasing.
- \* Adjust the current so that the laser is just above threshold. You can measure the laser current with a voltmeter. A diode current of 50 mA. will give 5.0 Volt output on the LASER CURRENT in the MONITORS section. You can compare your measured value with the threshold current recorded on your data sheet. A lower threshold current represents better optical alignment. Do not be concerned if your threshold current is slightly higher than that recorded on your data sheet. You will align the cavity in the next few steps after which you can measure the threshold current again.

*Note: Your laser was shipped with the laser aligned. In many cases it will need little if any adjustment. The following steps will allow you to check the alignment and optimize it, if necessary.*



5. Look at the laser head itself. You will see two knobs protected by the plastic cover. The upper or top knob controls vertical alignment. The lower or side knob provides a wavelength selective horizontal alignment. Before beginning your alignment, it is important that you have read the first section of this manual Diode Laser Physics. It will be much easier to follow the procedure if you have some idea of the physics behind these adjustments. This may be the most difficult procedure you will need to follow in this experiment. For the uninitiated it is very easy to totally misalign the laser, which can be both frustrating and time consuming. If you are not familiar with diode laser adjustment, we ask that you follow each step closely. If you have trouble or do not observe what is described in a given step, do not go on to the next step! We have tried to anticipate possible problems and direct you to the solution. We also do not want to make you overly timid by this statement. Alignment of the external laser cavity is something that any experimental physicist can accomplish. You will need to become facile in the alignment, not only because your students may misalign the cavity, but also because eventually your diode will burn out, and you will have to replace it. This will involve an alignment of the cavity, starting from scratch.

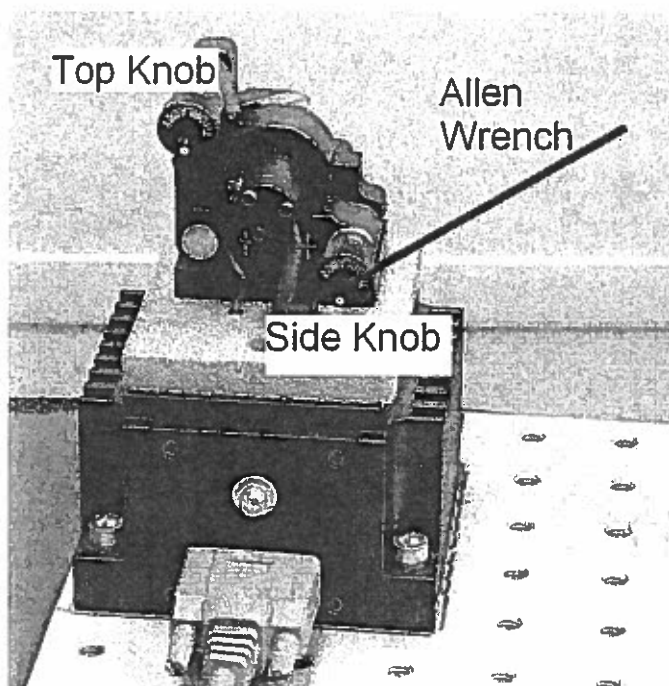


Figure 2: Picture showing TOP and SIDE Knobs used to align grating. Allen wrench is shown in Side Knob.

6. Vertical Alignment: Remove the plastic cover from the laser and set the current so that the laser is just above threshold. Adjust the TOP knob while watching the laser spot on the card using the TV camera. Keep track of where this knob started, and **DO NOT TURN THE KNOB MORE THAN ONE HALF TURN**. You may find it useful to use the 5/64" Allen wrench placed in the back of the knob as a position indicator. It is also easier to make small adjustments of the knob by using the long arm of the Allen wrench as a lever.

You should see the laser spot change in intensity as the TOP knob is turned. If you rotate the TOP knob very slowly, you will notice that the bright "region" actually changes from bright to dim. These are modes of the laser. You should be able to distinguish six to ten of these modes, with fewer modes when the current is just above threshold. You are seeing different longitudinal modes in the external cavity defined by the grating and back facet of the diode. As you turn the top knob you are not only changing the grating angle but also the external cavity length. You have changed the cavity length by one half wave length when you move from one bright peak to the next. You will need to have to set the current just above threshold to see this clearly. This may involve a few iterations of setting the TOP knob to give an intensity maximum and then adjusting the laser current.

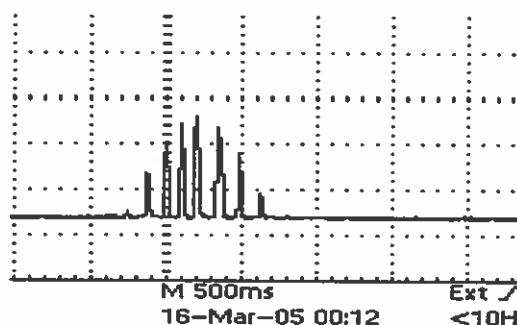


Figure 3, at the right, shows an oscilloscope trace of the intensity of the laser as the TOP knob is adjusted. It will give you an idea of how the brightness of the spots you are seeing is varying. It is hard to tell the middle ones apart. For best alignment leave the laser in the middle of this vertical mode pattern as best you can. It is not necessary to sit right on one of the mode maxima, but only near the center of the mode pattern. The correct mode

maximum will be set later with the side horizontal adjustment knob and piezo voltage.

Note that finger pressure on the knob also changes the grating alignment, so remove your fingers often during this adjustment. If you find it difficult to turn the knob with a light touch, then you can use the Allen wrench placed in the back of the knob as a lever for adjustment.

It is not critical for operation of your laser that you achieve near perfect vertical alignment of the grating. You will get adequate laser performance by simply turning the TOP knob to the intensity maximum. However, it has been found that the better the alignment the better the operation of the laser. Better operation being defined as wider mode-hop-free scans.

If you are not able to see any change in laser intensity as you adjust the Top knob then **STOP!** Do not continue. Most likely both the SIDE and TOP knobs have both been moved by accident or during shipping. Please refer to "Aligning the external cavity" in the Apparatus section of the manual.



*Operating note : The TOP and SIDE knobs are used to align the grating with respect to the diode. The lines on the grating run vertically. Figure 2 shows the diode laser with the cover off and the 5/64" Allen wrench placed in the SIDE knob. The first order diffraction from the grating is directed back into the diode. The zero order reflection from the grating is the light you observe leaving the laser. The TOP knob rotates the grating about an axis that is parallel to the table top. Turning the TOP knob changes the vertical angle of the light diffracted from the grating. But to first order it does not change the wavelength of the light that is diffracted back into the laser. The SIDE knob rotates the grating about an axis that is perpendicular to the table top. Turning the SIDE knob does change the wavelength of the light that is diffracted back into the diode.*

### E. Setting up to Observe Rubidium Fluorescence

1. Remove the index card and position the Rubidium Absorption Cell Assembly so that the laser beam passes through the center of the cell. You may use the IR viewing card to trace the path of the beam.

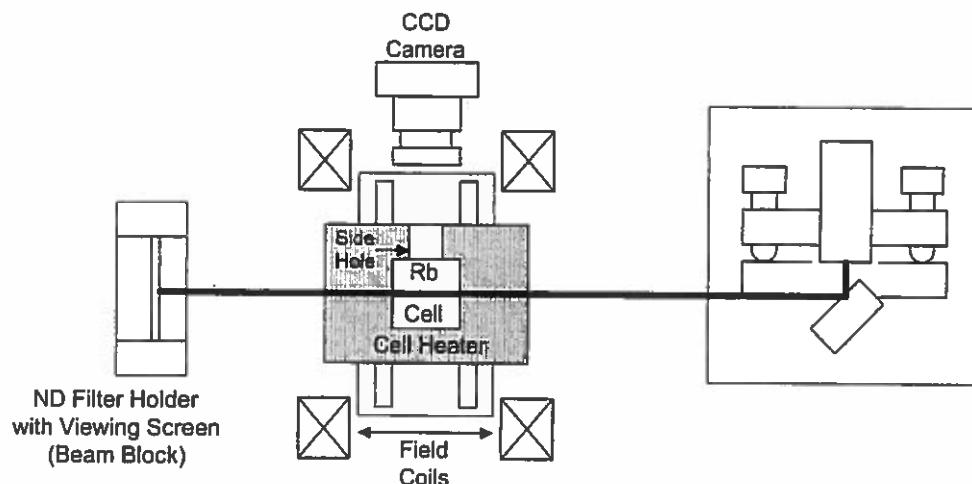


Figure 4. Setup for Observing Rubidium Fluorescence

2. Point the camera so it looks into the Rb cell from the Side Hole in the cell heater. If you place the camera up on the base of the cell holder you can position the camera so that it abuts the glass holder surrounding the Rb cell. It may also be helpful to dim the room lights since you will be looking for the fluorescence light emitted by the Rb atoms.
3. Set up the two channel oscilloscope that you will use for these experiments. Run a BNC cable from the RAMP OUTPUT of the RAMP GENERATOR module to an oscilloscope. Run a second cable from the RAMP GENERATOR SYNC. OUTPUT to the 'scope trigger. Observe the output on the 'scope as you adjust the RAMP GENERATOR settings.

#### 4. Use The RAMP GENERATOR and PIEZO CONTROLLER to Set the Frequency Sweep

- a. Turn the ramp amplitude down and connect the RAMP OUTPUT from the oscilloscope to the modulation input connection on the PIEZO CONTROLLER MODULE. This is a good place to use one of the short BNC cables that came with the system.
- b. Connect the MONITOR OUTPUT of the PIEZO to Channel 1 of the oscilloscope. Turn the piezo OUTPUT OFFSET knob to zero. (The OUTPUT OFFSET changes the DC level of the monitor output. It does not change the voltage applied to the piezo stack. This control is used when locking the laser to an absorption feature and is not needed here.)
- c. Set the ramp generator frequency to about 10 Hz. Turn the piezo ATTENUATOR knob to one (1). Set the ramp generator AMPLITUDE knob to ten (10) and use the DC OFFSET knob of piezo controller to produce a large-amplitude triangle wave that is not clipped at the top or bottom. The piezo MONITOR OUTPUT should have a signal that runs from about 3 volts to about 8 volts.

*Operating note: The PIEZO CONTROLLER drives a small piezoelectric stack that moves the optical feedback grating. This scans the laser frequency (see the Diode Laser Physics section of this manual for more on how this works).*

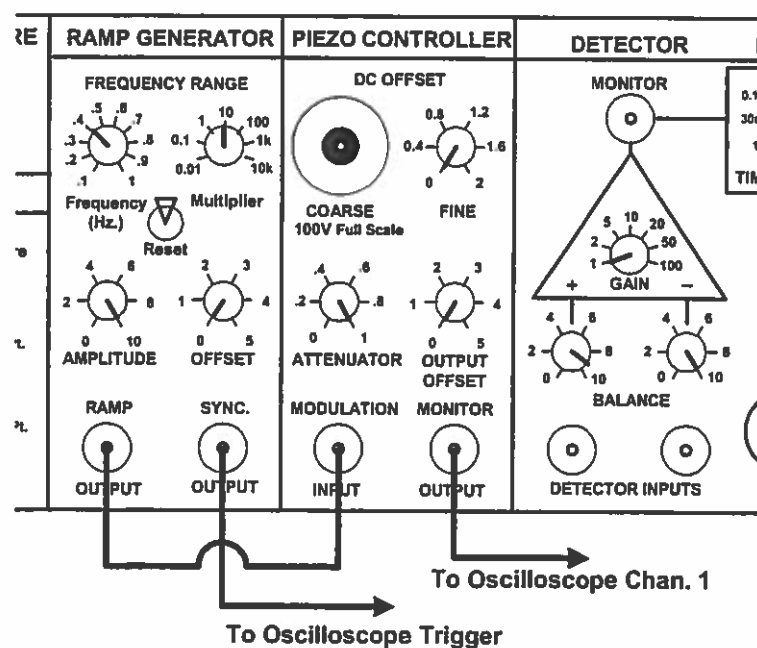


Figure 5: Modules showing connections for setting the frequency sweep.

#### F. Actually Finding the Rb Fluorescence, Initial Horizontal Adjustment

1. Set the laser current to the value listed on your data sheet. You will need to connect a voltmeter to the LASER CURRENT MONITOR to accurately set the current. If the horizontal grating position has not been changed much during shipping or because of accidental adjustment, then you will see a flashing streak of light within the cell on the TV monitor. This is rubidium fluorescence. Atoms of Rb in the cell, absorb laser light at the atomic resonance frequency and re-emitting it in all directions. *If you do not see any fluorescence, do not despair. You only need to make a slight adjustment of the SIDE knob.*
2. Put the 5/64" allen wrench (hex key) in the back of the SIDE knob and use it as a rotation marker. Remember the starting position of the wrench; you could even draw a little picture in your lab book. While you observe the TV screen looking for the fluorescence flash, slowly rotate the SIDE knob first one way and then the other. You should not need to rotate it more than one half turn in either direction.
3. If still no fluorescence is observed, then return the SIDE knob to the starting position, and adjust the current in 3mA increments (about 1/3 of a turn) both above and below the Laser current recorded on you data sheet. At each new current setting rotate the SIDE knob again, so that you don't lose your position, always return the knob to its starting position before changing the laser current. If you do NOT see any fluorescence, first repeat the above steps again, doing them with care. You might have someone else go through the steps as well. It's easy to miss some detail and thus not observe fluorescence. In particular check the laser temperature, the vertical alignment, and make sure you are sweeping the piezo.\*
4. If you still see no fluorescence then you can try making bigger excursions in the grating angle with the side knob (plus and minus one whole turn). It may be that the Cavity became grossly misaligned during shipping, refer to section A4-2. in the appendix for details on aligning the external cavity.
5. Once you see the fluorescence flash move the SIDE knob so that the fluorescence is always visible. Now adjust the laser current to make the fluorescence as bright as possible.

#### G. Observing the Absorption Spectrum Using a Photodiode Detector

1. Connect a Photodiode Detector (PD) cable to the DETECTOR POWER output of the laser controller, and connect the Photodiode Detector output BNC to Channel two (2) of the oscilloscope. Set the Channel two (2) input coupling to DC, the gain to 5 Volts/div, and the vertical position so that ground is in the middle of the oscilloscope display. The signal from the Photodiode Detector is *negative* and saturates at about -11.0 volts. *If you are uncomfortable observing a negative going signal, you can always use the invert function on your 'scope.*

---

\* You can check that the piezo is actually moving by doing the following. With the Ramp generator connected to the Piezo modulation input, turn the AMPLITUDE of Ramp to zero, change the ramp frequency to about 3 kHz. And then increase the AMPLITUDE. You should be able to hear the piezo vibrate. WARNING: Do not leave the piezo running at high frequency and amplitude for a long time. It will cause heating and damage to the piezo.

2. Put the Photodiode Detector in place to intercept the laser beam coming through the Rb cell. You can move the PD for alignment. You will have to adjust the Gain on the back of the PD. Make sure that the beam is hitting the sensor and bolt the photodetector down.

*Operating note: In the present configuration there is a very high intensity beam (power per unit area) going through the Rb cell. This much power "saturates" the transition, resulting in very little total absorption of the beam.*

3. Attenuate the Signal Reaching the Detector
  - a) Assemble the glass neutral density filter in a fixed mirror holder and place it in a post holder. Please refer to the Optics section in the Apparatus Chapter of the manual if you are unfamiliar with putting optical components into mounts.
  - b) Place the attenuator between the laser and the Rb cell (not between the cell and photodiode). Adjust the PD Gain so you can observe something on the 'scope showing that light is hitting the PD. For the best performance you want the PD Gain to be as high as possible without saturating the PD. This keeps the noise from the PD at a minimum. The PD gain changes in 1,3,10 steps, a signal level of 2 to 6 volts is reasonable. Block the beam with your hand to convince yourself that the PD is detecting the transmitted laser light.

You should see a 'scope signal that looks something like this:

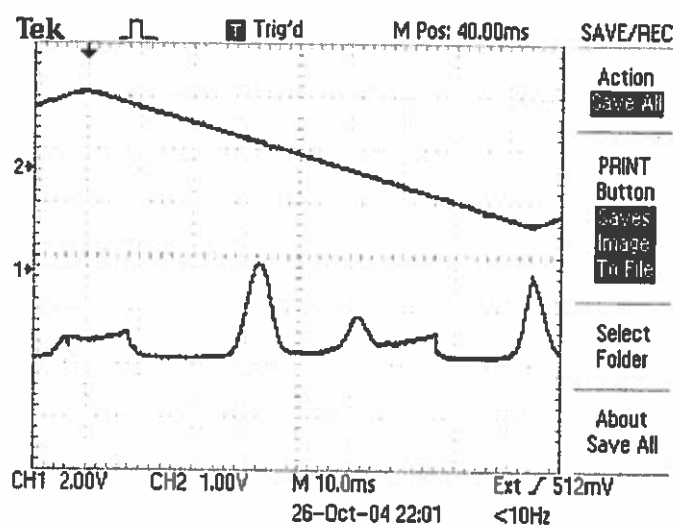


Figure 6: Upper trace (Channel 1) shows piezo monitor signal. Lower trace (channel 2) shows Detector output. Note that signal is "negative going" so absorption features appear as spikes.

#### 4. Interpreting the Oscilloscope Signals

- a) The upper trace shown in Figure 6 is the piezo monitor, which shows the voltage on the piezoelectric stack as a function of time. The lower trace is from the photodiode, showing absorption dips due to the Rb vapor. Because we have a negative going signal, these appear as spikes. If the laser scanned “perfectly” in frequency (that is no mode hopping), you would see just some fraction of the Rb absorption spectrum. The energy levels of  $^{85}\text{Rb}$  and  $^{87}\text{Rb}$  and the Doppler broadened spectrum are shown below:

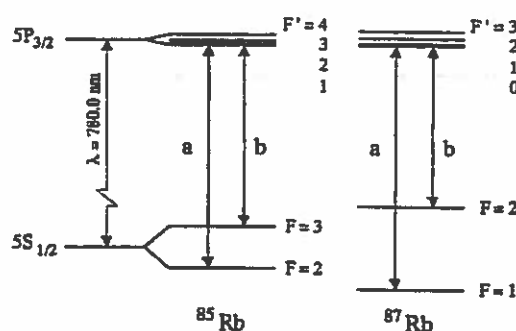


Figure 7: Energy level Diagrams

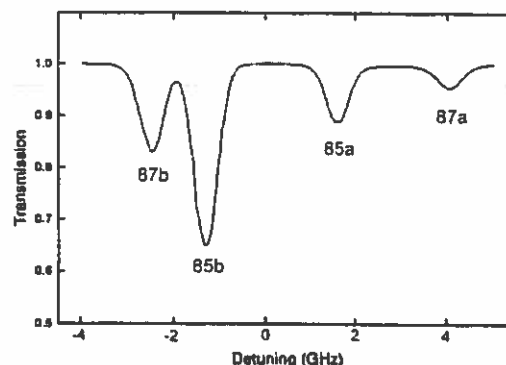


Figure 8: Doppler broadened spectrum

- b) The absorption dips in your trace are interrupted by various “mode hops” – when the laser frequency jumps suddenly. Refer to the Diode Laser Physics section for a discussion of mode hops. Observe how the signal changes when you vary the laser current and the piezo drive parameters. Please explore the parameter space.

#### H. Horizontal Modes, Final Horizontal Adjustment

1. Adjust the laser current and piezo voltage so that a “nice” absorption spectrum is centered on the oscilloscope. This takes a little practice. As with the vertical adjustment, there are also horizontal modes. These modes are slightly different, in that turning the horizontal move through two or three of these modes by changing the piezo DC LEVEL voltage.
  - a) Place the 5/64” allen wrench (hex key) in the back of the SIDE knob with the long arm of the allen wrench sticking out at about a 45° angle. (See picture at step 15). You will use the allen wrench as a lever to gently move through the horizontal modes.
  - b) Watch the oscilloscope display as you gently push on the end of the allen wrench. You should be able to identify six to eight modes in which the Rb absorption is still visible on the oscilloscope. You want to set the Side knob in the middle of this mode pattern.
  - c) You might notice that the modes at the ends have a shorter and more erratic scan over the Rb absorption. You do not need to make an exact adjustment with the Side knob as the Piezo DC OFFSET voltage can be used to fine tune to the mode. With proper alignment and laser current adjustment you should be able to set a scan that covers the first three lines in the absorption spectrum (87b, 85b, and 85a as shown in Figure 9).

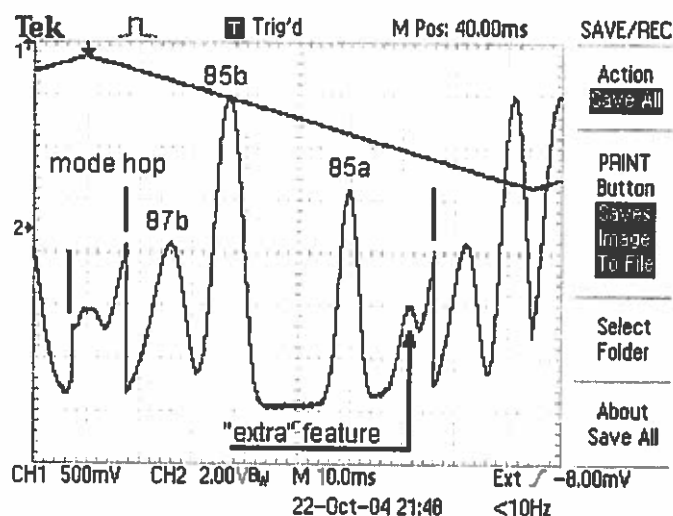


Figure 9: Scan showing first three absorption lines

2. You may notice a few “extra” features at the ends of a scan right before a mode hop. These feature look like (and are) replicas of the strong 85b and 87b absorptions and appear near where you would expect to find the 87a absorption. The “extra” features are associated with relaxation oscillations in the diode laser. (See Diode Laser Physics Section). By reducing the laser current and adjusting the Piezo DC LEVEL, you should be able to get a nice scan showing the 85a and 87a features. This is shown in Figure 10.

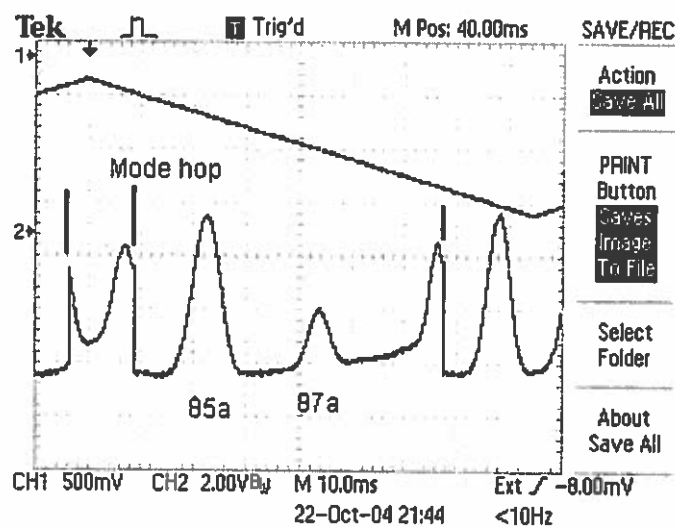


Figure 10: Scan improved by adjustments to laser current and piezo DC level.

- I. **Using Simultaneous Current and Piezo Modulation** to produce a larger scan range without mode hops. (See the Diode Laser Physics section for an explanation.)
1. Set the laser CURRENT ATTENUATOR knob to zero. Attach the BNC splitter "F" connector to the RAMP OUTPUT on the RAMP GENERATOR. Plug one BNC from the RAMP OUTPUT to the MODULATION INPUT of the PIEZO CONTROLLER, and the second BNC from RAMP OUTPUT to the CURRENT MODULATION INPUT.
2. Turn the ramp generator amplitude up to maximum, and watch what happens when you turn up the current attenuator knob. With some tweaking you should be able to produce a full trace over the Rb spectrum. *The oscilloscope invert function has been used to show the trace in what "looks" more like an absorption spectrum in the Figure 11.* Note the correspondence to the expected atomic Rb spectrum shown in Figure 8

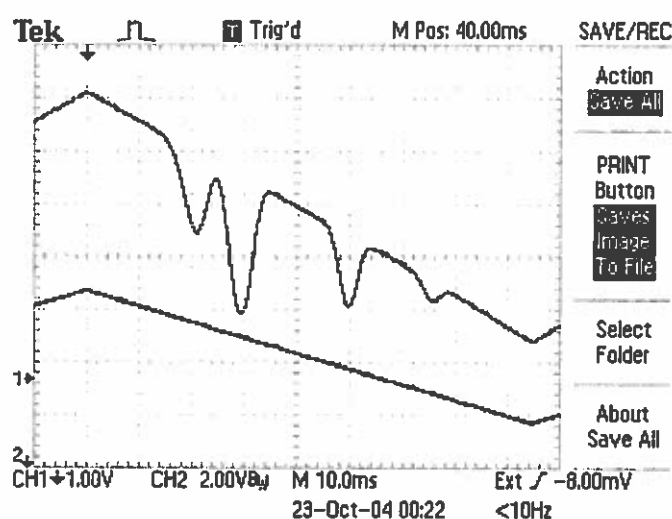


Figure 11: Expanded Scan Showing Four Absorption Lines

*Operating point: The depth of the lines depends on the length of the Rb cell and the atomic density, the latter depending on cell temperature. You can explore this by changing the cell temperature.*

3. You can see in the above that the background intensity changes considerably with the scan. This is because you are now scanning the laser intensity (via the current) together with the laser frequency (via the piezo). You can correct for this effect in a number of ways. One way is to digitally record a spectrum with the cell in place, and then record a second spectrum with the cell removed, and finally divide the two signals in software. This has the advantage that only a single photodetector is needed, but the disadvantage that the two traces are not recorded simultaneously. Another way to accomplish this is by using a second photodiode, as in the following layout.

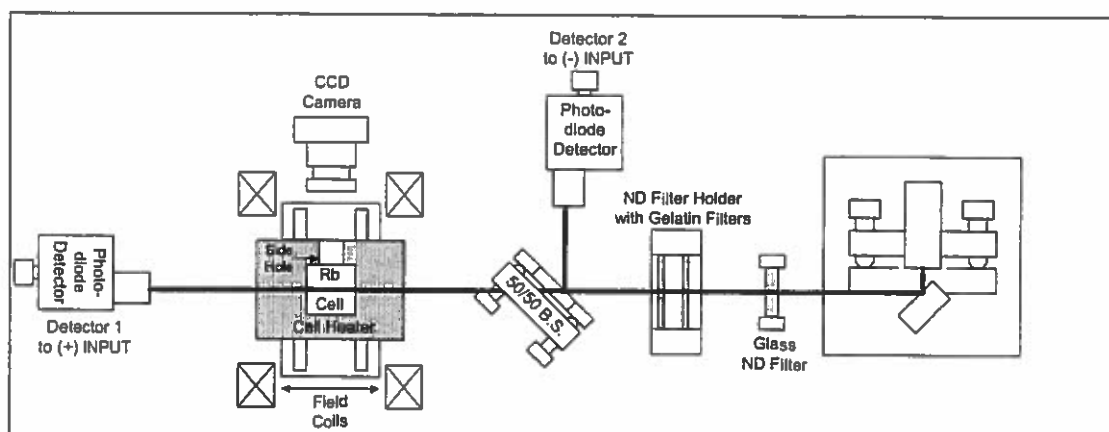


Figure 12: Apparatus set up to use two detectors

**J. Using Two Photodiode Detectors to Compare a Beam directly from the Laser to one that has passed through rubidium vapor**

1. You will need to place the 50/50 Beam splitter in a mirror mount. Please refer to the Optics section in the Apparatus Chapter of the manual if you are unfamiliar with putting optical components into mounts.
2. With this experimental configuration you will detect two simultaneous signals, one with and one without the Rb absorption, and then subtract the spectra. You will use the Detector electronics on the Laser Diode Controller.

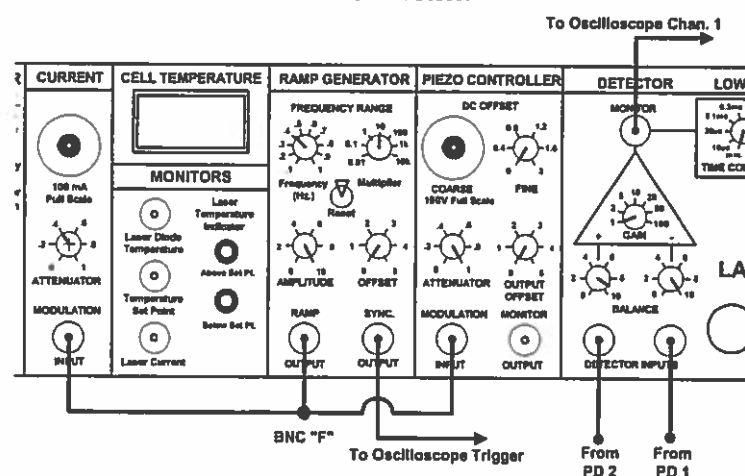


Figure 13: Controller Modules showing connections for using two photodiode detectors

3. Connect the BNC from the Photodiode Detector 1 to the right most (-) DETECTOR INPUT. (This will invert the signal from PD 1 so that absorptions will show as dips.) Set the BALANCE knob above the (-) INPUT to 1.0 (fully CW). Set the GAIN to 1. Connect a BNC Cable from the MONITOR connector above the gain triangle to Channel 1 on the 'scope.



Change the BALANCE knob and observe the effect on the 'scope. Position a second Photodiode Detector to intercept the beam that has been split off by the Beam Splitter. Connect the power cable of the detector to one of the open ports. Connect the BNC from Photodiode Detector 2 to the (+) or left most DETECTOR INPUT. Set the BALANCE knob above the (+) INPUT to 1.0 (fully CW) and turn BALANCE knob above the (-) INPUT to 0. Adjust the Gain on the back of Photodiode Detector 2 for a "good" (2-6 volts) level signal on the 'scope and position the photodiode for a maximum signal. Now increase the BALANCE knob above the (-) INPUT to 1.0 and adjust the BALANCE to get a spectrum like the one is Figure 14.

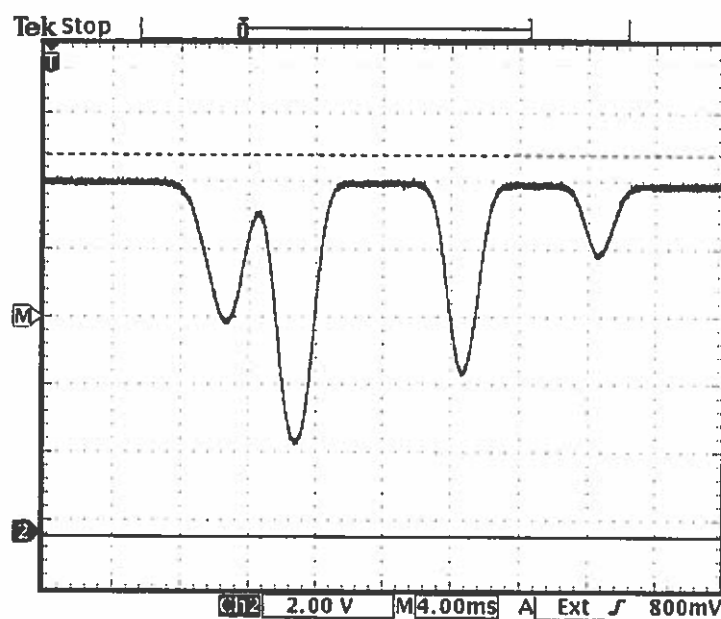


Figure 14: Trace for Channel 1 only showing the combined signal from the detectors. Subtracting the signals removes the effect of "ramping" the current. The beams reaching both detectors are varying at the same rate and the BALANCE controls are used compensate for any difference in intensity.

The trace shows an excellent correspondence to the expected spectrum, with all four Rb absorption dips on a flat background. Note, however, that the subtraction technique does not immediately give an absolute measurement of absorption, while the digital method does.

*Operating note: You should always be wary that zero light on a photodiode may not correspond to zero voltage output. You can check this by simply blocking the beam and noting the voltage*

### **K. All Finished**

At this point the initial alignment is complete, and you are ready to move on to the more sophisticated spectroscopy experiments. You may need to realign the grating feedback from time to time, following the above procedures. If not disturbed, however, the alignment will likely be stable for months.

### **L. Shutting Down**

If you are not using the laser for a few hours for some reason, you can leave the controller on. Then the diode laser and the Rb cell will stay at their operating temperatures and be ready to go when you need it.

**BUT TURN THE LASER CURRENT OFF.** You should turn the laser current down, and the laser power switch off, whenever you leave the lab. This is a safety precaution, plus it will prolong the life of your laser. With use the diode laser will eventually burn out and need to be replaced, so leave the laser itself off when not in use.

It's okay to leave the ramp generator and piezo controller on and running at whatever setting you wish (for examples, the settings determined above). You can also leave the Rb cell temperature at whatever setting you wish. Then these will be set up when you want to use the laser – just turn on the laser power switch and turn up the current. After the laser warms up briefly, you should have essentially the same spectrum you had when you turned the laser current off.

We do not recommend leaving the controller on overnight and unattended even if the laser current has been turned off.

### III. Observing Saturated Absorption

#### A. The Optical Plan

There are countless ways in which the optics could be configured to do observe the Saturated Absorptions Spectrum (SAS of Rubidium. A complete diagram of the configuration we will guide you in building is shown below in Figure I. (A different layout is used in the lab notes from Caltech which are at the end of this manual.)

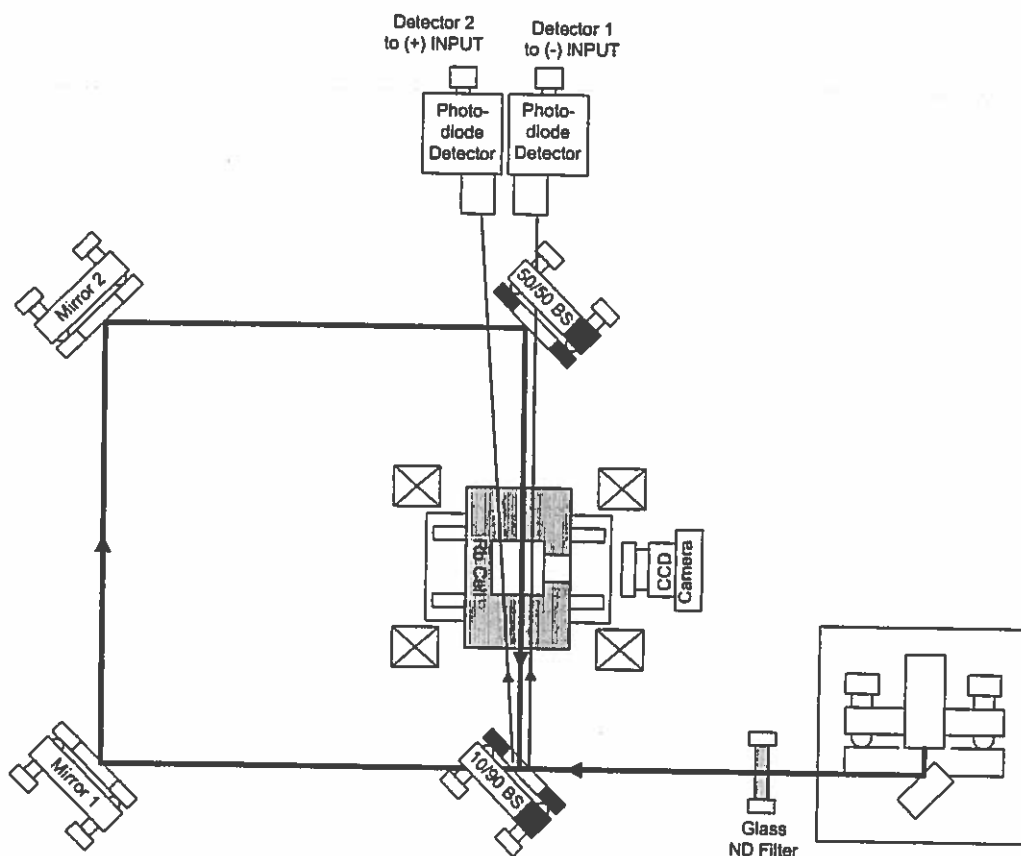
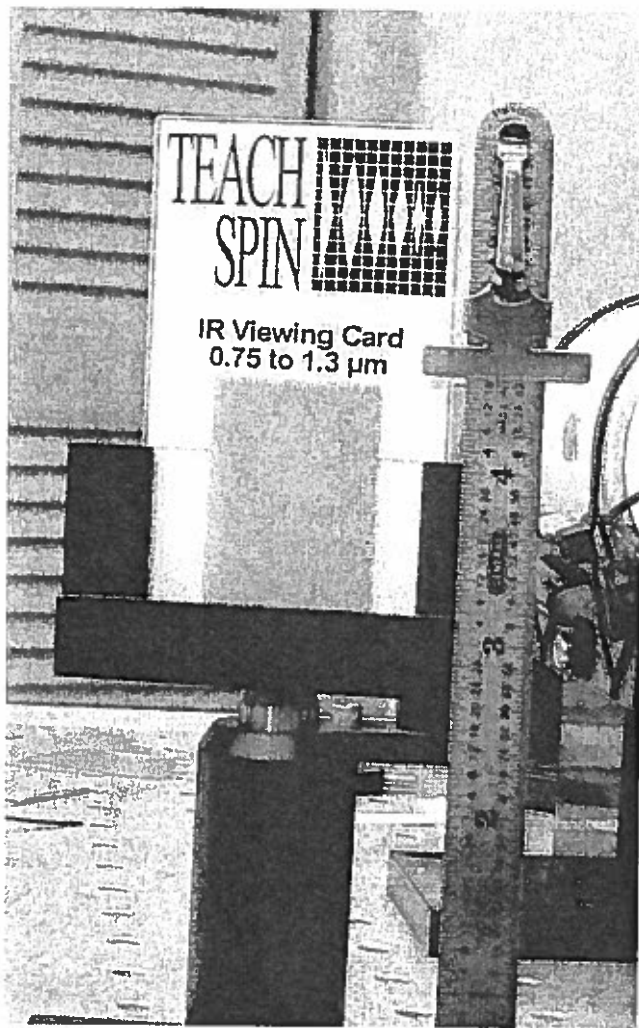


Figure I. Complete SAS setup

#### B. Some Basics Before We Begin

1. Keep the beam height above the table constant as you bounce the beam off the mirrors. Since the center of the absorption cell and the laser are 4" (10 cm) above the table top, the beam should be there also. You can use the viewing card to check the beam height. Place the viewing card in the neutral density beam holder so that the marked line matches the top of the holder. Now, set the height so that the top edge of the holder, and thus the center of the viewing card, is 4 inches above the tabletop.



2. When placing optics, try to start with the beam centered in the optic. This gives you maximum adjustment range before the beam “walks off” the end of the optic and you have to reposition the mount.
3. When using the optical mounts to hold beam splitters, observe that there are two possible configurations of the mount. When looking at the mount from above, the upper adjustment screw can be placed on the right or the left. If placed on the wrong side, the support for the upper adjustment screw will block the transmitted beam. *The upper screws are shown with a blackened edge in the figures below.* To change orientations, you must remove the mount from the post and use the orthogonal mounting hole.
4. Spend a bit of time planning your optical layout before you start.

### C. Placing the Components

Now that you have completed the Initial Setup and have observed the Doppler broadened absorption spectrum of Rubidium you are ready to look for saturated absorption.

1. Make sure you have two mounted mirrors, a 10/90 and a 50/50 beamsplitter assembled.
2. Reconfigure the apparatus you have been using into the layout shown in Figure 2. (This is only part of the complete SAS setup. We'll add the rest later.)

*BE SURE TO HAVE A BEAM BLOCK IN PLACE AS SHOWN*

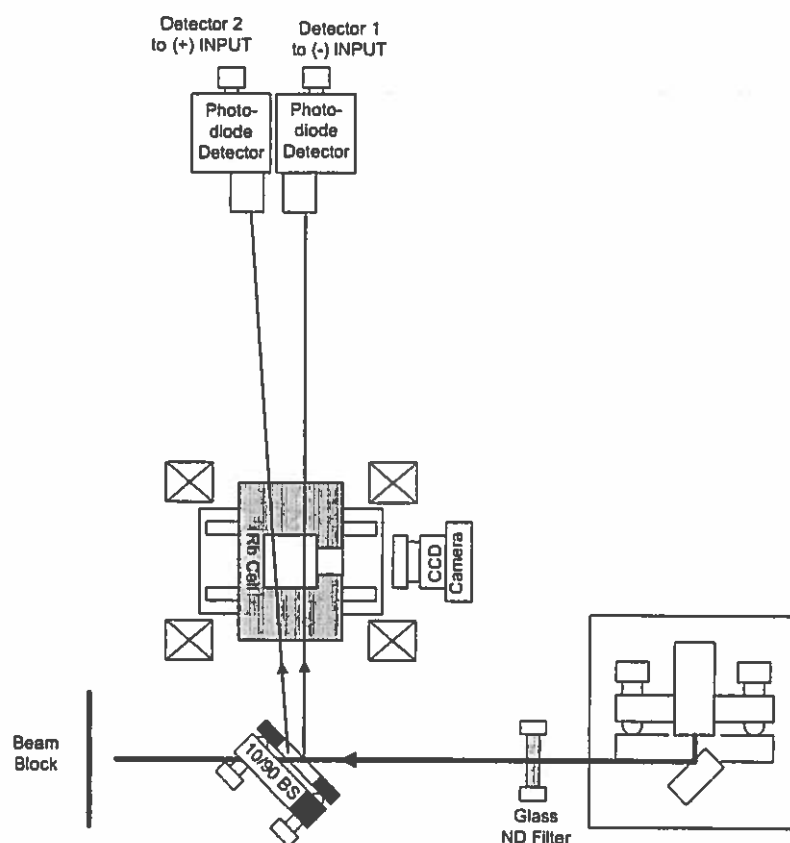


Figure 2. Start of SAS setup with  $1^\circ$  wedged beam splitter in place

We have used the  $1^\circ$  wedged beam splitter which yields two reflected beams, one from each face. The small angle of the wedge causes the beams to diverge slowly so that both beams can travel through the cell to the two photodetectors. The second photodetector (PD) is not needed to "see" the SAS. It is used in the final electronic subtraction to remove the absorptive background signal. If you do not intend to use this electronics "trick," you can leave the second detector out of the setup. Position the PD's to maximize the signal level from each.

Monitoring the output of the Detectors, you should observe the now familiar Rb absorption spectrum on your 'scope.

- Now, add the two turning mirrors to the setup, as shown in Figure 3. Move the Beam Blocker to the new location shown.

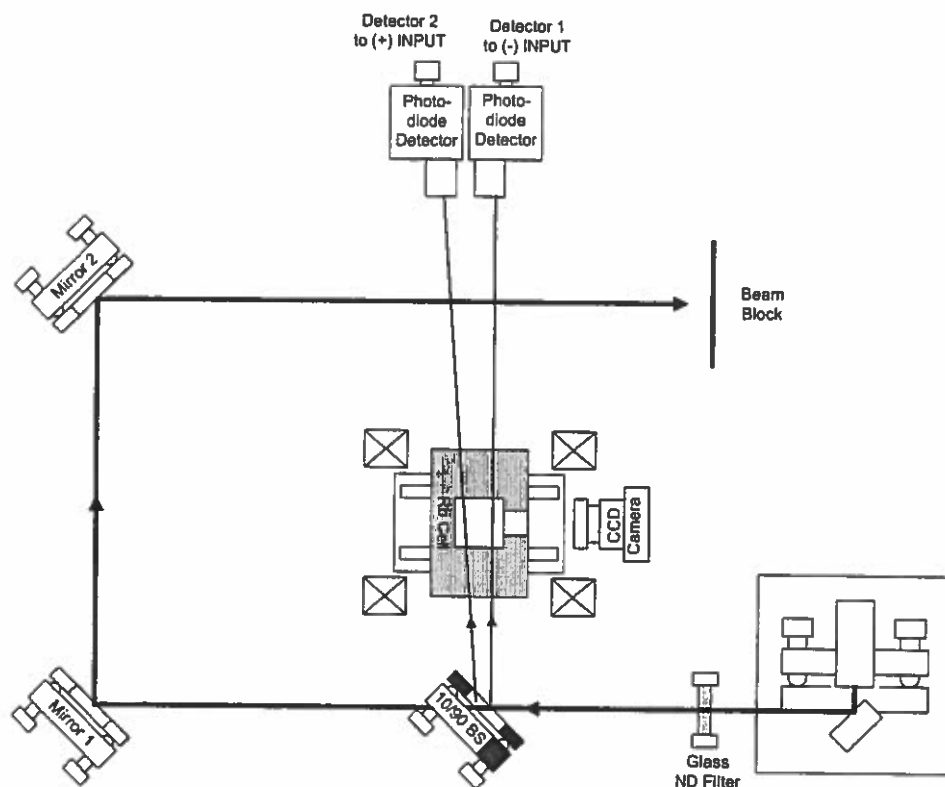


Figure 3. Turning mirrors added to setup.

#### D. Understanding the Functions of the Beams

We are now ready to add the important 50/50 beam splitter as shown in Figure 4. But first let's talk about the motivation for all the beams flying around. The initial 10%/90% beamsplitter has generated two weak 'probe' beams, and you've seen that each of them, passing through the cell to a photodetector, is a probe of the transmission of the cell. But the stronger beam transmitted through the 10/90 beamsplitter has now been brought around to the far side of the cell, and is ready to be sent through the cell, in the opposite direction of the probe beams, and overlapping one of the two probe beams inside the cell. (You want to overlap the beam going to Detector 1.) The stronger beam is called the 'pump' beam, and what it 'pumps' is the atoms being probed by only one of the two probe beams. Because we are using a 50/50 beamsplitter, only half the pump beam is sent through the cell, and only half of the probe beam gets through to the photodetector, PD1. The important function of the 50/50 BS, however, is to create the desired anti-parallelism of the pump beam and one of the probe beams.

There are two fine points to observe in Figure 4. First note the upper adjustment knob on the 50/50 BS mount is on the side such that the probe beam can pass through the mount. You should also observe that the mount is placed such that the beam going to Detector 1 passes through the 50/50 beam splitter, but the beam going to Detector 2 misses both the beam splitter and the edge of the mount that is holding the BS. With the 50/50 beam splitter in place, we are ready to align the strong pump beam so that it is anti-parallel to the weak probe beam going to detector 1. (You may want to read the appendix that has a short discussion of the algorithm used to position a beam in space.)

Remove the glass ND filter from the beam path. This will make it easier to see the two beams. Use the IR viewing card to observe the beams at position 1 which is right before the probe beam goes through the 50/50 BS. The IR viewing card has a circular hole on its backside so that you can observe beams from both directions.

Use the adjustment screws on Mirror 1 or 2 to overlap the two beam spots at position 1.

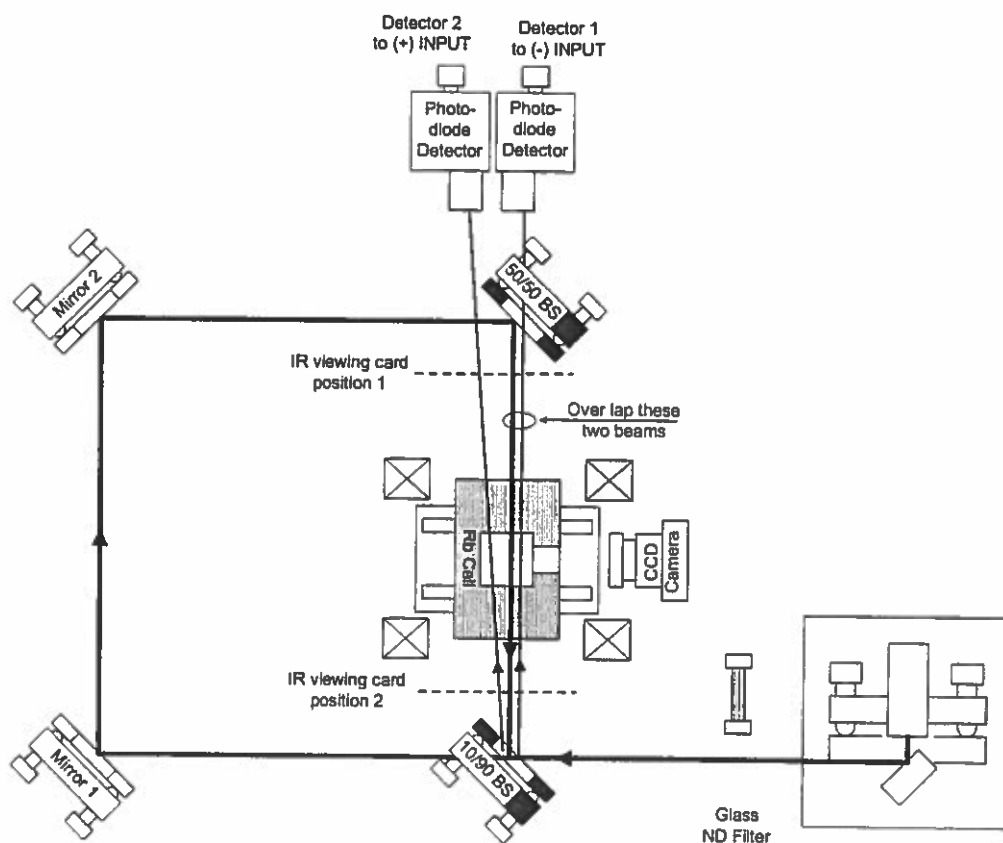


Figure 4. Aligning pump and probe beams.

Now, move the IR viewing card to position 2 (between the Rb cell and the 10/90 BS). Use the adjustment screws on the 50/50 BS mount to overlap the two beams at this position. It is very likely that the strong pump beam will not be visible at position 2 initially. You may have to loosen the screw that secures the post on the 50/50 BS and rotate it till you can find the beam.

If all else fails and you cannot get the beams to overlap easily, you can temporarily move the Rb cell and magnet off to the side so that you can trace the pump beam path from the 50/50 BS. Once the beams are overlapped at position 2, move back to position 1 and check the beams. Again use the mirrors to overlap the beams here. After a few iterations, you should be able to get the pump beam and one of the probe beams overlapping in space and anti-parallel in direction.

Now replace the glass ND filter (and the Rb cell, if you removed it) into the beam path. Look at the absorption signal on the oscilloscope. Expand the scale so that you can observe the two large absorption features. If your beams are close to being aligned, you will start to see some sharp spikes within the broad absorptions. See Figure 5. These "spikes" indicate that the ability of the rubidium atoms to absorb photons from the probe beam has been *diminished*; more light from the probe beam is actually reaching the detector. This is because atoms which, in the past, would have absorbed the probe beam photons are already in the excited state because they have absorbed photons from the "pump" beam. You may now try to maximize the size of these spikes by tweaking the adjustment screws on the mirrors and the 50/50 BS.

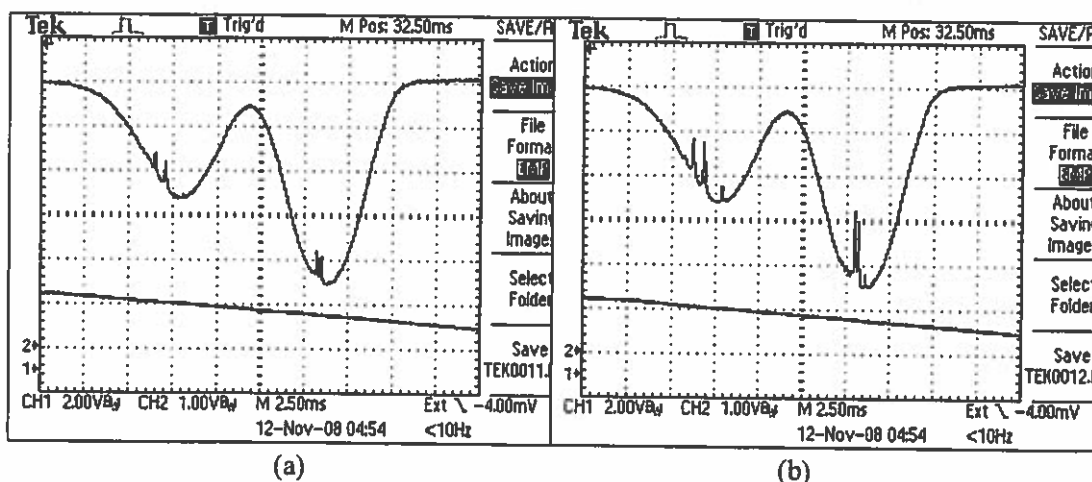


Figure 5. Observation of SAS features

- (a) Beams are partially overlapped and some SAS signal is visible
- (b) Signal after tweaking of mirrors and 50/50 beamsplitter.

If you are "too" good at this alignment, the two beams may be so perfectly anti-parallel that the strong pump beam comes through the cell and, bouncing off the 10/90, is reflected back into the laser. When this happens, the laser will no longer scan through the spectrum continuously, but in a series of steps. You may observe a spectrum that looks like that shown



in Figure 6. This feedback is undesirable, but it does show that you have perfected the alignment of the two beams. Now you can slightly misalign the two beams such that the feedback does not corrupt the smooth scan of the laser.

You may have noticed that the Caltech lab notes show an opto-isolator right after the laser. The opto-isolator will stop this feedback from getting into the laser, but it is not essential for operation of the system. Another technique to reduce feedback is to put more ND filters in the beam path. An added filter attenuates the reflected beam twice, once on the way out and again on the return trip.

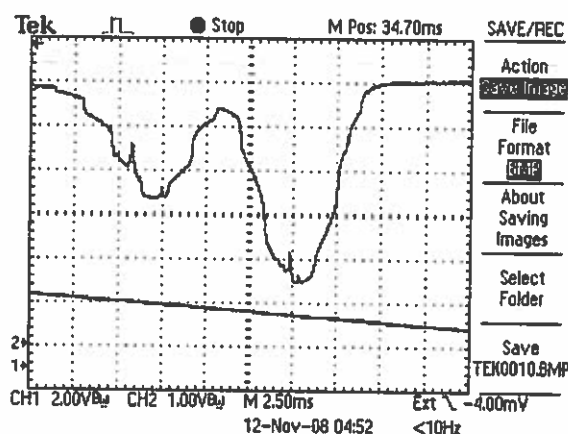


Figure 6. When the anti-parallelism is too close to perfect, there is feedback into the laser that corrupts the frequency sweep. The 'staircase' appearance of the absorption profile is the indication of this.

If you have set up the second photodetector, you will now be able to use an electronics "trick" to isolate the SAS features. To preview this capability, send the two photodetector signals to the two channels of an oscilloscope, and adjust things until you can see what's similar about the two signals, and what's different. Now you are ready use the detector electronics section of your electronics box to isolate that difference. (You will be subtracting out most of the broad absorption signal.)

Put the signal from Detector 1 into the minus input and that from Detector 2 into the plus input of the detector section of the electronics box. Attach the monitor output to the 'scope. Set the plus balance control to zero and the minus balance control to one and observe the signal from Detector 1 on the 'scope. Adjust the gain on Detector 1 so that you have a large signal (several volts) but not so large as to saturate the detector (maximum signal less than 10 volts). Now, set the plus balance to one and the minus balance to zero and observe the signal from Detector 2. It will be inverted, with negative voltage values. Again adjust the gain of Detector 2 for a signal level that is comparable to that seen by Detector 1. Because the beam going to Detector 2 is not attenuated by the 50/50 beam splitter, the gain needed on Detector 2 will be less than that of Detector 1. (Typically Detector 1 needs a gain setting of 1.0 M $\Omega$  and Detector 2 a gain of 330 k $\Omega$ .)

Now set both balance knobs to one and then reduce the balance on the larger signal so that the Doppler broadened background is removed. This subtraction is never perfect, so there will always be some residual broad absorption signal remaining. You may now raise the gain setting on the difference signal and bring the SAS spikes up to the volt level. You are now ready to record some beautiful SAS traces.

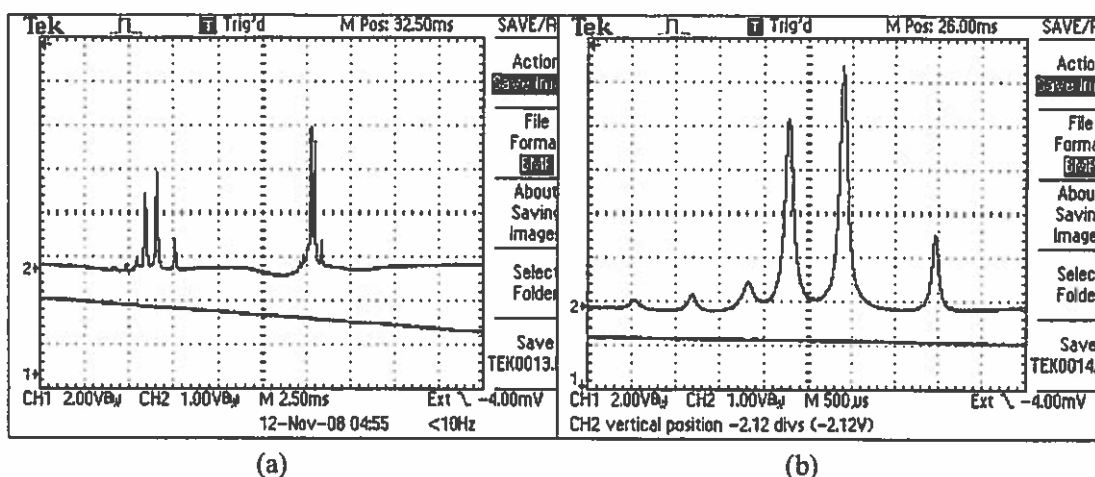


Figure 7. SAS traces with background subtraction.

(a)  $\text{Rb}^{87}$   $F=2$  and  $\text{Rb}^{85}$   $F=3$

(b) Expanded view of  $\text{Rb}^{87}$   $F=2$ .

It is interesting to study these signals as a function of the intensity in each of the beams. The above traces are power broadened. To observe the narrowest linewidths, you will have to work at very low optical power levels in both the pump and the probe beams. You can use neutral-density filters to attenuate the beams. You will also need to darken your room to minimize ambient light falling into your photodetectors.

## IV. Aligning a Michelson Interferometer

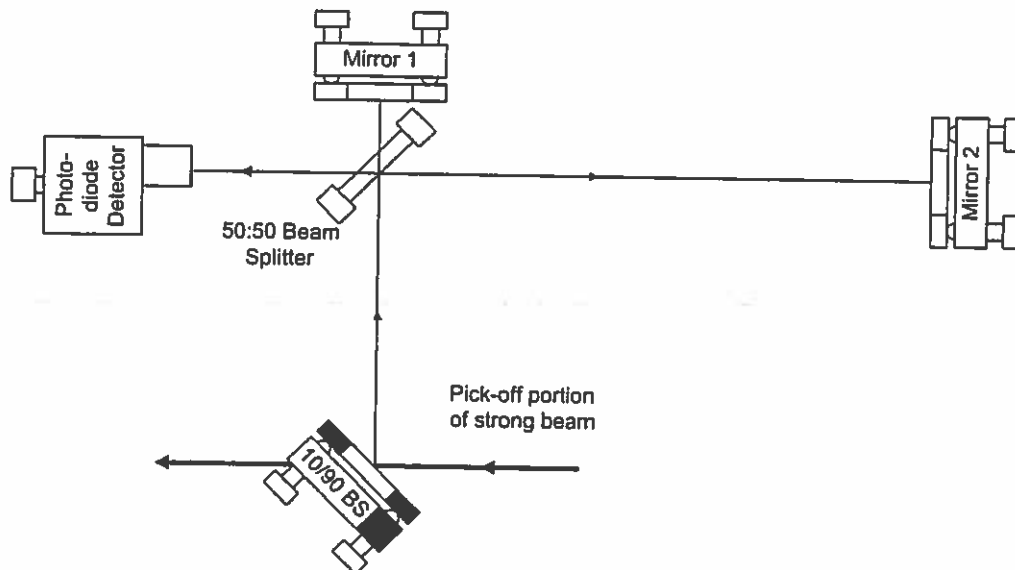


Figure 1: Overview of un-equal arm Michelson.

Find a spot on the table to lay out the Michelson interferometer (MI). You must use the filter holder to hold the 50/50 Beam Splitter (BS). A mirror mount will not allow the beam to come in and exit from all four directions. This complicates the alignment as one can only make coarse adjustments of the 50/50 BS.

Keep Mirror 1 as close to the 50/50 BS as possible.

Use a wedged or flat piece of glass as the 10/90 BS to pick off a fraction of the laser beam.

Now look at Figure 2 below. We will use a business card with a hole punched in it to observe the reflected beam from each of the mirrors. Adjust the business card and card holder so that the incoming beam goes through the hole. Use the CCD camera to observe the beam reflected from the mirror. Adjust the mirror to send the outgoing beam back through the same hole.

Do this for both mirrors as shown in Figure 2.

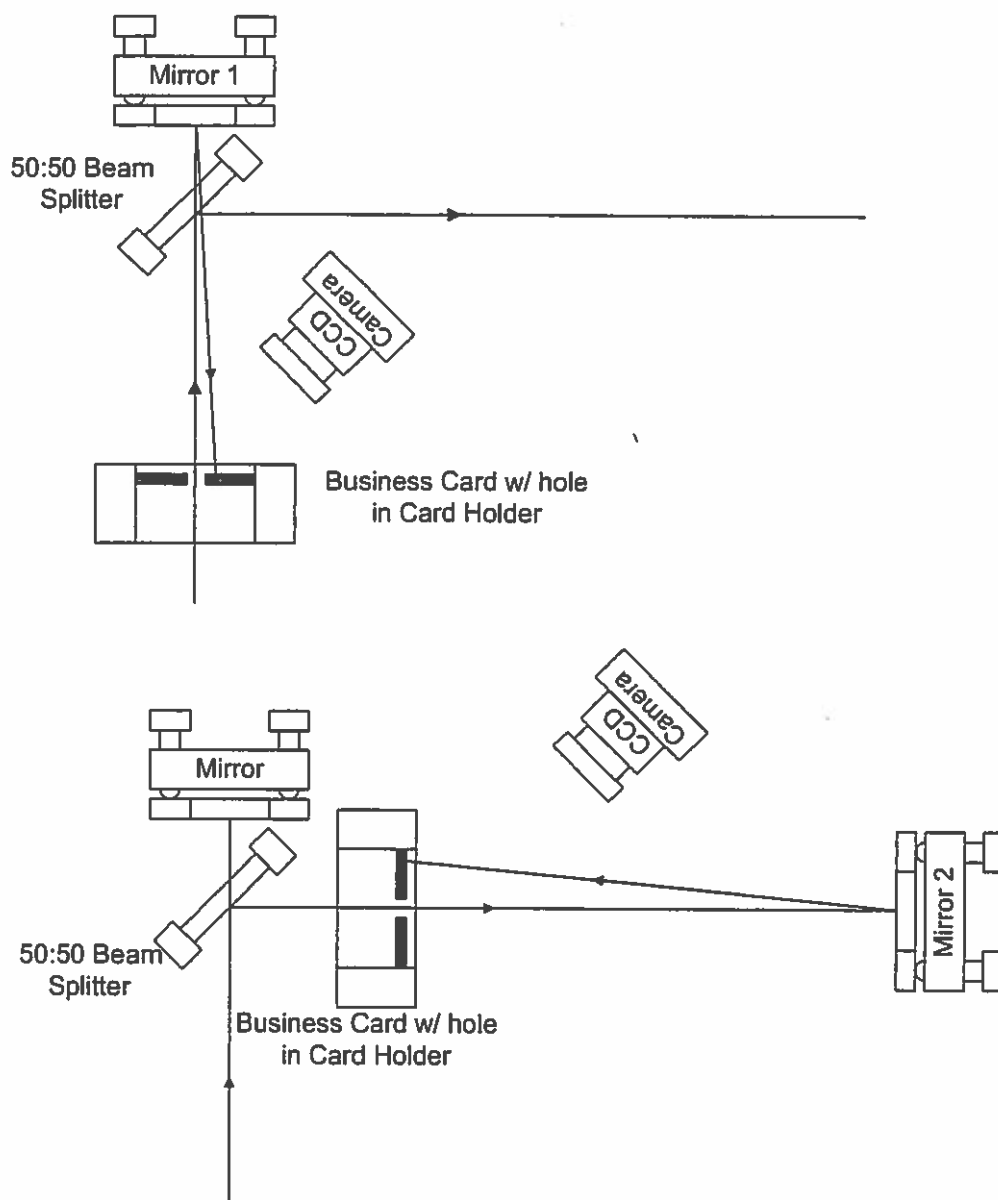


Figure 2: Use a business card with a hole punched in it to roughly align two mirrors.

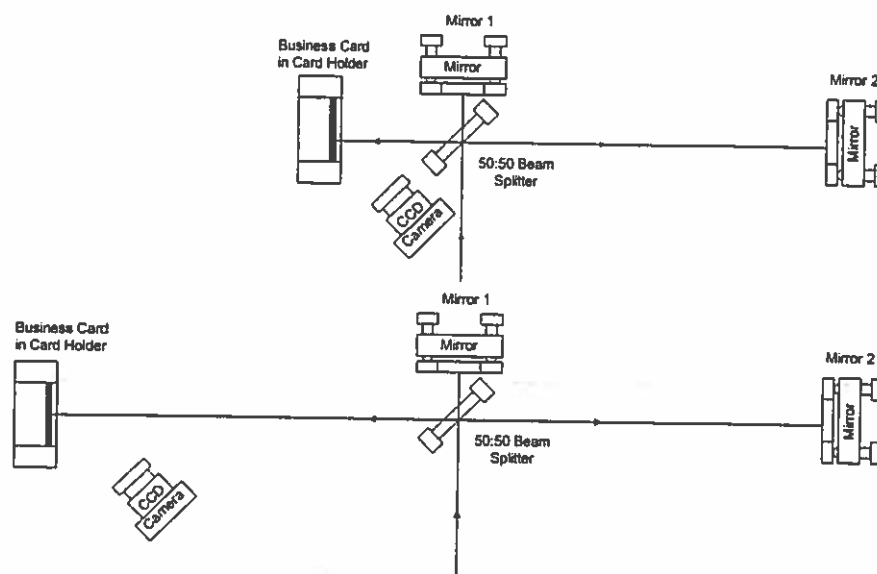


Figure 3 Iterative procedure to get two beam co-linear.

Now move the Card holder to the position shown in Figure 3. (Upper) You should see two beams on the card, one from each mirror.

With the card holder close to the 50/50 BS adjust mirror 2 to make the two beams overlap.

Then move the card holder to a position far from the 50/50 BS (a few feet, 1/2 meter or so.) Again, you should see two beams, now adjust mirror 1 to make the beams overlap.

Go back to the near position and repeat.

In a few iterations, you should start to see some fringes appear in the overlapped area of the two beams.

You will not see any fringes if the laser is scanning its wavelength, so turn off the wavelength scan during this part of the operation. (Set the Ramp Generator attenuator to zero.)

Once you see some fringes you can still repeat the above steps a few more times. If done correctly the fringe spacing should become larger as the alignment approaches optimum. Gently pushing on one of the mirror mounts should cause the fringe pattern to change.

Now put a photodiode in the beam and restart the laser scan. You should be able to see some nice periodic modulations of signal from the photodiode.

I find that a contrast ratio of 10% is about the best I can do. (minimum intensity is 10 % of maximum intensity.)

Other tips:

Remove the glass Neutral density filter from the laser beam when doing the alignment. This will help make the beams easier to see. You will have to replace the filter when you want to make scans.

Feed back from the interferometer can get back into the laser and corrupt the scan. If this is a problem adding more attenuators after the glass neutral density filter will help.

## V. Appendix – Making Beams Collinear

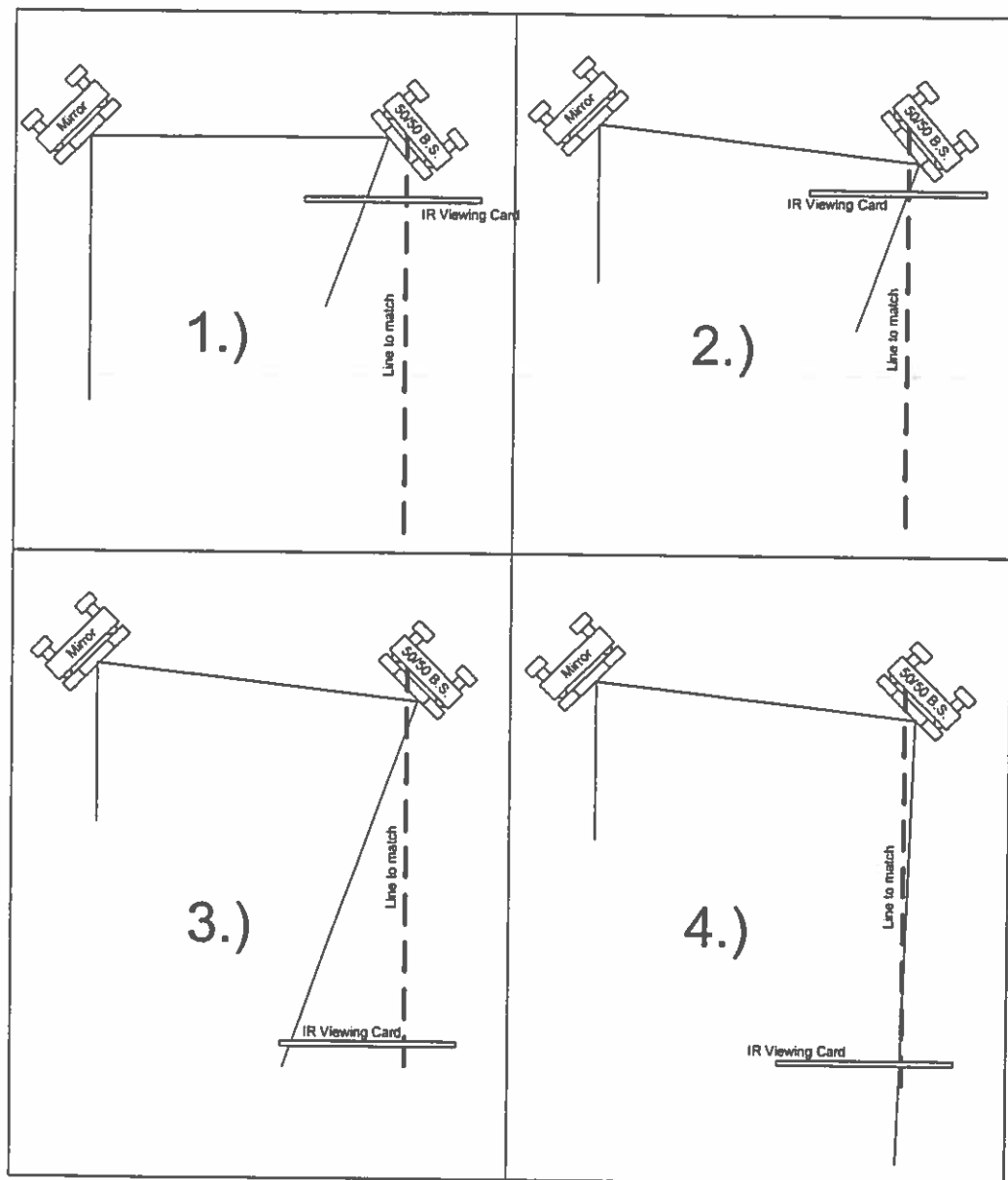
Two points define a line, iterative procedure to align a laser beam to a “line in space”. The pictures are only for aligning in one dimension.

The process is shown in the Figures 1 – 4 below. The objective is to get the laser beam, the narrow line, to be collinear to the “line in space” represented by the darker dashed line. The angles have been exaggerated to make it easier to see what is going on.

1. With the viewing card near to mirror M2, adjust angle of mirror M1 until the laser beam is intersecting with the desired “line in space”. See Diagrams 1 and 2.
2. Now, move the viewing card to a distance far away from M2, as shown in Diagram 3.
3. Adjust the angle of mirror M2 so that laser beam again intersects the “line in space”. You will notice that this makes the alignment at the first position, near M2, off a bit.
4. Now move the viewing card back to position shown in Diagram 1 and repeat.

You will probably have to repeat the process several times to get the beam where you want it. (That’s iterative for you!) The closer the viewing card is to M2, the faster this procedure converges.

You might ask where the “line in space” that you are trying to match comes from. It could be another laser beam or, perhaps, a desired beam path defined by two irises.



**EXPERIMENT SECTION**

**For**

**DIODE LASER  
SPECTROSCOPY**

**i. Saturated Absorption Spectroscopy**



# Ph 76 ADVANCED PHYSICS LABORATORY

## – ATOMIC AND OPTICAL PHYSICS –

### Saturated Absorption Spectroscopy

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#### I. BACKGROUND

One of the most important scientific applications of lasers is in the area of precision atomic and molecular spectroscopy. Spectroscopy is used not only to better understand the structure of atoms and molecules, but also to define standards in metrology. For example, the second is defined from atomic clocks using the 9192631770 Hz (exact, by definition) hyperfine transition frequency in atomic cesium, and the meter is (indirectly) defined from the wavelength of lasers locked to atomic reference lines. Furthermore, precision spectroscopy of atomic hydrogen and positronium is currently being pursued as a means of more accurately testing quantum electrodynamics (QED), which so far is in agreement with fundamental measurements to a high level of precision (theory and experiment agree to better than a part in  $10^8$ ). An excellent article describing precision spectroscopy of atomic hydrogen, the simplest atom, is attached (Hänsch *et al.* 1979). Although it is a bit old, the article contains many ideas and techniques in precision spectroscopy that continue to be used and refined to this day.

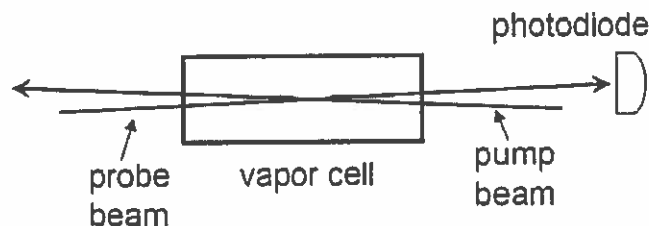


Figure 1. The basic saturated absorption spectroscopy set-up.

**Qualitative Picture of Saturated Absorption Spectroscopy – 2-Level Atoms.** Saturated absorption spectroscopy is one simple and frequently-used technique for measuring narrow-line atomic spectral features, limited only by the natural linewidth  $\Gamma$  of the transition (for the rubidium D lines  $\Gamma \approx 6$  MHz), from an atomic vapor with large Doppler broadening of  $\Delta\nu_{Dopp} \sim 1$  GHz. To see how saturated absorption spectroscopy works, consider the experimental set-up shown in Figure 1. Two lasers are sent through an atomic vapor cell from opposite directions; one, the “probe” beam, is very weak, while the other, the “pump” beam, is strong. Both beams are derived from the same laser, and therefore have the same frequency. As the laser frequency is scanned, the probe beam intensity is measured by a photodetector.

If one had 2-level atoms in the vapor cell, one might record spectra like those shown in Figure 2. The upper plot gives the probe beam absorption without the pump beam. Here one sees simple Doppler-

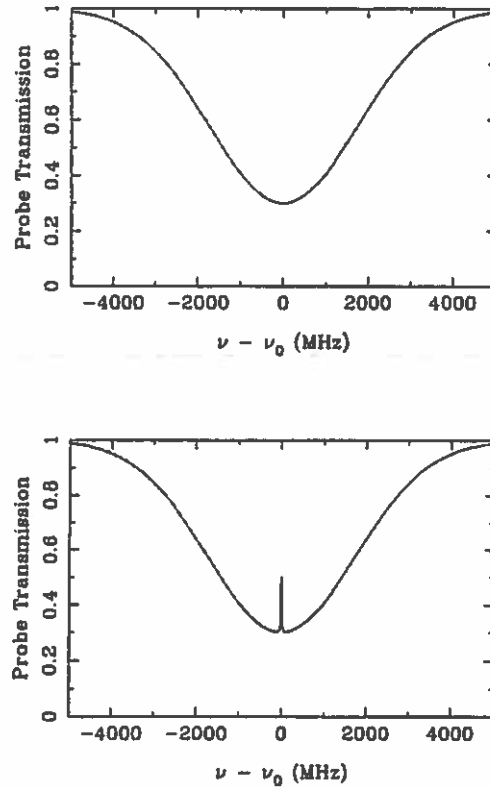


Figure 2. Probe absorption spectra for 2-level atoms, both without (upper) and with (lower) the pump beam.

broadened absorption; in our case the Doppler width is much larger than the natural linewidth,  $\Delta\nu_{Dopp} \gg \Gamma$ , and the optical depth of the vapor is fairly small  $\tau(\nu) \lesssim 1$  (the transmitted fraction of the probe is  $e^{-\tau(\nu)}$ , which defines the optical depth;  $\tau$  is proportional to the atomic vapor density and the path length), so the probe spectrum is essentially a simple Gaussian profile.

The lower plot in Figure 2 shows the spectrum with the pump beam, showing an additional spike right at the atomic resonance frequency. The reason this spike appears is as follows: If the laser frequency is  $\nu_0 - \Delta\nu$ , then the probe beam is absorbed only by atoms moving with longitudinal velocity  $v \approx c\Delta\nu/\nu_0$ , moving toward the probe beam. These atoms see the probe beam blueshifted into resonance; other atoms are not in resonance with the probe beam, and so they do not contribute to the probe absorption. These same atoms see the pump beam red-shifted further from resonance (since the pump beam is in the opposite direction) so they are unaffected by the pump beam. Thus for laser frequencies  $\nu \neq \nu_0$ , the probe absorption is the same with or without the pump beam. However if  $\nu = \nu_0$ , then atoms with  $v = 0$  contribute to the probe absorption. These  $v = 0$  atoms also see an on-resonance pump beam, which is strong enough to keep a significant fraction of the atoms in the excited state, where they do not absorb the probe beam (in fact they increase the probe beam intensity via stimulated emission). Thus at  $\nu = \nu_0$  the probe absorption is *less* than it was without the pump beam. (If the pump beam had infinite intensity, half of the atoms would

be in the excited state at any given time, and there would be identically zero probe absorption. One would say these atoms were completely "saturated" by the pump beam, hence the name saturated absorption spectroscopy.) The advantage of this form of spectroscopy should be obvious ... one can measure sharp Doppler-free features in a Doppler-broadened vapor.

**Qualitative Picture of Saturated Absorption Spectroscopy – Multi-level Atoms.** If the atoms in the absorption cell had a single ground state and two excited states (typically an electronic level split by the hyperfine interaction), and the separation of the excited states was less than the Doppler width, then one would see a spectrum like that shown in Figure 3. The peaks on the left and right are ordinary saturated absorption peaks at  $\nu_1$  and  $\nu_2$ , the two resonance frequencies. The middle peak at  $(\nu_1 + \nu_2)/2$  is called a "cross-over resonance." If you think about it for a while you can see where the extra peak comes from. It arises from atoms moving at velocities such that the pump is in resonance with one transition, and the probe is in resonance with the other transition. If you think about it a bit more you will see there are *two* velocity classes of atoms for which this is true – atoms moving toward the pump laser, and away from it.

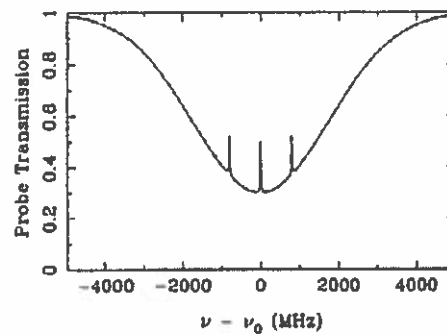


Figure 3. Saturated absorption spectrum for atoms with a single ground state and two closely spaced excited states.

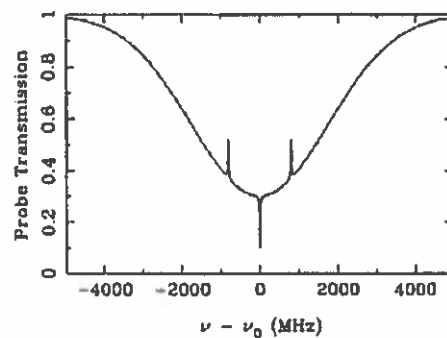


Figure 4. Saturated absorption spectrum for atoms with a single excited state that can decay into either of two closely spaced ground states.

If the atoms in the vapor cell had a single excited state but two hyperfine ground states (we call them both "ground" states because neither can decay via an allowed transition), and the separation of the ground states was less than the Doppler width, then one might see a spectrum like in Figure 4. The extra cross-over dip results from a phenomenon called "optical pumping," which occurs because atoms in the excited state can decay into either of the two stable ground states. Thus if atoms are initially in ground state  $g1$ , and one shines in a laser that excites  $g1 \rightarrow e$ , atoms will get excited from  $g1 \rightarrow e$  over and over again until they once spontaneously decay to  $g2$ , where they will stay. The state  $g2$  is called a "dark state" in this case, because atoms in  $g2$  are not affected by the laser. We see that a laser exciting  $g1 \rightarrow e$  will eventually optically pump all the atoms into  $g2$ .

To see how optical pumping produces the extra crossover dip, remember that only the pump laser can optically pump – the probe laser is by definition too weak. Also remember the atoms in the cell are not in steady state. When they hit the walls they bounce off about equally distributed in both ground states, and the optical pumping only operates for a short period of time as the atoms travel through the laser beams. If you think about it a while you can see there are two velocity classes of atoms that are responsible for the dip. For one velocity class the pump laser excites  $g1 \rightarrow e$ , which tends to pump atoms into  $g2$ . Then the probe laser, which excites  $g2 \rightarrow e$  for these atoms, sees extra absorption. For the other velocity class the pump laser excites  $g2 \rightarrow e$ ,  $g1$  gets overpopulated, and again the probe laser (which now excites  $g1 \rightarrow e$  for these atoms) sees more absorption.

**Quantitative Picture of Saturated Absorption Spectroscopy – 2-Level Atoms.** One can fairly easily write down the basic ideas needed to calculate a crude saturated absorption spectrum for 2-level atoms, which demonstrates much of the underlying physics. The main features are: 1) the transmission of the probe laser beam through the cell is  $e^{-\tau(\nu)}$ ,  $\tau(\nu)$  is the optical depth of the vapor; 2) the contribution to  $\tau(\nu)$  from one velocity class of atoms is given by

$$d\tau(\nu, v) \sim (P_1 - P_2)F(\nu, v)dn(v)$$

where  $P_1$  is the relative population of the ground state,  $P_2$  is the relative population of the excited state ( $P_1 + P_2 = 1$ ),

$$dn \sim e^{-mv^2/2kT}dv$$

is the Boltzmann distribution (for  $v$  along the beam axis), and

$$F(\nu, v) = \frac{\Gamma/2\pi}{(\nu - \nu_0 + \nu_0 v/c)^2 + \Gamma^2/4}$$

is the normalized Lorentzian absorption profile of an atom with natural linewidth  $\Gamma$ , including the Doppler shift. Putting this together, we have the differential contribution to the optical depth, for laser frequency  $\nu$  and atomic velocity  $v$ :

$$d\tau(\nu, v) = \tau_0 \frac{\nu_0}{c} (P_1 - P_2) F(\nu, v) e^{-mv^2/2kT} dv.$$

The overall normalization comes in with the  $\tau_0$  factor, which is the optical depth at the center of resonance line, i. e.  $\tau_0 = \int d\tau(\nu_0, v)$  with no pump laser (the integral is over all velocity classes). 3) The populations of the excited and ground states are given by  $P_1 - P_2 = 1 - 2P_2$ , and

$$P_2 = \frac{s/2}{1 + s + 4\delta^2/\Gamma^2}$$

where  $s = I/I_{sat}$  and  $\delta = \nu - \nu_0 - \nu_0 v/c$ .  $I_{sat}$  is called the saturation intensity (for obvious reasons ... if you consider the above formula for  $P_2$  with  $\delta = 0$ ,  $P_2$  "saturates"  $P_2 \rightarrow 1/2$  as  $I/I_{sat} \rightarrow \infty$ ). The value of

$I_{sat}$  is given by

$$I_{sat} = 2\pi^2 \hbar c \Gamma / 3\lambda^3.$$

For the case of rubidium,  $\Gamma \approx 6$  MHz, giving  $I_{sat} \approx 2$  mW/cm<sup>2</sup>.

The underlying physics in points (1) and (2) should be recognizable to you. Point (3) results from the competition between spontaneous and stimulated emission. To see roughly how this comes about, write the population rate equations as

$$\begin{aligned}\dot{P}_1 &= \Gamma P_2 - \alpha I (P_1 - P_2) \\ \dot{P}_2 &= -\Gamma P_2 + \alpha I (P_1 - P_2)\end{aligned}$$

where the first term is from spontaneous emission, with  $\Gamma$  equal to the excited state lifetime, and the second term is from stimulated emission, with  $\alpha$  a normalization constant. Note that the stimulated emission is proportional to the intensity  $I$ . In the steady-state  $\dot{P}_1 = \dot{P}_2 = 0$ , giving

$$P_2 = \frac{\alpha I / \Gamma}{1 + 2\alpha I / \Gamma}$$

The term  $\alpha I / \Gamma$  corresponds to the  $s/2$  term above (note  $I_{sat}$  is proportional to  $\Gamma$ ). A more complete derivation of the result, with all the normalization constants, is given in Milonni and Eberly (1988), and in Cohen-Tannoudji *et al.* (1992), but this gives you the basic idea.

Assuming a fixed vapor temperature, atomic mass, etc., the saturated absorption spectrum is determined by two adjustable external parameters, the pump intensity  $I_{pump}$  and the on-resonance optical depth  $\tau_0$ . The latter is proportional to the vapor density inside the cell. Figure 5 shows calculated spectra at fixed laser intensity for different optical depths, and Figure 6 shows spectra at fixed optical depth for different laser intensities.

In Figure 5 one sees mainly what happens when the vapor density is increased in the cell. At low densities the probe absorption is slight, with a Gaussian profile, and the absorption increases as the vapor density increases. At very high vapor densities the absorption profile gets deeper and broader. It gets broader simply because the absorption is so high near resonance that the probe is almost completely absorbed; for greater vapor densities the probe gets nearly completely absorbed even at frequencies fairly far from resonance; thus the width of the absorption profile appears broader. The saturated-absorption feature in Figure 5 does pretty much what you would expect. The probe absorption is reduced on resonance, due to the action of the pump laser. At very high vapor densities the saturated-absorption feature becomes smaller. This is because while the pump laser reduces the absorption, it doesn't eliminate it; thus at high vapor densities the probe is nearly completely absorbed even with the pump laser. The moral of this story is that the vapor density shouldn't be too low or high if you want to see some saturated-absorption features.

In Figure 6 one sees that if the pump intensity is low, the saturated-absorption feature is small, as one would expect. For larger pump intensities the feature grows in height and width. The width increases because at high laser intensities the effect of the pump laser saturates on resonance, and continues to grow off resonance; thus the width of the feature increases, an effect known as "power broadening."

Finally, it should be noted that calculating the saturated absorption spectrum for real atoms, which must include optical pumping, many different atomic levels, atomic motion in the vapor cell, and the polarization of the laser beams, is considerably more subtle. A recent paper by Schmidt *et al.* (1994) shows much detailed data and calculations for the case of cesium.

**Problem 1.** Show that  $\tau_0 = \int d\tau(\nu_0, \nu)$  when the pump laser intensity is zero, from the formula above.

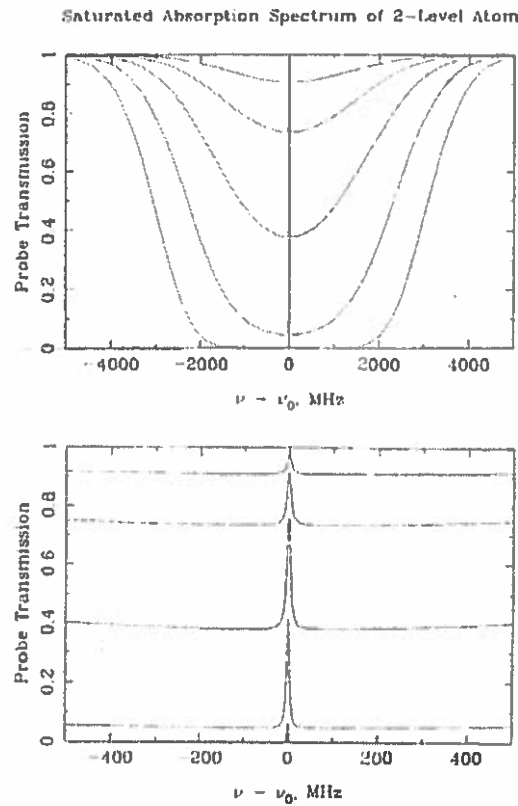


Figure 5. Calculated saturated-absorption spectra for two-level atoms, for  $(\tau, I/I_{sat}) = (0.1, 10), (0.316, 10), (1, 10), (3.16, 10), \text{ and } (10, 10)$ . The two plots show the same spectra with the frequency axis at different scales. Note the overall Doppler-broadened absorption, with the small saturated-absorption feature at line center.

Hint: the integral is simplified by noting that  $\Gamma \ll \Delta\nu_{Dopp}$ .

**Problem 2.** The above calculations all assume that the pump laser has the same intensity from one end of the cell to another. This is okay for a first approximation, but calculating what really happens is an interesting problem. Consider a simple laser beam (the pump) shining through a vapor cell. If the laser intensity is weak, and the atoms are all pretty much in the ground state, then the laser intensity changes according to the equation  $dI/dx = -\alpha I$ , where  $\alpha = \alpha(\nu)$  depends on the laser frequency, but not on position inside the cell ( $\alpha^{-1}$  is called the absorption length in this case). This equation has the solution  $I(x) = I_{init}e^{-\alpha x}$ , where  $I_{init}$  is the initial laser intensity. The transmission through the cell,  $e^{-\alpha L}$ , where  $L$  is the length of the cell, is what we called  $e^{-\tau}$  above.

Your job in this problem is to work out what happens when the input laser beam is not weak, and thus we cannot assume that the atoms are all in the ground state. In this case  $\alpha = \alpha(\nu, x)$ , which makes the differential equation somewhat more interesting. Assume the laser is on resonance for simplicity. Then the attenuation coefficient at any position  $x$  is proportional to  $P_1 - P_2$ , which in turn is proportional to

Saturated Absorption Spectrum of 2-level Atom

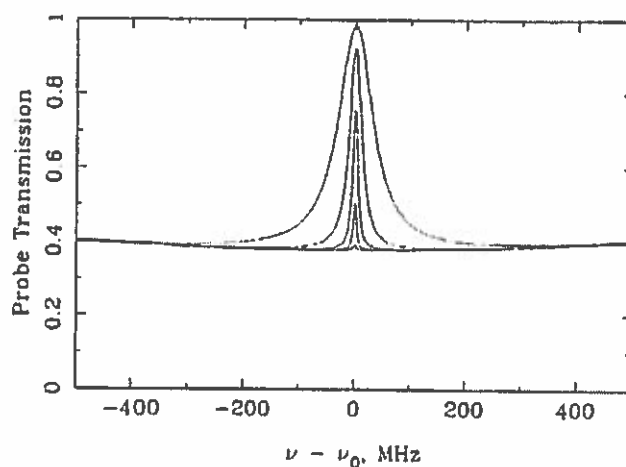


Figure 6. Calculated saturated-absorption spectra for two-level atoms, for  $(\tau, I/I_{sat}) = (1, 0.1), (1, 1), (1, 10), (1, 100),$  and  $(1, 1000)$ . Note at large laser intensities the saturated absorption feature is "power broadened" as the line saturates.

$1/(1 + s)$ . Thus we have  $\alpha(\nu_0, x) = \alpha_0/(1 + s(x))$ . In the weak beam limit  $I \ll I_{sat}$  this reduces to our previous expression, so  $\alpha_0 = \tau_0/L$ . Write down an expression which relates the saturation parameter of the laser as it exits the cell  $s_{final}$ , the saturation parameter at the cell entrance  $s_{initial}$ , and the weak-limit optical depth  $\tau_0$ . Check your expression by noting in the limit of finite  $\tau_0$  and small  $s$  you get  $s_{final} = s_{initial}e^{-\tau_0}$ . If  $\tau_0 = 100$ , how large must  $s_{initial}$  be in order to have a transmission of  $1/2$  (i. e.  $s_{final} = s_{initial}/2$ )?

**Atomic Structure of Rubidium.** The ground-state electronic configuration of rubidium consists of closed shells plus a single 5s valence electron. This gives a spectrum which is similar to hydrogen (see attached Scientific American article). For the first excited state the 5s electron is moved up to 5p. Rubidium has two stable isotopes:  $^{85}\text{Rb}$  (72 percent abundance), with nuclear spin quantum number  $I = 5/2$ , and  $^{87}\text{Rb}$  (28 percent abundance), with  $I = 3/2$ .

The different energy levels are labeled by "term states", with the notation  $^{2S+1}L'_J$ , where  $S$  is the spin quantum number,  $L'$  is the spectroscopic notation for the angular momentum quantum number (i. e. S, P, D, ..., for orbital angular momentum quantum number  $L = 0, 1, 2, \dots$ ), and  $J = L + S$  is the total angular momentum quantum number. For the ground state of rubidium  $S = 1/2$  (since only a single electron contributes), and  $L = 0$ , giving  $J = 1/2$  and the ground state  $^2S_{1/2}$ . For the first excited state we have  $S = 1/2$ , and  $L = 1$ , giving  $J = 1/2$  or  $J = 3/2$ , so there are two excited states  $^2P_{1/2}$  and  $^2P_{3/2}$ . Spin-orbit coupling lifts splits the otherwise degenerate  $P_{1/2}$  and  $P_{3/2}$  levels. (See any good quantum mechanics or atomic physics text for a discussion of spin-orbit coupling.)

The dominant term in the interaction between the nuclear spin and the electron gives rise to the magnetic hyperfine splitting (this is described in many quantum mechanics textbooks). The form of the interaction

term in the atomic Hamiltonian is  $H_{hyp} \propto \mathbf{J} \cdot \mathbf{I}$ , which results in an energy splitting

$$\Delta E = \frac{C}{2} [F(F+1) - I(I+1) - J(J+1)]$$

where  $F = I + J$  is the total angular momentum quantum number including nuclear spin, and  $C$  is the "hyperfine structure constant." Figures 7 and 8 shows the lower S and P energy levels for  $^{85}\text{Rb}$  and  $^{87}\text{Rb}$ , including the hyperfine splitting.

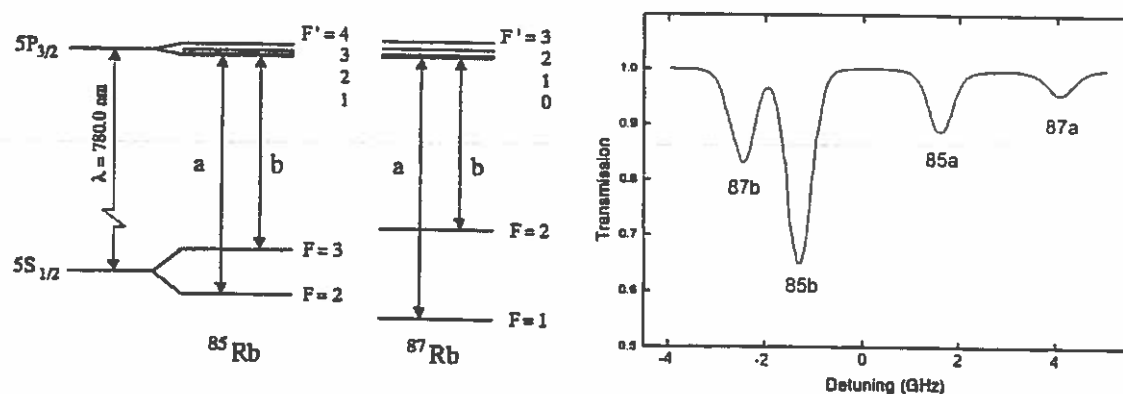


Figure 7. (Left) Level diagrams for the D2 lines of the two stable rubidium isotopes. (Right) Typical absorption spectrum for a rubidium vapor cell, with the different lines shown.

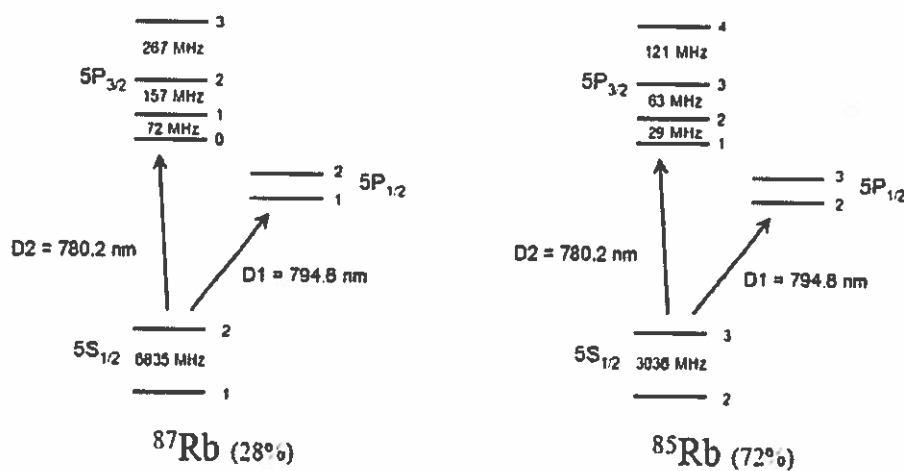


Figure 8. More rubidium level diagrams, showing the hyperfine splittings of the ground and excited states.

## II. LABORATORY EXERCISES.

The goal of this section is first to observe and record saturated absorption spectra for as many of the



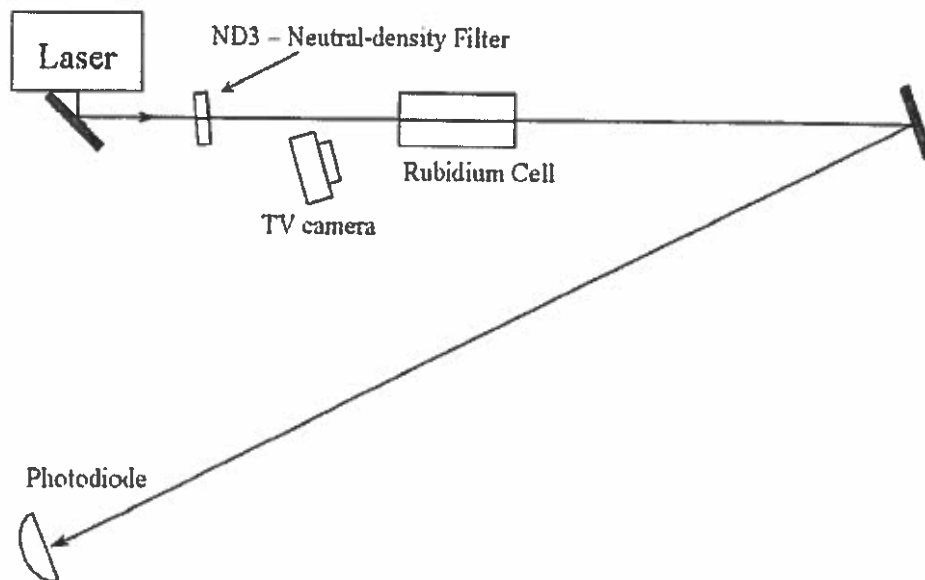


Figure 9. Recommended set-up to get the laser running on the rubidium resonance lines.

rubidium lines as you can, and then to see how well you can measure the  $P_{3/2}$  hyperfine splitting of  $^{87}\text{Rb}$  using a auxiliary interferometer as a length standard.

Remember that eye safety is important. First of all the laser operates at 780 nm, which is very close to being invisible. Thus you can shine a beam into your eye without noticing it. Also, the laser power is about 20 milliwatts, and all that power is concentrated in a narrow beam. Looking directly at the Sun puts about 1 milliwatt into your eye, and that much power is obviously painful. It is certainly possible to cause permanent eye damage using the Ph76 laser if you are not careful. Therefore – be careful. ALWAYS WEAR LASER GOGGLES WHEN THE LASER IS ON! As long as you keep the goggles on, your eyes will be protected.

#### Week 1 – Getting the Laser On Resonance.

The first step is to get the laser turned on and tuned to hit the rubidium lines. We see in Figure 7 that the lines span about 8 GHz, which can be compared with the laser frequency of  $\nu = c/\lambda = 4 \times 10^{14}$  Hz. Thus to excite the atoms at all the laser frequency must be tuned to about a part in  $10^5$ . Start with the simple set-up shown in Figure 8. The ND filter can be removed when aligning the laser beam.

Once you have the beam going about where you want it, sweep the high-voltage going to the grating PZT with a triangle wave, so that the voltage varies from about 0 to 100 volts. Use the HV/100 to monitor the high voltage on the oscilloscope. Sweeping this voltage sweeps the grating position using a small piezo-electric actuator (made from lead zirconate titanate, hence PZT). While the high voltage is scanning you should then also change the laser injection current up and down by hand. The current makes large changes in the laser frequency, while the PZT makes small changes (see the laser primer for details).

The plan is that with all this sweeping the laser will sweep over the rubidium lines and you will see some fluorescence inside the vapor cell. This will appear as a bright line inside the cell; don't be confused

by scattering off the windows of the cell. If you cannot see the atoms flashing at all, ask your TA for help. The laser may need some realignment, or you may just not be doing something right.

Once you see fluorescence, compare the photodiode output to the rubidium spectrum shown in Figure 7. Usually you can only get the laser to scan over part of this spectrum without mode hopping (see the laser primer). Record your best spectrum using the digital oscilloscope and print it out. At this point the laser is tuned to the rubidium lines. Before proceeding with the rest of the experiment, move the ND filter from its location in Figure 9 to a new position right in front of the photodiode. If you look closely you'll see the absorption lines are still there, but much weaker. How come? There are two reasons. First, optical pumping is faster with more laser power, so the atoms are more quickly pumped to the dark state. That makes the absorption less. Second, the atoms become saturated with the high power, just like you calculated above. That also reduces the absorption.

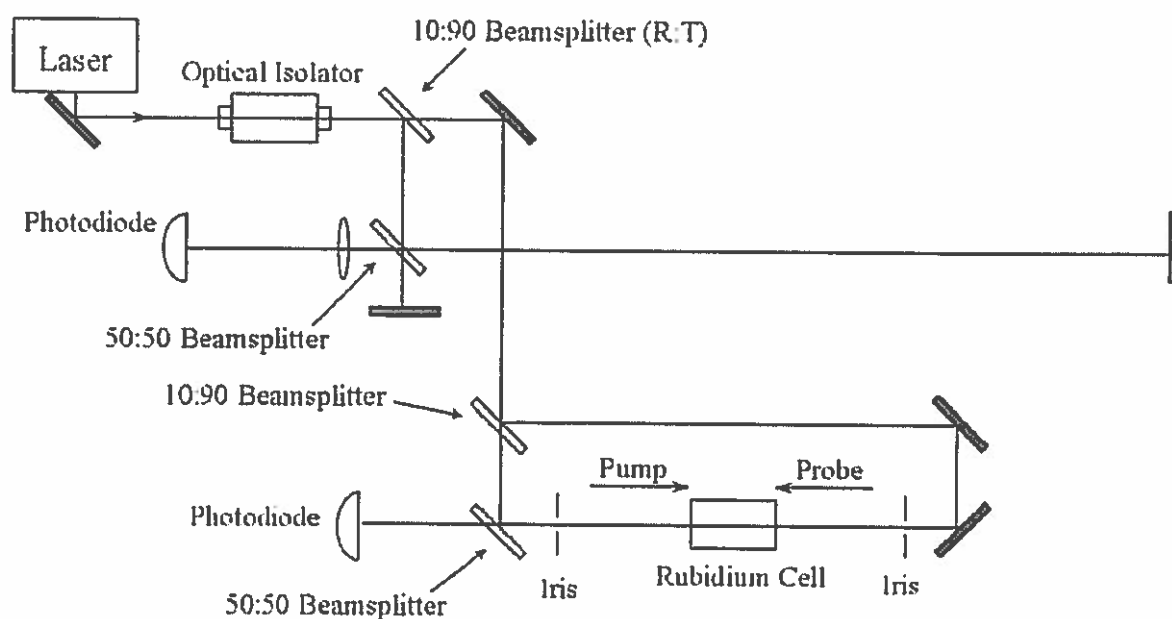


Figure 10. Recommended set-up to record rubidium saturated absorption spectra, and for measuring the hyperfine splittings.

### Week 1 – Getting a Saturated Absorption Spectrum.

The suggested set-up for observing saturated absorption spectra is shown in Figure 10. Since the laser is on resonance from the last section, leave it alone while you change the set-up. Ignore the interferometer part for now; that comes in after you've gotten some spectra. The optical isolator is a device that contains a two polarizers, a special crystal, and strong permanent magnets (see Appendix I). The first polarizer is aligned with the polarization of the input laser (vertical), and simply transmits the beam. The crystal in the magnetic field rotates the polarization of the beam by about 45 degrees, using the Faraday effect, and the beam exits through the second polarizer, which is set at 45 degrees. A beam coming back toward the

laser sees all this in reverse; the beam polarization gets rotated in the crystal, so that the polarization is 90 degrees with respect to the vertical polarizer, and the beam is not transmitted. These devices are also sometimes called optical diodes, since light only passes through them in one direction. We use an optical isolator here to keep stray light (generated downstream...note the pump beam goes backward after it passes through the cell) from getting back to the diode laser, where it can adversely affect the frequency stability.

Note the 10:90 beamsplitter puts most of the laser power into the probe beam. The irises are an alignment guide; if you have both the pump and probe beams going through small irises, then you can be assured that the beams overlap in the rubidium cell. If you block the pump beam you should get a spectrum that looks pretty much the same as you had in the previous section.

**Lab Exercise 1.** Observe and record the best spectra you can for whatever rubidium lines you can see, especially the two strongest lines (87b and 85b in Figure 7). Get some nice spectra and put hard copies into your notebook. Note (but don't bother recording) that the saturated absorption features go away if you block the pump beam, as expected.

## Week 2 – Measuring the Hyperfine Splitting.

Now finish the set-up in Figure 10 by adding the interferometer. (Turn off the laser frequency scanning while setting up the interferometer, so the fringes are stable.) Make the arm difference as long as you can. If you want you can add another mirror to the long arm to bounce it across the table. The longer the long arm, the better your measurement will be. Recombine the beams on the beamsplitter and send one of the output beams through a strong lens, so that the beam is expanded quite a bit. Align the overlap of the beams (in position as well as angle) until you see nice fringes on the expanded beam. Align the overlap so the fringes spacing is very large. Place the photodiode such that it only intercepts the light from one fringe of the interferometer.

If you now scan the laser frequency you should observe temporal fringes on the photodiode output. The fringe spacing can be computed from the arm length difference, which you should measure. When a beam travels a distance  $L$  it picks up a phase  $\varphi = 2\pi L/\lambda$ , so the electric field becomes

$$E = E_0 e^{i\omega t} e^{i\varphi}$$

When the beam is split in the interferometer, the two parts send down the two arms, and then recombined, the electric field is

$$\begin{aligned} E &= E_{arm1} + E_{arm2} \\ &= E_0 e^{i\omega t} \left[ e^{i4\pi L_1/\lambda} + e^{i4\pi L_2/\lambda} \right] \end{aligned}$$

where  $L_1$  and  $L_2$  are the two arm lengths. The additional factor of two comes from the fact that the beam goes down the arm and back again. Squaring this to get the intensity we have

$$\begin{aligned} I &\sim \left| e^{i4\pi L_1/\lambda} + e^{i4\pi L_2/\lambda} \right|^2 \\ &\sim 1 + \cos\left(\frac{4\pi\Delta L}{\lambda}\right) \end{aligned}$$

where  $\Delta L = L_1 - L_2$ . If the laser frequency is constant, then the fringe pattern goes through one cycle every time the arm length changes by  $\lambda/2$ .

**Problem 3.** If  $\Delta L$  is fixed, how much does the laser frequency have to change to send  $I$  through one brightness cycle? For your known  $\Delta L$ , what is the fringe period in MHz? From this you can convert your

measurement of  $\Delta L$  into a calibration of the laser frequency scan.

Use the two oscilloscope traces to plot the interferometer fringes and the saturated absorption spectra at the same time, as you scan the laser frequency. Watch that the interferometer fringes are uniform as a function of PZT voltage; if not the nonlinearities could compromise your calibration. Zoom in on the hyperfine features you want to measure. You will need to know which features belong to which lines, so identify the features by comparing your spectra with the level diagrams in Figures 7 and 8. Print out some good spectra, measure the spacings of the various features using a ruler, and you can turn this all into a direct measurement of the hyperfine splittings. Try to do this for both lines 87b and 85b in Figure 7. Note there are no tricks or complicated math in any of this. You just have to understand what's going on, and not lose any factors of two. No fair adjusting the answer by factors of two until it agrees with the known splittings.

**Lab Exercise 2.** Measure and record the largest  $P_{3/2}$  hyperfine splittings for  $^{85}\text{Rb}$  and  $^{87}\text{Rb}$ , in MHz. Estimate the accuracy of your measurement, knowing the various uncertainties you encountered along the way.

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## Chapter 5 - Apparatus

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# **DIODE LASER SPECTROSCOPY**

## **APPARATUS SECTION**

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## I. Laser

### I.A. 9 PIN CABLE AND CONNECTOR

The 9-pin cable provides electrical connections between the laser head and electronics box. A pin-out of the connector is shown in Figure 1. Your Laser diode head was shipped with a protective plug on the 9-pin connector on the laser head. When you are ready to use the laser diode remove the protective plug and attach the 9-pin cable. Do not discard the protective shipping plug. It can be used to protect the laser whenever the cable to the controller is removed. For both operational and safety reasons, it is important to keep the 9-pin electrical cable connected between the laser head and Laser Diode Controller box whenever possible.

There is protection circuitry inside the laser head, but large electrostatic voltages may still damage the laser diode. Ground yourself before removing the plug and attaching the cable. When the instrument is turned on there is also the possibility that high voltage is present on the cable (a maximum of 100 Volts that drives the piezo stack). Always connect the 9-pin cable before connecting the controller box to AC power. Figure 1 shows the pin out of the 9-pin connector and the protection diodes that are mounted inside the laser head.

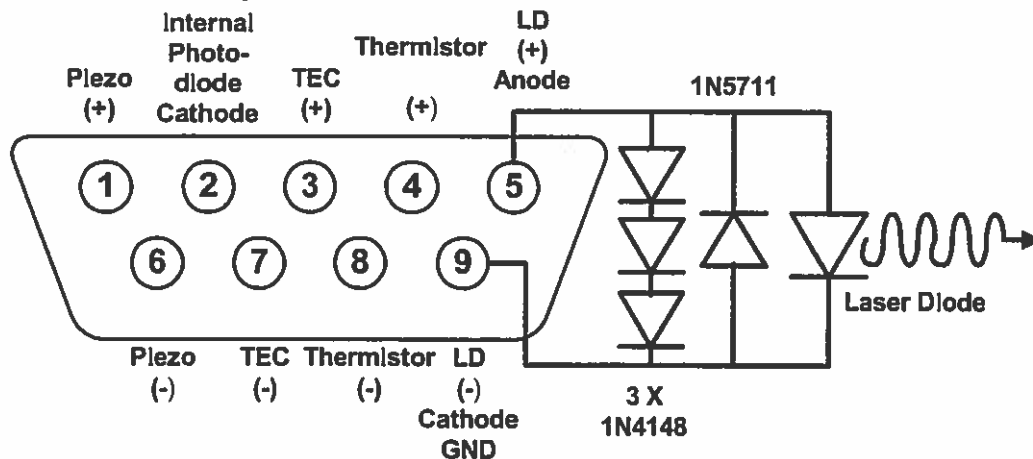


Figure 1: 9-pin Connector Pin-out

## I.B. LASER TEMPERATURE

Temperature has several effects on the laser. The frequency of a "bare" diode laser changes with temperature for two reasons. First the wavelength dependence of the overall gain\* changes with temperature. As shown in Figure 6 of Section 1, this change is reflected in the large-scale slope of the wavelength versus temperature graph ( $\approx 0.23 \text{ nm}/^\circ\text{C}^\dagger$ ). Secondly the optical length of the "bare" diode increases with temperature. This is shown in the small-scale slope of the individual "steps" in Figure 6. From this slope ( $0.05 \text{ nm}/^\circ\text{C} \approx 25 \text{ GHz} / ^\circ\text{C}$ ) we can estimate that a temperature stability of  $40 \mu^\circ\text{C}^\ddagger$  is necessary for the variation in the laser frequency to be less than 1MHz. The temperature also changes the length of the external cavity formed by the grating. From the linear expansion coefficient of aluminum  $\alpha \approx 2.5 \times 10^{-5} \text{ }^\circ\text{C}^{-1}$  we can estimate a change in wavelength of  $0.015 \text{ nm } ^\circ\text{C}^{-1}$ ,  $\approx 7.5 \text{ GHz } ^\circ\text{C}^{-1}$ . §

Temperature also affects two other laser parameters. First, the threshold current increases with temperature. Second, if the current is kept constant, the laser intensity will decrease as the temperature is increased.

### I.B.1. Specifications

Temperature Range	0 to 60 $^\circ\text{C}$
Temperature Stability	better than 0.05 $^\circ\text{C}$
Control process	Proportional, Integral, Derivative
Adjustment	Back Panel Potentiometer
Thermo electric cooler	20 W @ 2.5 A
Sensor	10 k $\Omega$ thermistor
Modulation Input	12 k $\Omega$ Input Impedance +5 V in = -1 Volt Set Point Voltage Change

\* The overall gain is the uppermost curve in figure 5 of section 1. (Diode Laser Physics)

† This is a useful number if you wish to tune the laser to a new wavelength.

‡ This estimate appears to be a severe restraint on the temperature. In practice the temperature stability needed is less restrictive. First, the external cavity modes "trump" the temperature variations of the internal modes. Secondly, there is a natural time scale for changing the temperature of any object. In an analogy to electronic circuits, a time constant may be defined as the product of the thermal resistance and the heat capacity. If we model the thermally connected parts as a cubic piece of aluminum, this leads to the following expression .... The mass of the mirror mount, cold plate, and collimation tube assembly is 168 grams which gives a time constant of about 20 seconds. Since we typically sweep through the absorptions in a time interval of about 0.1 sec, the amount of temperature change possible is small.

§ For an optical cavity,  $\lambda = 2L/m$ , where L is the cavity length and m is an integer. It is interesting that the change in wavelength with temperature depends only on the material and wavelength and not on the cavity length.  $\Delta\lambda = \alpha\lambda$ .



### I.B.2. Laser Head

Figure 2 shows the Laser Head without the insulation between the cold plate and heat sink. The Thermo-electric cooler (TEC) is visible between these two aluminum pieces. The thermistor, located close to the diode laser in the collimation tube holder, is also shown. Four stainless steel screws secure the TEC between the cold plate and heat sink. These screws pass through nylon shoulder washers inside the heat sink, which provide electrical and additional thermal isolation between the cold plate and heat sink. (Note: stainless steel is a poor thermal conductor.) A 1/4-20 brass screw passes through the cold plate and mirror mount and threads into the collimation tube holder. This screw and the large aluminum contact area thermally link the cold plate with the diode laser. On the other side of the laser head (not visible in the picture), copper braid is used to thermally link the cold plate to the grating holder and the movable portion of the mirror mount.\*

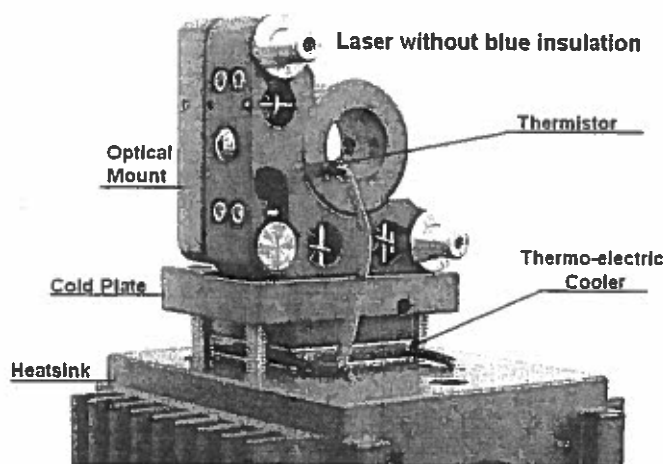


Figure 2: Picture of Laser Head

#### I.B.2-a. Plexiglas Cover

A Plexiglas cover over the laser provides isolation from air currents. There are two holes in the cover to allow the laser beam to exit both with and without the diffraction grating in place. When operating the laser at a temperature below the local dew point, condensation may be a problem. In such cases, it is advisable to put tape over the un-used hole and tape a piece of glass (microscope slide or cover slip) over the hole through which the laser beam exits.

---

\* Though better than no braid at all, we believe that this is the weak link in the thermal stability chain as it relates to wavelength stability. When operating at temperatures far from room temp there is a significant temperature difference between the movable mirror mount section that holds the grating and the rest of the mirror mount (about 6 °C at a 60 °C set point).

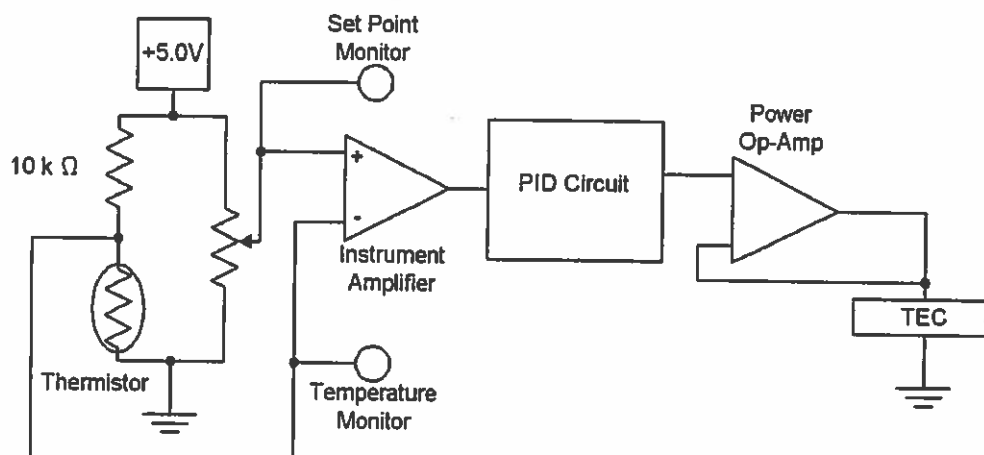
### I.B.3. Laser Temperature Electronics

The TEC is a Melcor, model CP1-127-08 with dimensions of 30 mm. by 30 mm., a maximum current/voltage of 2.3A/15.4V and a cooling power of 21.4 Watts. The TEC transfers heat between the cold plate and heat sink. (When run in "reverse" direction, the cold plate becomes a hot plate and the heat sink a heat source.) Temperature is sensed with a 10k thermistor used in a bridge circuit (see Figure 3). An instrument amplifier generates an error voltage that is the difference between the set point voltage and the voltage across the thermistor. A PID circuit conditions the error signal into a control voltage that operates the TEC through a power amplifier. The entire circuit is bipolar so that both cooling and heating may be accomplished.

Analysis of the bridge circuit leads to the following relation between thermistor resistance (RT) and voltage (VT):  $VT = 5.0 RT / (10,000 + RT)$ .

Values of thermistor resistance and voltage for temperatures from -10 to 60°C are listed in Table 1, on the following page.

The set point voltage is adjusted using the ten-turn potentiometer, located on the back panel. The set point may also be controlled remotely with the temperature modulation input on the back panel. The set point voltage is the difference between the voltage set by the potentiometer and the modulation voltage.



**Figure 3: Laser Temperature Control Electronics**

The voltage modulation circuit is not shown in Figure 3. Modulation input voltage is attenuated by one fifth so a five volt change in the modulation voltage leads to a minus one volt change in the set point voltage. In the MONITORS section of the front panel, the LASER DIODE TEMPERATURE and SET POINT voltages may both be measured. Two LEDs, mounted on the front panel, indicate when the laser head is above or below the set point temperature.

### Thermistor Resistance and Bridge Voltage as a Function of Temperature

Temperature °C	Resistance Ohms	Voltage Volts	Temperature °C	Resistance Ohms	Voltage Volts
-10	55,330	4.2347	25	10,000	2.5000
-9	52,440	4.1992	26	9574	2.4456
-8	49,690	4.1623	27	9165	2.3911
-7	47,070	4.1239	28	8779	2.3375
-6	44,630	4.0848	29	8410	2.2841
-5	42,340	4.0447	30	8060	2.2315
-4	40,170	4.0034	31	7722	2.1786
-3	38,130	3.9611	32	7402	2.1268
-2	36,190	3.9175	33	7100	2.0760
-1	34,370	3.8731	34	6807	2.0250
0	32,660	3.8279	35	6532	1.9756
1	31,030	3.7814	36	6270	1.9269
2	29,500	3.7342	37	6017	1.8783
3	28,060	3.6863	38	5777	1.8308
4	26,690	3.6372	39	5546	1.7837
5	25,400	3.5876	40	5329	1.7382
6	24,170	3.5367	41	5116	1.6922
7	23,020	3.4858	42	4916	1.6479
8	21,920	3.4336	43	4725	1.6044
9	20,880	3.3808	44	4543	1.5619
10	19,900	3.3278	45	4369	1.5203
11	18,970	3.2741	46	4202	1.4794
12	18,090	3.2200	47	4042	1.4393
13	17,260	3.1658	48	3889	1.4000
14	16,470	3.1111	49	3743	1.3618
15	15,710	3.0552	50	3603	1.3243
16	15,000	3.0000	51	3469	1.2878
17	14,330	2.9449	52	3340	1.2519
18	13,680	2.8885	53	3217	1.2170
19	13,070	2.8327	54	3099	1.1829
20	12,500	2.7778	55	2986	1.1497
21	11,940	2.7211	56	2878	1.1174
22	11,420	2.6657	57	2774	1.0858
23	10,920	2.6099	58	2675	1.0552
24	10,450	2.5550	59	2580	1.0254
25	10,000	2.5000	60	2488	0.9962

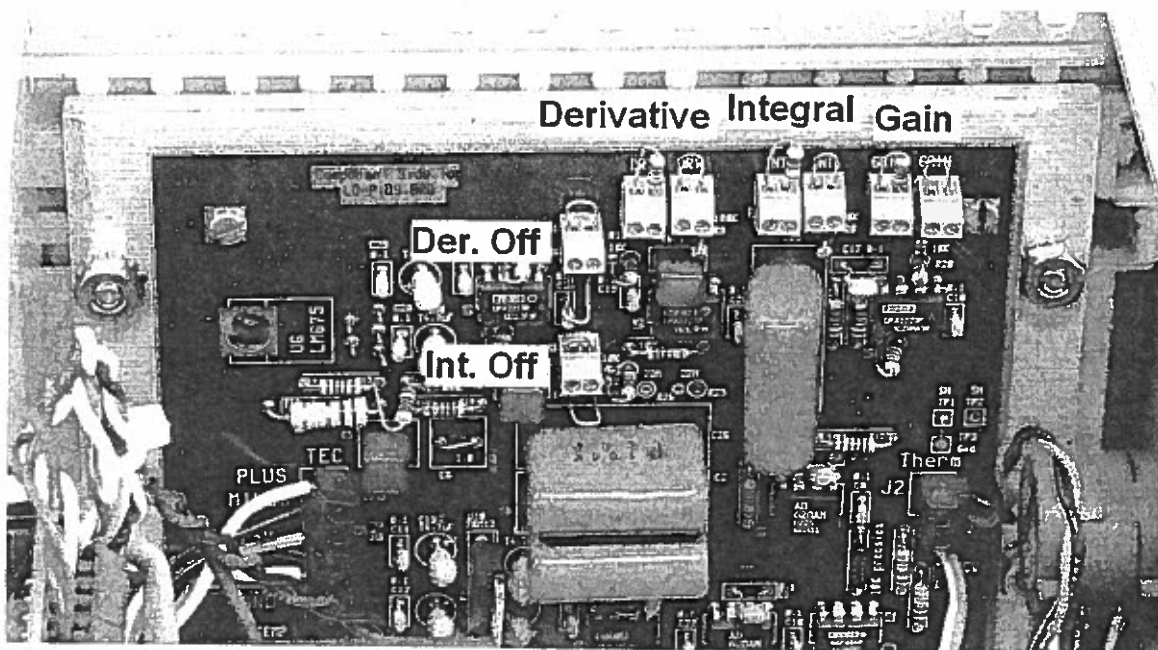
Table 1: Thermistor Resistance and Bridge Voltage versus Temperature

#### I.B.4. Laser Temperature Electronics Advanced Details

The circuit is a modification of that described by C.C. Bradley et al Review of Scientific Instruments, 61, 2097 (1990). The PID control parameters were determined from the Zeigler-Nichols closed loop tuning method, and then tweaked to give better performance. These parameters give adequate performance but they are not guaranteed to be optimal, especially if you operate your laser at temperatures far from room temperature.

##### I.B.4-a. Changing the PID Control Parameters

To change the PID control parameters the top cover of the electronics box must be removed. Because of the high voltage in the box we require that you turn off the AC power and unplug the electronics from the wall outlet before removing the top cover. Four side screws hold the top cover in place. When looked at from the front, the temperature control board is located on the back left hand side. Three 1% metal film resistors are used to set the control parameters. These resistors are held in a series of terminal blocks, see picture below.



**Figure 4: Picture of temperature control board showing terminal blocks**

There are two terminal blocks wired in series for each parameter. The value is the sum of the resistances in each block. This allows for fine-tuning of the parameters. In the Zeigler-Nichols tuning method, both the derivative and integral term need to be disabled. The terminal blocks labeled (Der. Off) and (Int. Off) are used to enable or disable the derivative and integral control parameters respectively. To turn a parameter off you must remove the wire from the terminal block AND cut the wire loop that is located just underneath the block. To re-enable these terms the wire loops must be reinstalled. As shipped, the wire in the block and the loop underneath it are redundant. Both allow the parameter to be active.

Table 2 lists the various control terms and the standard values that the unit was shipped with. Once the changes have been made, the top cover should be reinstalled before the power is applied to the electronics.

Control Parameter	Equation	Standard Values	Value
Gain (P)	$G = (R_{xt1} + R_{xt6} + 10k) / 10k$	$R_{xt1} = 20\text{ k}\Omega$ $R_{xt6} = 0$	$G = 3$
Integral (I)	$I = 20\mu\text{F} * (R_{xt2} + R_{xt4} + 100k)$	$R_{xt2} = 2.2\text{ M}\Omega$ $R_{xt4} = 0$	$I = 44\text{ sec.}$
Derivative (D)	$D = 10\mu\text{F} * (R_{xt3} + R_{xt5} + 100k)$	$R_{xt3} = 1\text{ M}\Omega$ $R_{xt5} = 0$	$D = 10\text{ sec.}$

**Table 2: PID Default values**

## I.C. LASER CURRENT CONTROLLER

The amount of current determines (in part) the gain of the laser. Below the threshold current, the overall gain is less than one, and the light coming from the diode is incoherent and broadband, similar to light from an LED. At currents above the threshold, the light coming from the diode becomes coherent narrow-band laser light\* and the intensity increases linearly with the current. Increasing the current also increases the temperature of the diode. This changes the wavelength of the laser in a manner similar to that of external heating.<sup>†</sup> As discussed in Chapter 1, Section IIB, the small-scale local slope of the steps in Figure 7 makes it possible to estimate that a current noise of 0.5  $\mu$ A would produce a laser line width of about 1 MHz. (See Chapter 1, pages 6 & 7, Figure 7, wavelength versus current for a "bare" diode).

### I.C.1. Specifications

Current Range	0 - 100 mA
Current Noise <sup>‡</sup>	< 50 nA <sub>RMS</sub> (3 Hz - 20 kHz. bandwidth)
Modulation	
Front Panel	
Gain	2 mA/Volt
Maximum Amplitude	$\pm 11$ mA
Frequency	DC to 1 MHz
RF on Laser Head	
Gain	20 mA/Volt
Frequency	100 kHz to 100 MHz <sup>§</sup>
Current Monitor Gain	100 mV / mA (10 mA = 1.0 V)
Current Limit	(50 – 100 mA) set at 80 mA
ESD protection	Schottky diode (reverse voltage) Three switching diodes 1N4148 (over voltage)

\* Some fraction of the light remains LED like, at least for currents just above threshold where both types of light can be seen.

<sup>†</sup> Changing the current can be thought of a means of rapidly changing the diode temperature, for times longer than 1  $\mu$ s. The current also changes the carrier density in the diode, which changes the index of refraction. This effect is smaller than the thermal effects and predominates only at time scales shorter than 1  $\mu$ s. This shortest response time is set by the relaxation oscillation frequency.

<sup>‡</sup> We measured the current noise with the Teachspin Signal Processor/ Lock-in Amplifier (SPLIA), configured in the amplitude detection mode, by detecting the voltage noise across a 100  $\Omega$  resistor in series with the diode. Unfortunately most of the noise measured was not current noise, but voltage noise from the Lock-in Pre-Amplifier (about 10 nV / Hz<sup>1/2</sup>). A more sensitive front end would be needed to get an accurate measure of the noise.

<sup>§</sup> Most likely higher modulation frequencies are possible. This is highest frequency for which the laser has been tested.

## I.C.2. Current Electronics

The ten-turn potentiometer of the CURRENT module is used to adjust DC laser current. One turn of the dial will change the current by about 10 mA. The BNC plug labeled modulation input is used for external modulation of the current. The attenuator dial is linked to the current modulation input. With a maximum modulation frequency of 1 MHz, and with the attenuator turned to 1 (full on), the input provides a modulation of 2 mA/Volt. The current itself can be measured using the BNC labeled laser current, which is in the MONITORS section of the front panel. The conversion factor is 1 Volt = 10 mA.

### I.C.2-a. Diode Protection

Currents injected in the wrong direction or in excess amounts can render your diode inoperable. The laser head is shipped with a protective shorting plug. This must be removed before attaching the 9-pin cable. Protective diodes are present in the laser head. (Refer to Figure 6 for details) When the laser is on, the three over-voltage diodes will conduct slightly, about 10% of the current from the electronics box will flow through these protection diodes. Current to the diode laser is shunted to ground when the front panel laser power toggle switch is in the off position. There is also a slow start circuit in the current controller that applies power to the electronics slowly after the AC power is switched on.

### I.C.2-b. Current Limit

Diodes are specified by the maximum optical power that they will produce and not by the maximum current. For each individual diode, the current that will produce this specified power is different, with values ranging from 80 mA (min) 110mA (typ.) and 140mA (max.)\* (See spec sheet in appendix.) Your instrument has a current limit that has been set to approximately 80 mA. This value has been chosen so that no diodes can be damaged by excess current from the controller. However this also means that the typical diode will not reach its maximum specified output power (70 mW). For the typical student experiment the current limit will not be a problem, because the diode has excess power and one is typically attenuating the beam when taking data. A user needing the full power may adjust this current limit. (See section I.B.2)

The current limit does not affect the currents injected either through the front panel current modulation input or through the SMA connector on the laser head. The front panel has a maximum modulation amplitude of 11 mA. This means that a maximum current of 91 mA (the sum of the modulation input and DC current) can be applied to the diodes by the students. It is possible that this may be enough current to damage a few select diodes. Please warn your students. There is no over-current protection limiting the amount of current that can be sent through the RF connector. *The RF input is for advanced users only.*

### I.C.2-c. Applying Power

Before turning on the AC line power to the electronics, make sure that the laser power toggle is off, that the Current ten-turn pot is set to zero, and that there is no external modulation. Once AC power is applied you may turn on the laser power toggle and then finally increase the Current with the ten-turn pot. When shutting off the unit the steps should be followed in reverse. First set the current to zero, disconnect any external modulation, turn the laser power toggle off and finally shut off the AC power to the electronics box. All these steps are meant to ensure a maximum lifetime for your diode laser.

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\* This is for operation at 25 °C. At higher temperatures more current is needed to reach a specified output power. See Diode spec sheet.

### I.C.3. Current Controller Advanced Details

The current control is based on the design of K.G. Libbrecht and J. L. Hall (Rev. Sci. Instrm. 64 (8) 2133 1993).

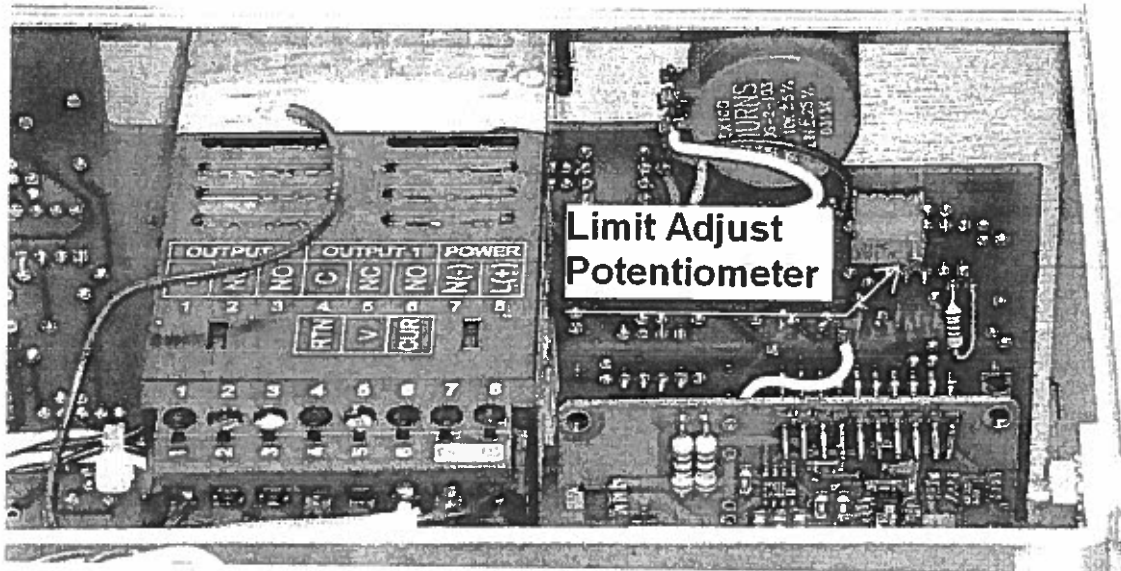


Figure 5: Picture showing current limit trim pot and test points

#### I.C.3-a. Current Limit Adjustment

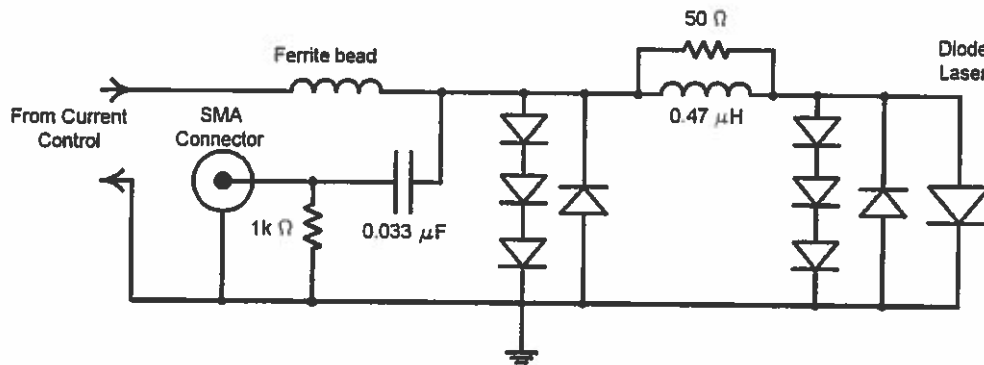
Advanced users may want to change the current limit so that they can get more power from an individual diode. Increasing the current limit could lead to overdriving of the laser diode and permanent damage. This procedure is only for those who understand this and can set an appropriate current limit.

The circuit limits the current by setting the supply voltage. The supply voltage is dropped across the 50 ohm current sensing resistor, the 5 ohm current monitor resistor and then across the diode laser. Different diode lasers will have different forward biased voltage drops and hence the ultimate current limit will change slightly for different diodes. Turn off the power to the laser controller and unplug the AC power line from the wall. Turn the electronics box over and remove the four screws that hold the bottom cover of the electronics box in place and remove the cover. The current limit trim pot (potentiometer) is located on the front panel circuit board, underneath the cell heater controller. Figure 5 shows a picture of the current control circuit board with the location of the supply voltage potentiometer and test point indicated. Turning the trim pot counter clockwise, when viewed as shown in Figure 5, will increase the supply voltage and current limit. One turn of the trim pot will increase the voltage by about 0.2 V and the current by about four milli-amperes (4 mA).



**I.C.3-b. High Frequency Modulation**

Figure 6 shows a schematic of the high frequency modulation circuit connected to the SMA connector on the laser head. A  $0.033\ \mu\text{F}$  capacitor is used to AC couple the RF into the diode. The RF is sent into the laser diode through the  $50\ \Omega$  resistor. The resistor also acts as a  $50\ \Omega$  impedance match for the RF. The connections are made on a small circuit board inside the laser head base right above the 9 pin connector. Also shown in the figure are the two sets of protection diodes on both sides of the  $50\ \Omega$  resistor and  $47\ \mu\text{H}$  inductor. We included two sets of protection diodes to provide maximum electrostatic protection.



**Figure 6: Schematic High Frequency Modulation Circuit.** Also shown are two sets of protection diodes. The three diodes in series are 1N4148's and the diodes used to prevent reverse voltages are 1N5711's.

#### I.D. LASER OPTICS AND DIODE

Figure 7 is a diagram of the Laser Head as viewed from above. The diagram includes the diode, collimating lens, grating, PZT stack, ball tipped setscrew that provides contact between the mirror mount and grating holder, and the 6-32 socket head cap screws that fix the grating holder to the mirror mount. The basic design is from Arnold et al, Review of Scientific Instruments, 69, 1236 (1998). The only major change is the use of a flexure mount to hold the diffraction grating. The diode is held in a Thor Labs Collimation tube (LT230P-B), which also holds the aspheric collimation lens (C230TM-B) ( $f = 4.5$  mm, 0.45 na). The holographic diffraction grating is from Edmunds Optics (R43-775) and has 1800 lines/mm. The actuators used for adjusting the grating and mirror mount have 100 threads per inch. From the grating equation ( $\lambda = 2d\sin\theta$ ) and dimensions given above one can calculate the wavelength tuning rate of the actuators to be about 5.2 nm per turn.

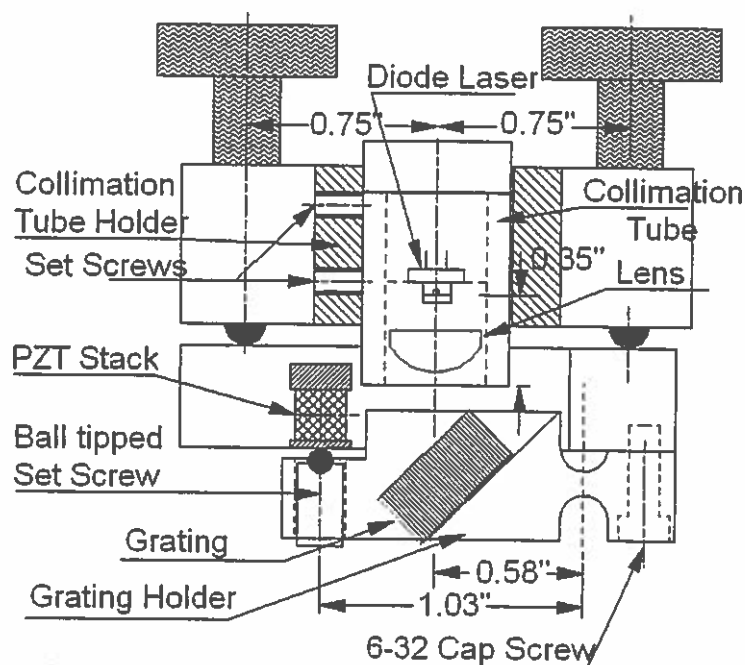


Figure 7: Overview of Laser Head

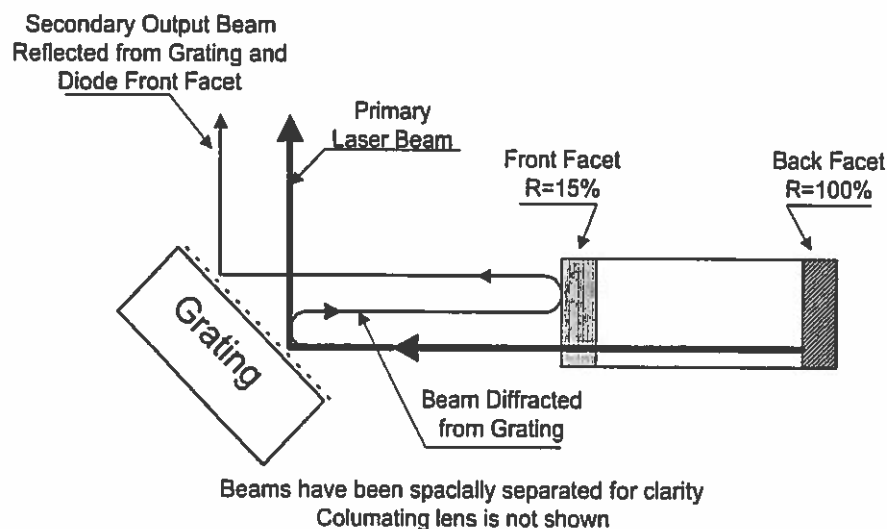
### I.D.1. Laser Diode

The diode is a Sanyo DL-7140-201S infrared laser diode with a nominal wavelength of 785 nm and a maximum output power of 70 mW. The data sheet is included at the end of this section. The data sheet shows the output power as a function of current for different laser temperatures. The point where the power rises sharply is called the threshold current and is the start of lasing action. There are also graphs of the threshold current as a function of temperature. When the diode is placed in an aligned optical system, the threshold current is reduced below that for the "bare" diode. When the laser beam is viewed on a white card with the CCD camera, you can observe the threshold as a sudden brightening of the beam spot. Measuring, or just observing, this threshold condition will be used in the following section for aligning the grating and correctly positioning the lens. (Section I.D.2-c)

If you notice that the laser experiments are not functioning properly, even though they did previously, you might have a damaged diode that needs to be replaced. Diode lasers rarely burn out completely before they lose the ability to function adequately in the laser lab. Thus, it is not always readily apparent when a laser needs to be replaced. The telltale signs of a damaged laser are: The laser power (as a function of current) is reduced from nominal values. The laser threshold is not abrupt and obvious at the nominal threshold current. The output beam profile of the diode may also change.

### I.D.2. External Cavity

To align the external cavity you must adjust the angular orientation of the grating so that the beam diffracted from the grating is sent back into the diode. The beam labeled "Secondary Output" is also called the *retro-reflected* beam. Figure 8 diagrams the process.



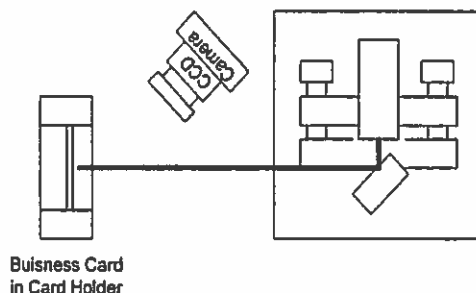
**Figure 8: Diagram Showing Origin of both the Primary and Secondary (Retro-Reflected) beam Spots**

### I.D.2-a. Finding the Retro Reflection

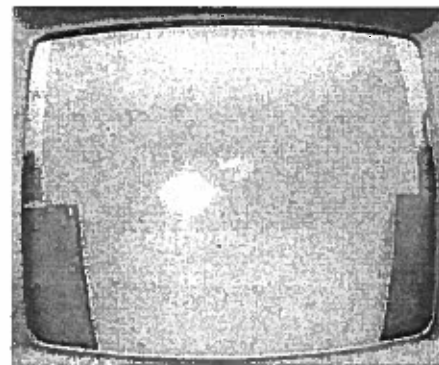
Use the blank backside of a business card as a viewing screen. Place the card in front of the laser and use the CCD camera and video monitor to view the output beam as shown in Figure 9. Turn on the laser power and set the laser current two to three milliamps above threshold. Check that the Laser TEMPERATURE SET POINT is correct (Refer to section I.B.3, Laser Temperature Electronics, for how to change temperature set point.)

The picture of the TV monitor in Figure 10 shows both the primary and retro-reflected beams. The intensity of the retro-reflected beam is only 2-3% that of the main beam. You will have to set the laser current a few milliamps above threshold to see the retro reflection. As discussed in Initial Setup of Chapter 3, Section II.D.5, the TOP knob is used to change the vertical position of the beam and the SIDE knob is used to change the horizontal position. See Figure 2 of Initial Setup on Chapter 3 page 6.

Use the TOP knob to set the beam height at 4.0". (If the grating has been removed refer to Section I.D.3.b and c; Installation of the grating and setting the beam height.) Dim the room lights. The retro reflected beam may appear above or below and to the right or left of the main beam spot. Be sure to position the viewing card with the main beam spot in the center.



**Figure 9: Setup for Viewing Beam Profile and Retro-reflection.**



**Figure 10: Laser Beam Image**  
Misaligned external cavity both main beam and retro-reflection are visible.

Turn the SIDE knob until you see the weak retro reflection on the monitor. You may have to make several turns of the SIDE knob in both directions. Reposition the viewing screen to keep the main beam centered on the screen. If you cannot find the retro reflection make sure that the laser is above threshold (Section I.C.3 or I.D.3-d). Increase the laser current by 2 mA and search again. If you still cannot find the retro reflection turn the TOP knob three turns in and search again. Then turn the TOP knob out six turns, (this gives a net of three turns out from the starting position), and search again.

### I.D.2-b. Aligning the External Cavity

Once you see the retro reflection, adjust both the SIDE and TOP knobs so that the main beam and the retro reflection overlap. You should notice an increase in the laser intensity when this happens. You should also observe that, when turning the TOP knob, the main and retro beams move in opposite directions and when the SIDE knob is turned only the main beam moves.

### I.D.2-c. Measuring the Threshold Current

Threshold current measurements are used to set the lens position. Again use the setup shown in Figure 9. Dim the room lights and reduce the laser current to just above threshold. Connect a voltmeter to the laser current in the MONITORS section of the front panel. Adjust the TOP and SIDE knobs to find the region of maximum laser intensity.\* Reduce the current until it is again just above threshold. Use the 5/64" Allen wrench, as shown in Figure 2 of Initial Setup, to gently change the knob positions. A flicker in the laser spot indicates that the laser is passing through a series of modes. You should be able to observe six or more vertical modes as you move the TOP knob and tens of modes as you move the SIDE knob. Position both knobs so that the laser is near the center of these mode patterns. Position the TOP knob so that you are at a mode maximum and reduce the current till you can just see the diode start to lase. We will define this as the threshold current. This procedure is a little subjective, but as long as you are consistent it will work fine.

### I.D.3. Diffraction Grating Holder

The grating holder may be removed either to study aspects of the diode laser without the external cavity or to adjust the position of the collimating lens.

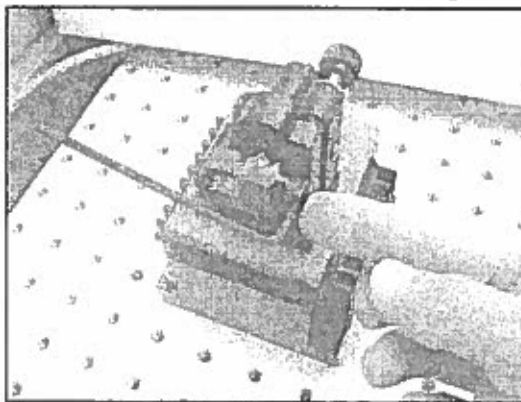
#### I.D.3-a. Grating Removal

Set the Laser Current to zero and turn off the Laser Power. Set the Piezo dc offset to zero and disconnect any cables from the Piezo modulation input. Loosen the ball tipped setscrew that contacts the piezo stack. (See Figure 7). Remove the two 6-32 socket head cap screws that hold the grating holder to the mirror mount. It will be necessary to hold the mirror mount with one hand as you loosen the 6-32 screws. Remove the grating holder and set it aside. Be careful not to touch the front face of the grating.

#### I.D.3-b. Installing the Grating

Place the grating holder on the mirror mount; insert and tighten the two 6-32 socket head cap screws. You will have to hold the movable end of the mirror mount while doing this.

There is a certain amount of "play" in the angular position of the grating holder. This "play" allows for the beam height to be set to 4.0" (See below). For the initial installation, press the grating holder from the side so that the holder makes contact with both 6-32 screws as you tighten the screws. See picture in Figure 11. This will approximately set the correct beam height.



**Figure 11: Initial installation of the Grating:**  
Grating holder is pressed against screws as screws are tightened

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\* This procedure is the same as outlined in Chapter 3, Section II.D, Aligning the Laser. The one difference is that you will now also adjust the SIDE knob.

### I.D.3-c. Setting the Beam Height

After the initial installation of the grating holder, turn on the laser and align the external cavity (See Section I.D.2-b). Place the viewing screen or IR viewing card at the far end of the optical table from the laser in a position to view the beam. Loosen the two 6-32 socket head cap screws and tilt the grating holder to set the beam height at four inches (4") above the optical table as seen on the viewing card. Retighten the 6-32 socket head cap screws. Align the external cavity once again and confirm that you have the correct beam height.

### I.D.3-d. Contacting Piezo Stack with Ball Tipped Setscrew

Once the beam height has been set, turn the ball tipped setscrew until it makes contact with the piezo stack. Once the ball tipped setscrew just makes contact, the screw should be tightened an additional one-quarter turn. *DO NOT tighten it more than one-quarter turn as this could lead to damage to the piezo stack when the high voltage is applied.* This preloads the piezo stack. If you find it difficult to tell when the setscrew has made contact, you can turn on the laser power and current and use the viewing screen and CCD camera to look at the beam spot as you tighten the ball tipped setscrew. When the beam spot starts to move, the setscrew is in contact with the piezo stack.

### I.D.4. Collimation Tube

Figure 12 shows an exploded view of the collimation tube and associated parts. The aspheric lens threads into the front side of the collimation tube. The split aluminum adapter\* and diode laser slide into the backside of the collimation tube. The black plastic retaining ring threads into the backside of the collimation tube and holds the diode in place. The printed circuit board (PCB) and 5.6 mm socket plug into the back of the diode. The strain relief body slides over the PCB and threads into the backside of the collimation tube. Three screws hold the strain relief cap onto the strain relief body.

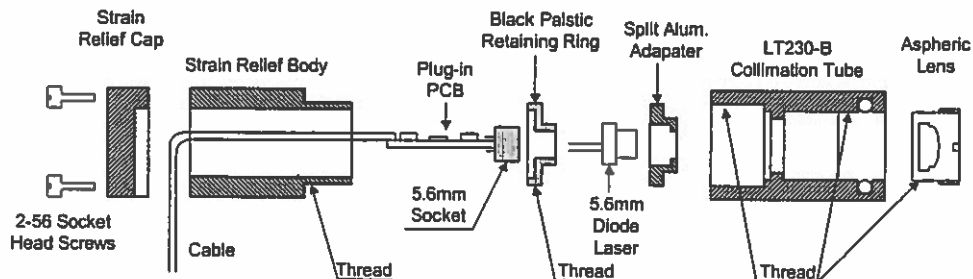


Figure 12: Exploded View of Collimation Tube

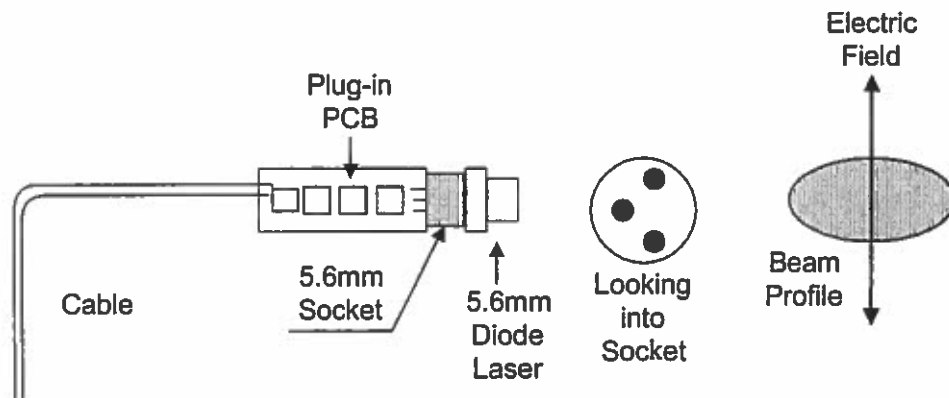
\* The aluminum adapter and retaining ring are for use with 5.6 mm diode lasers. Included with your laser is a different retaining ring that can be used with 9 mm diodes if you ever want to try different makes of diode in your laser head. With 9 mm diodes the aluminum adapter is not used.

#### I.D.4-a. Replacing the Diode

First, turn off the AC power to the Laser Diode Controller. Before removing the diode from the laser you must set up an electrostatically safe place to work. This should include a grounded table surface and a grounded wrist strap.

**Diode lasers are easily damaged by electrostatic voltages.**

Loosen the two setscrews on the side of the collimation tube holder (see Figure 7) and slide the collimation tube out of the holder. Remove the three 2-56 socket head cap screws from the strain relief cap and set the cap and screws aside. Unthread the strain relief body from the collimation tube and slide it over the cable. Do not allow the cable to twist with the strain relief body, but keep it fixed with respect to the collimation tube. You will have to unbend the cable somewhat to slide the strain relief body over it. Unplug the PCB and socket from the diode.



**Figure 13: Diagram showing relation between cable bend, diode pin out, beam profile and laser light polarization.**

With the spanner wrench provided, unthread the retaining ring from the collimation tube and remove the diode laser and adapter. Place the old diode aside, perhaps in a bag marked, "old diode", and remove the new diode from its bag. Put the new diode into the collimation tube. Place the diode into the adapter. Then, drop the assembly into the collimation tube. The diode-adapter assembly should fit snugly into the tube without cocking. Now, thread the retaining ring into place. Attach the socket and PCB to the diode and screw the strain relief body over the PCB and into the collimation tube. As before, keep the cable fixed with respect to the collimation tube. Attach the cap to the back of the strain relief body. Note: The cap has a cutout to accept the bent cable.

*Operating note: Figure 13 shows the relationship between the bend in the cable, the diode pin-out, the beam profile and the laser light electric field direction. In the next section, we will discuss how to orient the laser so that the long axis of the elliptical beam profile is horizontal. In this orientation, the grating provides the maximum resolution as the beam "covers" the largest number of lines in the grating.*

#### I.D.4-b. Setting the Laser Orientation and External Cavity Length

Place the collimation tube assembly in the collimation tube holder and lightly tighten one of the setscrews. The position of collimation tube within the holder determines the cavity length. The major effect of the cavity length is to determine the external cavity mode spacing. (See diode laser physics section) It is found that a short cavity works best.\* Position the tube so that there is a 2 to 3 millimeter gap between the collimation tube and diffraction grating. Do not let the collimation tube touch the grating. You need to leave space for the grating to move.

If not already connected, attach the 9-pin cable to the laser head and turn on the AC power to the Laser Diode Controller. The angular orientation of the laser within the collimation tube holder can be determined either by measurement of the polarization direction or observation of the beam profile. Figure 9 showed the setup to observe the beam profile as well as the retro-reflection. Figure 14 shows several images of the beam profile. In image 15c, the glass Neutral Density filter has been placed in the beam path so that the LED light from the diode does not interfere with imaging of the laser light. Turn on the Laser Power and increase the current till the laser is above threshold. Loosen the setscrew and rotate the collimation tube within the holder until the long axis of the beam imaged on the video screen is horizontal. (Figure 14c) You might also notice that two streaky features above and below the image that are from the LED light. Making these streaky lines vertical also sets the correct orientation.

To measure the polarization direction of the beam place a linear polarizer (available only with the complete optics package) after the glass ND filter and turn the polarizer until a minimum intensity image is observed on the video monitor. The electric field is polarized 90 degrees to the direction indicated on the polarizer.

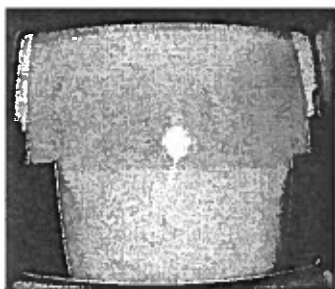


Figure 14a: Laser Beam with laser current *below* threshold, Only incoherent LED light is visible.

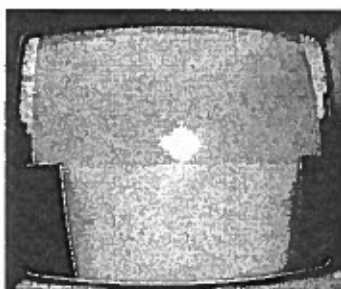


Figure 14b: Laser Beam with laser current *just above* threshold, laser light and LED light visible

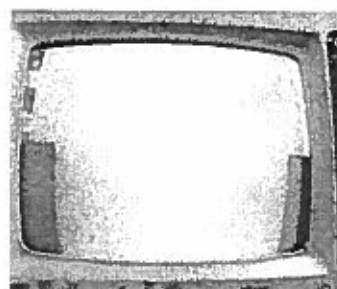


Figure 14c: Laser Beam with laser current *well above* threshold. An ND filter has been placed between laser and viewing screen, only laser light is visible

\* There exists a "magic" cavity length for which, as the angle of the grating is changed, both the wavelength diffracted by the grating and the wavelength of an external cavity mode, (determined by the cavity length), change at the same rate with angle. This distance can be determined from the diffraction angle and distance from the grating pivot point to the center of the beam spot on the grating. For the TeachSpin laser head this distance is about 0.58 inches (=14.7mm). This would seem to promise extremely long mode-hop-free scans. Unfortunately, the presence of internal cavity modes in the diode itself destroys the potential of long scans. (See Diode Laser Physics Section) A diode with an antireflection (AR) coating on its output facet would have no internal cavity modes and should show these long scans. The cost of AR coating a diode (\$2,000.00) has precluded any investigations by TeachSpin. We would be interested in hearing from anyone who has access to or has tried diodes with an AR coating.



#### **I.D.4-c. Adjustment of Lens Position**

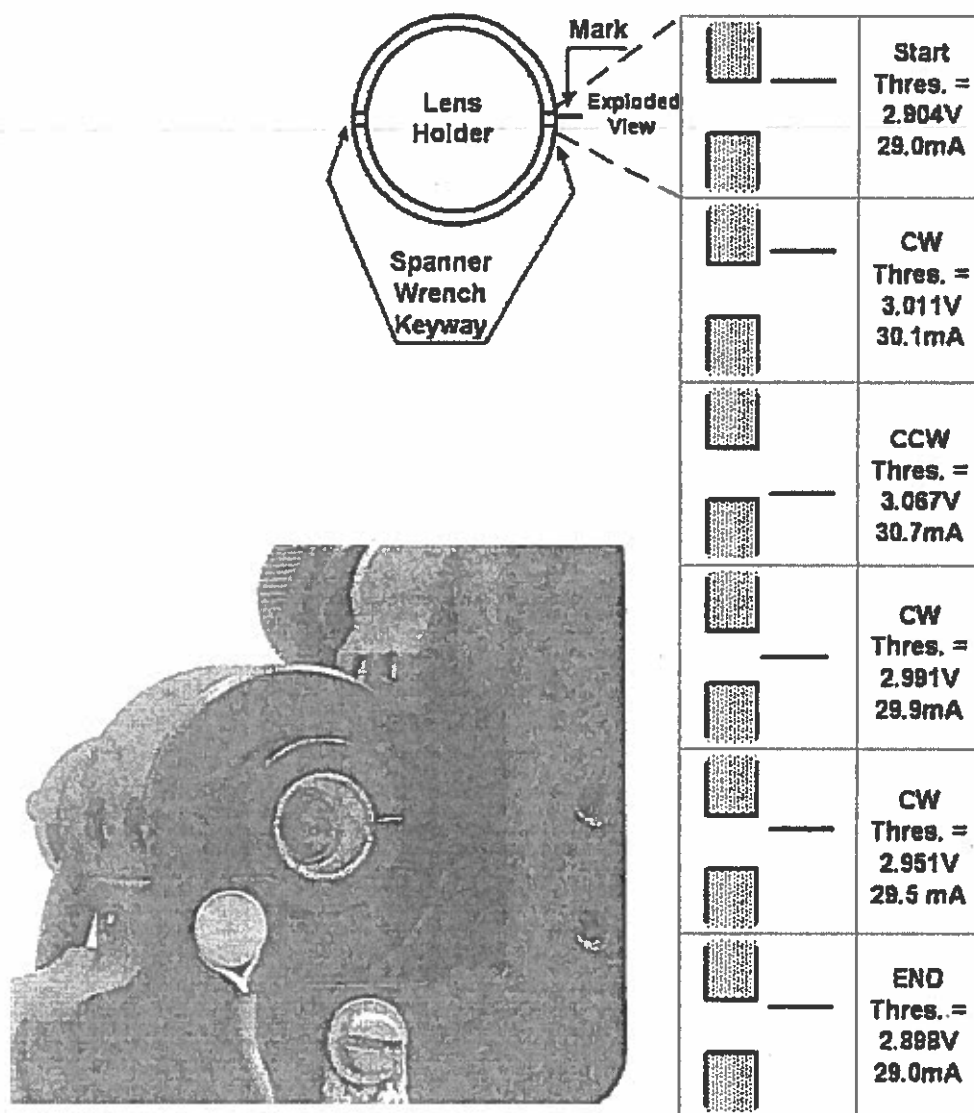
Optimal alignment of the diode laser involves adjustment of the lens position within the collimation tube. We have found that proper lens position is crucial for obtaining long mode-hop-free scans of the laser. When installing a new diode, we have found that you have to adjust the lens position about half of the time. For some of the new diodes, the old lens position will work just fine. To determine whether the lens position needs to be adjusted, we observe the laser behavior as we scan with the piezo only (no current scan) through the rubidium absorption features. If, after careful external cavity alignment, you can sweep through the first three absorption features (87b, 85b and 85a) (See the diagram in Initial Setup section 27.), then the lens position is fine. If on the other hand you find that you cannot make a nice long sweep, the lens position may need adjustment.

*Operating note: During the following procedures you will be turning the laser current on and off while you adjust the lens position. To adjust the position you will be looking almost directly into the output of the laser. We strongly urge you to exercise extreme caution and use proper laser safety. Keep your laser safety goggles on and always check that the laser current is set to zero and that the laser power has been turned off before you check the lens position.*

**I.D.4-c.1 Coarse Lens Adjustment:** If you are installing a new diode into a collimation tube that has been previously used, you may skip the following step. Usually, this step is only necessary if you are installing a new collimation tube or if the lens position has been grossly misadjusted. Coarse adjustment involves collimating the laser beam so that the beam size does not change with distance. Turn the laser power on and adjust the laser current above threshold. Use the IR viewing card or the viewing screen, CCD camera, and TV monitor to observe the spot size first near the output of the laser and then at a point several meters away. If the beam size changes, use the spanner wrench to adjust the lens until the beam is collimated.

**I.D.4-c.2 Fine Lens Adjustment:** Fine lens adjustment involves measuring the threshold current as a function of the lens position. At the optimal lens position, the threshold current is a minimum. The following steps need to be repeated until the minimum threshold current is found: Align the external cavity and measure the threshold current (section I.D.2-b&c). Remove the grating (section I.D.3-a). Adjust and record the lens position (I.D.4-c.3). Reinstall the grating (I.D.3-b). Align the external cavity and then measure the new threshold current. You may be tempted to remove the collimation tube from the tube holder, adjust the lens position and then reinstall the collimation tube in the holder, thus skipping the removal and installation of the grating. However, the threshold current is a strong function of the electric field polarization direction and we have found it difficult to reinstall the collimation tube in a repeatable manner. This is why we favor the above procedure. When reinstalling the grating, it is not necessary to set the beam height or contact the piezo stack with the ball tipped setscrew. These steps need only be done at the end, once the correct lens position has been determined. However, you should attempt to install the grating holder in a reproducible manner, pressing the grating holder against the 6-32 cap screws before tightening the screws as shown in Figure 11.

**I.D.4-c.3** The lens position may be determined by a mark that has been placed on the end of the collimation tube near one of the spanner wrench keyways. See the picture in Figure 15. Figure 15 also shows a series of measurements that were taken as a function of lens position. The pictures show the relative position of the mark and keyway. You should realize that the mark stays fixed as the lens and keyway are rotated, though the picture appears to show the opposite. You should notice in the picture that we are making very small changes in the lens position, only a few degrees, and that the threshold current is changing by a milliamp or less.



**Figure 15: Picture of Scratch Mark on Collimation Tube and Diagram Showing Threshold Current Measurement as a Function of Lens Position.**

## I.E. PIEZO STACK

The piezo stack is an NEC / Tokin model AE0203D04, which has a nominal displacement of  $3\text{ }\mu\text{m}$  at 100V. The piezo stack is polarized and voltage of only one polarity should be used. The stack is sandwiched between two metal plates. A setscrew contacts the bottom metal plate from the side and holds the stack in the movable portion of the mirror mount (See Figure 7). A ball tipped setscrew in the grating holder contacts the piezo stack. When voltage is applied to the piezo stack the ball tipped setscrew transmits the motion of the stack to the holder and grating, changing the grating position. Both the distance from the grating to the laser (the cavity length) and the angle of the grating are changed by the expansion and contraction of the piezo stack.

### I.E.1. Electronics

Voltage is applied to the piezo stack through the 9-pin cable. The PIEZO CONTROLLER module in the electronics box adjusts the voltage applied to the stack.

Piezo Displacement	$3.0\text{ }\mu\text{m} \pm 1.5\text{ }\mu\text{m}$ @ 100 Volts
Piezo Maximum Voltage	150 volts
Piezo Frequency Response	DC to 1 kHz
DC OFFSET COARSE FINE	Ten turn 0 to 100 Volts Single Turn 0 to 2 Volts
MODULATION INPUT Input Impedance ATTENUATOR	1 V input = 5 V across piezo stack 10 k $\Omega$ Reduces MOD. Input
MONITOR OUTPUT OUTPUT OFFSET	1/10th of voltage across stack Changes DC level of monitor voltage 0 to -5V, does not change piezo stack voltage

The voltage applied to the piezo stack is the sum of the voltage set by the DC OFFSET controls and the voltage from the modulation input. To avoid overdriving the stack, both positive and negative voltage clamps have been built into the electronics. These are +110V and -6V respectively. When used with the triangle wave from the Ramp Generator, the clamps may clip the triangle wave at the top or bottom, depending on the DC OFFSET of the Piezo Control. Thus, it is essential that you monitor the output on an oscilloscope. The maximum amplitude change, when using the 10 V p-p Ramp output, is 50 Volts

The DC OFFSET FINE control and OUTPUT OFFSET are only needed when side locking the laser to a spectral feature. In normal operation, both these controls should be set to zero.

## I.F. RAMP GENERATOR

The Ramp Generator provides a bipolar variable amplitude and frequency triangle wave. The frequency may be changed from 1 mHz to 7 kHz. The maximum amplitude is 10 Volts peak to peak, (plus and minus 5 volts about ground). The highest frequency output of the generator is 7 kHz. (Though the dials would lead you to believe that 10 kHz was the highest frequency.) At frequencies of 1 kHz and higher, the high frequency Fourier components of the triangle wave are attenuated and you will observe a "rounded" triangle wave.

The high frequencies have little use in taking data and are only used to investigate the frequency response of the Piezo and Current controller. The long sweep times were incorporated for use in slow temperature sweeps of the laser. The reset toggle switch stops the triangle wave generator and takes the output to the minimum value. This is useful in starting and stopping slow sweeps. The reset can also be used to disable the sweep. This is useful when you are trying to observe the fringes while setting up an interferometer. The SYNC output provides a -5 to +5 volt square wave that can be used to trigger an oscilloscope.

**Ramp Generator Noise:** The rms noise on the ramp generator output is about 50  $\mu$ V rms. If you use the Ramp Generator to provide a simultaneous Current and Piezo sweep of the laser frequency, while observing very narrow Doppler-free features (12 MHz or less), the lines will be slightly broader than when doing only a Piezo sweep. If you wish to observe very narrow Doppler-free features, you should use the Ramp Generator to sweep the Piezo only!

## II. Photodiode Detectors and detector/low pass/dc level Electronics

### II.A. PHOTODIODE DETECTORS

Photodiodes	Photonic Detectors Model PDB-C108
Active Area	0.25" Diameter Circle
Responsivity	about 0.6 A/W (1.7 W/A) at 800nm
"Gain"*	10 M $\Omega$ to 333 $\Omega$

The photodiode detectors contain a current to voltage converter. The switch on the back of the detector allows gain setting of 10 M $\Omega$  to 333  $\Omega$  in ten steps. Table 3 lists the high frequency 3dB points and noise for the different detector gains. The detectors have separate signal and power cables. Three detector power plugs are on the front panel. The signal is on the coax cable with BNC connector. The polarity of the signal is negative. If you plug the signal into an oscilloscope, the signal will be from 0 to -11.0 Volts. The detector voltage saturates at about -11 volts. **You should adjust the gain of the detector so that you are not near the saturation voltage.**

Gain	High Frequency 3dB.	Noise*
10 M $\Omega$	5.8 kHz	1.57 $\mu\text{V} / \text{Hz}^{1/2}$
3.3 M $\Omega$	10.3 kHz	0.90 $\mu\text{V} / \text{Hz}^{1/2}$
1.0 M $\Omega$	20 kHz	0.42 $\mu\text{V} / \text{Hz}^{1/2}$
330 k $\Omega$	28 kHz	0.20 $\mu\text{V} / \text{Hz}^{1/2}$
100 k $\Omega$	54 kHz	91 nV / $\text{Hz}^{1/2}$
33 k $\Omega$	88 kHz	48 nV / $\text{Hz}^{1/2}$
10 k $\Omega$	165 kHz	24 nV / $\text{Hz}^{1/2}$
3.3 k $\Omega$	260 kHz	16 nV / $\text{Hz}^{1/2}$
1.0 k $\Omega$	480 kHz	13 nV / $\text{Hz}^{1/2}$
330 $\Omega$	720 kHz	13 nV / $\text{Hz}^{1/2}$

**Table 3: Photodiode Detector Parameters**

\* Measured in 3 Hz to 44 kHz. frequency range.

At high light intensities the response of the photodiodes becomes non-linear. (A doubling of the light intensity gives an output voltage that is less than double.) This occurs at an output current of about 0.5 mA. If you wish to use the photodiode as a power meter, you should make sure that the light current is below this value. If it is not, place a ND filter in front of the photodiode. Students will need to calibrate the Neutral Density filters using the photodiode detectors at low laser light levels.

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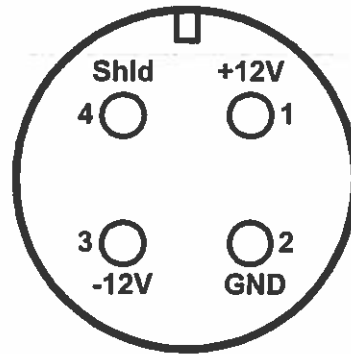
\* The current to voltage converter gain has units of ohms.  $I_{IN} = V_{OUT} / R_{GAIN}$ , from which the input power can found using photodiode responsivity (0.6 Amps/watt).

## II.B. DETECTOR / LOW PASS / DC LEVEL ELECTRONICS

Detector electronics on the front panel allow for conditioning of the signals. The BALANCE controls are two, input attenuating, potentiometers that can be adjusted to balance two signals from the photodiode detectors. The internal instrument amplifier can be used to take the difference of the two signals with a GAIN from 1 to 100. Table 4 lists the gain and high frequency 3dB point.

Gain	3dB. Freq. (Hz)
1	1.3 M
2	1.0 M
5	780 k
10	650 k
20	470 k
50	220 k
100	110 k

**Table 4: High Frequency Response of Detector versus Gain**



**Figure 16: Detector Power Pin-out (looking into connector on front panel)**

The LOW PASS filter and DC LEVEL controls are provided for side locking the laser to a spectral feature. The single pole low pass filter has switch selectable time constant from 10  $\mu$ s to 0.1 seconds. The DC LEVEL has a ten-turn potentiometer that provides a DC offset from minus five volts to plus five volts. For positive offset voltages, the voltage may be read off the dial directly. For voltages less than zero the voltage is found by subtracting ten from the number displayed on the dial. (9.0 dial = -1.0V, 7.2 dial = -2.8V). There is a final DC gain stage of 1 to 30 after the DC level adjustment. There are monitor outputs after the first difference and gain stage, and after the low pass filter. These can be used to record data or to check the function of the different sections.

### III. Absorption Cell Assembly

The absorption cell assembly consists of an outer glass cylinder, several melamine foam insulation and support pieces, the heater assembly, a type T thermocouple sensor, a cold-finger, and the Rb cell. The heater is an aluminum cylinder about which is wound a bifilar heater wire. The heater has a resistance of about fifty ohms ( $50\ \Omega$ ). Wires from the heater and thermocouple plug into the back panel of the electrical box.

#### III.A. SPECIFICATIONS

Maximum temperature	$\approx 90\ ^\circ\text{C}$
	$\approx 140\ ^\circ\text{C}$ with $\frac{1}{2}$ " hole foam inserts
Temperature differential across Cell	
T= $50\ ^\circ\text{C}$ (min. on bottom max. on top)	$10\ ^\circ\text{C}$
	$2.0\ ^\circ\text{C}$ with $\frac{1}{2}$ " hole foam inserts
Heater resistance	$\approx 50\ \Omega$
Temperature Controller	1 Hz PWM* PID
Controller Resolution	$0.1\ ^\circ\text{C}$
Regulation (no air currents)	$0.2\ ^\circ\text{C}$
Rubidium Cell	25 mm Diameter and 25 mm Length natural isotopic Rb. (no buffer gas)

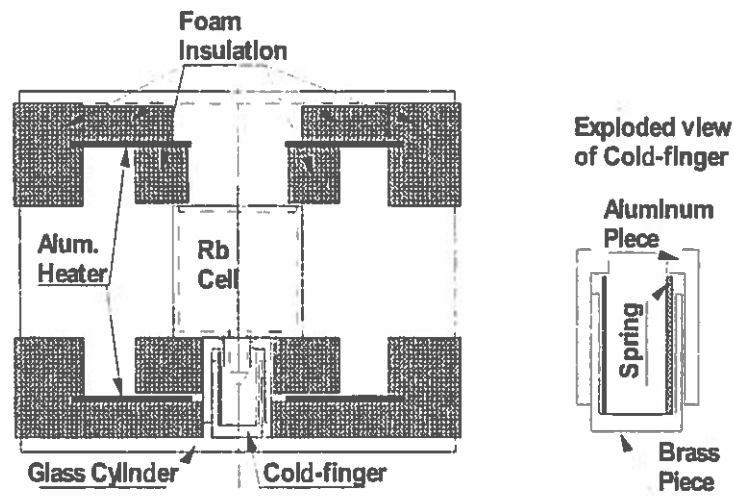


Figure 17: Cross section of Cell Heater Assembly

\* PWD means Pulse Width Modulated output voltage (pulse rolled off with a maximum frequency of 1 kHz.), PID is Proportional, Integral, Derivative control algorithm.

### III.B. CELL HEATER AND COLD-FINGER

#### III.B.1. Description

A cross sectional view of the Cell Heater is shown in Figure 17. The spring loaded cold-finger makes contact between Rb cell tip and the outer glass cylinder. A white piece of thermal adhesive is placed around the cell tip to increase the contact area between the cell and cold-finger. The thermocouple temperature sensor has been placed between the cell and the foam near the cell tip. The junction is soldered together and the wires are covered with black heat shrink tubing.

#### III.B.2. Removal of Cell Heater and Cold-finger

To remove the cell and cold-finger, first turn off the power and let the unit cool to room temperature.

Loosen the Nylon setscrew on the side of the rotatable cell mount and remove the heater assembly with attached aluminum holder from the base. Set the assembly on the table. We will describe the removal of the cell and cold-finger while leaving the glass cylinder attached to the aluminum holder.

Remove the foam ends caps. When you remove the end cap with the wires for the heater and thermocouple (TC), the TC will come out with the end cap. Slowly push the foam and cell assembly out of the glass cylinder. Push towards the end where the heater wires come out. Be prepared to catch the bottom of the spring loaded cold-finger as it clears the end of the glass cylinder when the assembly is half way out.

When the foam and cell assembly is out of the glass cylinder, remove the remaining piece of the cold-finger. This is the aluminum piece that contacts the rubidium cell at the tip. You may need a pair of tweezers to pull this piece out of the foam. Now push the Rb cell and foam support piece out of the aluminum heater. This completes the removal.

#### III.B.3. Installation

Installation is the reverse process of removal. Put the cell into the foam support piece. It is easy to tear the foam so be gentle. The small hole in the support piece is for the tip, and the larger hole is for viewing. Slide the cell and foam support into the aluminum heater. The large hole in the aluminum heater is for the cold-finger and the smaller hole is for the viewing window. Note, there is a little area of aluminum heater exposed around the viewing window; this is to keep the viewing window hot and prevent Rb metal condensation.

Place the aluminum cold-finger in the foam support piece so that it covers the cell tip. You should notice that the cold-finger pieces have been machined to fit the curve of the cell.

Slide the assembly into the glass cylinder. When the assembly is half way in, insert the spring and brass part of the cold-finger. Adjust the cell and foam pieces so that the cell is centered in the heater and also centered in the viewing window. Place the thermocouple sensor next to the cell just under the foam support near the cold-finger. We suggest that you keep the viewing window and cold-finger horizontal (Viewing window on one side and cold-finger on other.)

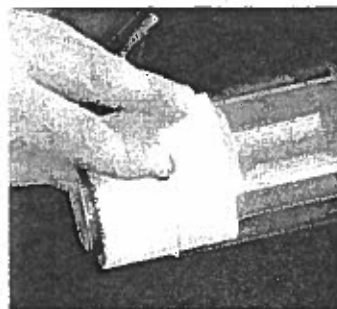


Figure 18: Insertion of Cold-finger into Cell Assembly



### **III.C. THERMOCOUPLE POSITION AND TEMPERATURE**

There is a significant thermal gradient across the cell of about 10 °C at a set point of 50 °C. The thermal gradient is mostly vertical with the bottom cooler and the top hotter. The density of rubidium in the cell is determined by the temperature of the pool of excess rubidium that condenses in the tip near the cold-finger. If you need to have a reasonably accurate measure of the rubidium density, you should check that the thermocouple is placed close to the cold-finger. (For most experiments the exact temperature is not important) We have included some foam inserts that may be placed in the foam end caps for higher temperature operation.

### **III.D. CONDENSATION OF Rb ON THE CELL WINDOWS**

Rubidium metal condensed on the cell windows creates a silver, mirror-like layer on the inside of the cell. This reflects part of the laser beam and can lead to confusing results. Because there is a vertical temperature gradient across the cell the first condensation will probably be on the lower portion of the windows. The heater assembly has been designed to keep any excess Rb metal in the cell condensed in a hidden tip rather than the end windows. To accomplish this, equal areas of the aluminum heater must be exposed at each end of the assembly (See Figure 16 on page 5-25). If you notice Rb condensing on just one of the end windows of the cell, adjust the cell and foam support to expose slightly more of the heater on the side where the Rb is condensing. (Push gently on the foam and cell from the side where the metal is condensing.) See the addendum at the end of this section for detailed instructions on how to transfer the Rb from the end windows to the tip.

### **III.E. CELL TEMPERATURE CONTROLLER**

#### **III.E.1. Operation of Cell Temperature Controller**

The Omega temperature controller is mounted on the front panel. (A manufacturer's manual for the controller has been included.) Reading from left to right across the face of the unit, the four keys used to program the controller are: MENU, UP, DOWN and ENTER. When the controller is in the normal or RUN mode, the temperature is displayed in degrees Celsius. Under normal operation, you will be changing only the temperature set point. In the RUN mode, the controller will display the current temperature. To get into the Configuration Mode, press the MENU key once. SP1 will be displayed. Now, press the ENTER key. The display will show the current "Setpoint1." Use the UP and DOWN arrow keys to change the value. Once the correct value has been selected, press the ENTER key again to store the value. The display will show "StRd" briefly indicating your value has been registered. Return to the MENU key and continue pressing until RUN is displayed.

#### **III.E.2. Configuration of Cell Temperature Controller**

The configuration of the controller has been done by TeachSpin. Unless the controller has been accidentally reset you should not need to change the configuration. The Instrument Configuration list, at the end of this section, includes only those items that have been changed by TeachSpin. The value in parenthesis is the main menu heading under which the changed settings are located. All other values are the factory default. See page 62 of the Controller Manual for details and additional explanations.

To change the Proportional, Reset or Rate values, enter the Instrument Configuration mode by pressing the MENU key until CNFG is displayed, and then press ENTER. Using the MENU key, scroll through the various options until OUT1 (Output 1) is displayed, then, press ENTER. Again scroll through the options with the MENU key until the CTRL option is displayed and ENTER. Use MENU to set the CTRL to PID and ENTER.

Now that you are in the Configuration mode, use MENU to scroll until PROP, REST or RATE is displayed. Press ENTER, then use the UP and DOWN arrow keys to change the value of the selected parameter. Press ENTER again to save and store the value. Once all changes have been made, use the Menu key to return to RUN mode. Please refer to section 3, page 15, of the controller manual for a complete description.

#### Instrument Configuration List for Temperature Controller

Set Point 1 (SP1)	50.0
Input Type (INPT)	TC = t
Temperature Unit (RDG)	TEMP = C
Filter (RDG)	FLTR = 16
Control (OUT1)	CTRL = PID
Proportional Value (OUT1)	PROP = 005.8
Reset Value (OUT1)	REST = 0480 (Seconds)
Rate Value (OUT1)	RATE = 090.0 (Seconds)
Cycle period (OUT1)	CYCL = 0001
Damping Value (OUT1)	DPNG = 0005

We have chosen the PID values (P = Proportional, I = Integral (reset), D = Derivative (rate)) for reasonable temperature stability without the extra 1/2" hole foam inserts in place.

#### III.F. MAGNETIC FIELD COILS

The Helmholtz magnetic field coils were designed to provide a field of about 10 mT at a current of three amperes (3.0 A). The average radius of a coil is 3.44" (87.4 mm). There are 320 turns of 18 gauge copper wire on each coil (16 turns per layer and 20 layers). The room temperature resistance of each coil is about four ohms (4  $\Omega$ ). The terminal block on the side of the cell holder can be used to connect to the coils. You will have to provide your own power supply to energize the coils.

For the Helmholtz configuration we estimate the field in Gauss from,

$$B \text{ (Gauss)} \approx 0.9 * N \text{ (turns per side)} * I \text{ (A)} / R \text{ (cm)}$$

## IV. Optics

Table 5 lists the optical components included in the complete instrument. The thin film components (Wratten neutral density filters, linear polarizers and quarter wave plates) can be damaged by the full power of the laser\*. You should attenuate the beam before sending through one of these components.

OPTICS	SOURCE	STOCK NUMBER	MATERIAL	FLATNESS $\lambda$ / INCH	OTHER
Mirrors (protected aluminum)	Thor Labs	ME1-G01	Float Glass	$< 5\lambda$	Scratch/ Dig 60 - 40
Beam Splitter 50/50 NIR	Edmunds Optics	Y45-853	BK7	$1\lambda$	Scratch/ Dig 60 - 40
Beam Splitter 2° Wedge	Red Optonics	RWP 101	BK7	$\lambda/4$	Scratch/ Dig 60 - 40
Beam Splitter 1° Wedge	Red Optonics	RWP 10X	BK7	$\lambda/4$	Scratch/ Dig 60 - 40
Beam Splitter 0.0° 1/4 " thick	Rolyn Optics	55.1025	Pyrex		Scratch/ Dig 80 - 50
Neutral Density Filter Glass	Thor Labs	NE10B	Schott NG4	$1\lambda$	$\approx 15\%$ trans. @ 780 nm.
Wratten Neutral Density Filter	Kodak	EK141 0042 filter #96	Gelatin ND 0.7		$\approx 33\%$ trans. @ 780 nm.
Linear Polarizer	American Polarizer (3M)	98-0440- 0968-0	HN-32 0.03"		$\approx 42\%$ trans. @ 780 nm.
Quarter Wave Plate	American Polarizer (3M)	98-0440- 1064-7			

**Table 5: Optical components**

\* We have only noticed damage when using the laser at high current without the grating attached. There we have damaged both linear polarizers and the Wratten neutral density filters. You should be very careful using these components for this laser configuration. But this is not the normal mode of operation. When operating with the grating attached to the laser we have not noticed any damage, but we do observe some rather strange behavior at higher powers. (See discussion in section IVC on page 5-30))

#### IV.A. MIRRORS

Economy mirrors from Thor Labs have a reflectivity of about 85%. We have noticed no effects of the rather poor surface flatness of these mirrors in the interferometer setups.

#### IV.B. BEAM SPLITTERS

The NIR 50/50 Beam splitter has been coated so that the reflection and transmission are both about 50%. You should be aware that this is for unpolarized light and that there will be some polarization dependence. The other three beam splitters are uncoated pieces of glass. There will be reflections from both the front and back surfaces of the glass. With the wedged beam splitter, it is not easy to determine which surface a particular beam is coming from. It is sometimes easier to use a visible laser to identify the beams. The amount of reflection will also be polarization dependent.

#### IV.C. NEUTRAL DENSITY (ND) FILTERS

All the ND filters are absorptive rather than reflective. The glass ND filter can be used with any laser power. The thin film Wratten ND filters should only be used with low power laser light (2 mW or less). At laser powers up to 30 mW, there is no permanent damage to the filters. However, above 2 mW of laser power, we start to notice transient effects. The power transmitted fluctuates by about 0.5% in a way that is reminiscent of a damped harmonic oscillator with a time constant of tens of seconds. This is also true of the linear polarizers.

#### IV.D. LINEAR POLARIZER IN ROTATABLE MOUNT

The linear polarizers have been marked such that when the tick mark is at 0° the light transmitted by the polarizer has a vertically polarized electric field. The mark should be accurate to  $\pm 5^\circ$ . Figure 19 shows the amount of light transmitted by the polarizer. The linear polarizers work well at laser powers of 2mW and below. At powers between 2 mW and 30 mW, they show transient behavior. With laser powers above 30mW, they can be permanently damaged

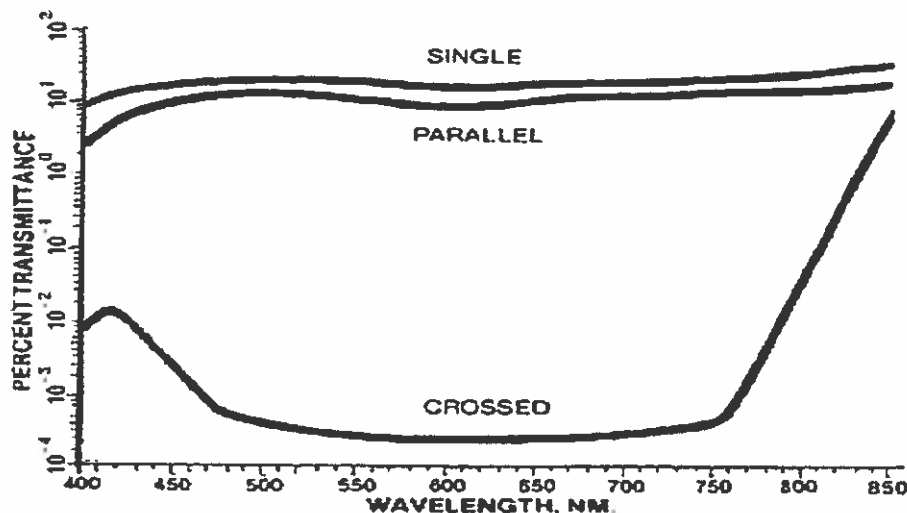


Figure 19: Percent Transmittance of Linear Polarizers

#### IV.E. QUARTER WAVELENGTH PLATE IN ROTATABLE MOUNT

Diameter 50 mm, "optical thickness"  $200 \pm 5$  nm: When properly oriented, the quarter wave plate allows linearly polarized light to be converted to circularly polarized light. The plate has two optical axes (at 90 degrees to each other) with different indices of refraction along each axis. Light travels at different speeds along each axis. The axes are called the "fast axis" and "slow axis". To produce circularly polarized light, monochromatic, linearly polarized light is placed incident to the plate at  $45^\circ$  to each axis. If the plate is of the correct thickness, then the phase lag along the slow axis causes the light exiting the plate to be circularly polarized. The "optical thickness" of the plate may not be the desired value.

Tuning the optical thickness (retardation) can be accomplished by rotating the plate about the vertical axis. Rotation about the slow axis increases the retardation, and about the fast axis decreases it. See Figure 20. This tuning method requires either the fast or slow axis to be aligned vertically.

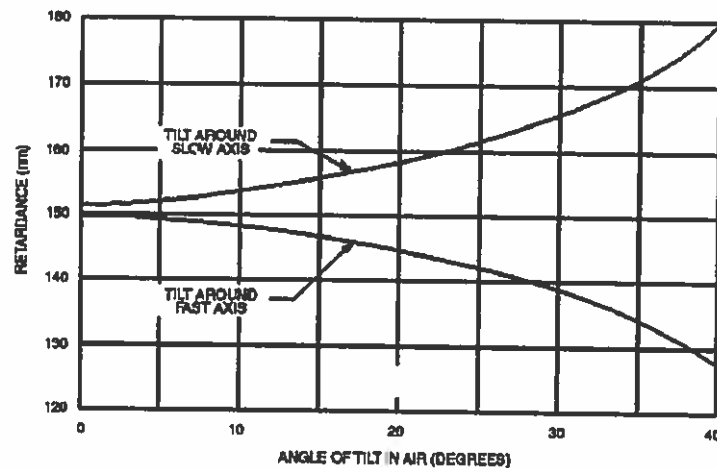


Figure 20: Tilt Tuning of Quarter Wave Plate

#### IV.F. ASSEMBLY AND CARE OF OPTICAL COMPONENTS

Loading optical elements into mirror mounts: You will have to place the various optical components into the mirror mounts. It is best to do this without touching the components with your fingers. If you must touch the components, wear protective gloves and touch the components only at the edges.

## **V. TV Monitor and CCD Camera**

### **V.A. THE TV MONITOR**

The TV monitor was shipped with its wall mounted AC to DC power supply in the box. The TV requires 12 V DC at 850 mA. The CCD camera power supply (12 V DC at 250 mA) plugs into the red plug on the cable attached to the back of the camera. The yellow plug on the same cable is the video output, which plugs into the back of the TV monitor. We have included an extension video cable for the camera and there may be an adapter plug attached to the extension cable, to make the cable compatible with the video input on the back of the TV.

VB Camera focus

### **V.B. CAMERA FOCUS**

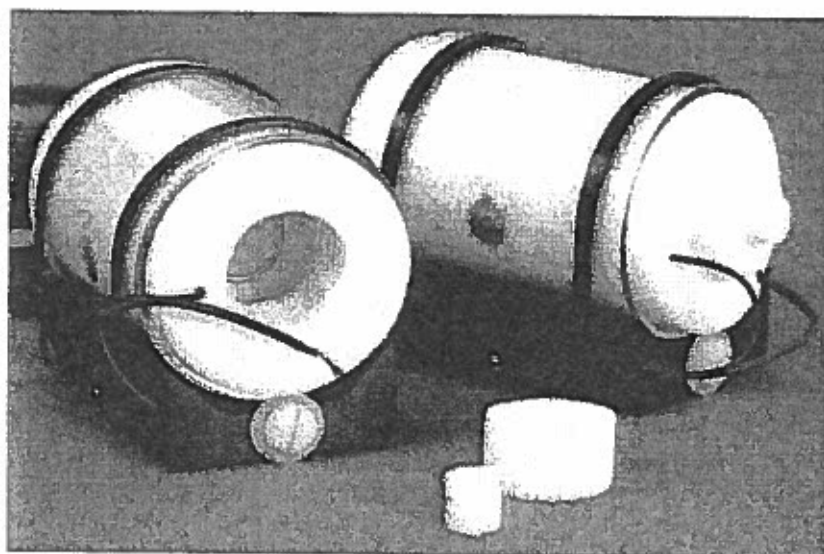
The CCD camera focus may be adjusted by turning the lens on the front of the camera. You may have to loosen a small setscrew to do this. The camera has an automatic gain control so that it adjusts to low and high light levels. To get a nice image on the TV monitor, it is often necessary to adjust either (or both) the background room light and laser intensity. Use the neutral density filters to adjust the laser intensity. This is particularly true if you are trying to image the laser beam profile or when you are looking for fringes while lining up an interferometer.

## VI. Addendum

### VI.A. CONDENSING RUBIDIUM IN THE TIP

When operating the cell at elevated temperatures (above the "normal" 40 – 50 °C.) it is possible that excess rubidium may move out of the cooled tip and condense on the windows. The following procedure may be used to evaporate the Rb off the windows and condense it back in to the tip.

1. Place the foam inserts into the open ends of the cell heater as shown in the figure below. (The smaller foam plug was only included in Diode Laser's with serial numbers DL154 and greater. If you have an earlier model Diode Laser, just use a piece of foam or insulation to block the opening in the cell heater.)
2. Increase the cell temperature set point to about 120 °C. The exact value is not important. See section A8-5 and A8-6 for details on cell temperature controller.
3. Let the cell heat up and stay hot for about 1 hour. (You can remove the foam plugs quickly and check to see if all the Rb has moved off the windows.)
4. After the Rb has been evaporated off the windows, return the cell temperature set point to its usual operating point (40 – 50 °C). Leave the foam plugs in place as the cell cools! This is critical. The windows must be kept warm to assure that the Rb will now condense in the tip.
5. Once the cell cools, the plugs may be removed and the cell heater returned to normal operation. If you are doing high-temperature experiments, it is always advisable to put the plugs into the open ends of the cell before turning off the power to the heater. This will prevent Rb from condensing onto the end windows as the cell cools.



**Figure 21: Cell assembly showing placement of foam plugs**

