

Appendix 1: DODE 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 ($\sim \$100,000.00$) 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 ($\Delta\nu < 1 \text{ MHz}$, $\Delta\lambda < 1.5 \times 10^{-6} \text{ nm}$). For these reasons, tunable diode lasers have rapidly become commonplace in modern research laboratories.

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, ~ 2 microns high, ~ 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.

Interior Diagram of TOLD9200 Series

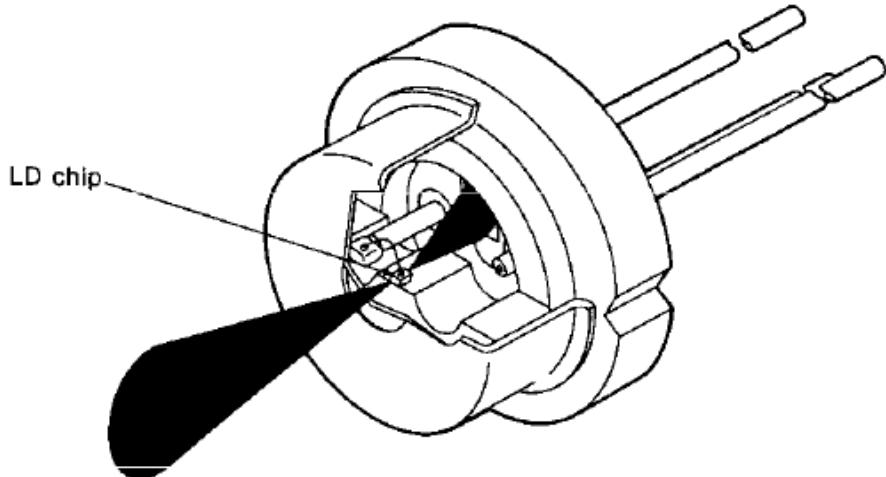


Figure 1. Cut-away view of a typical laser diode.

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.

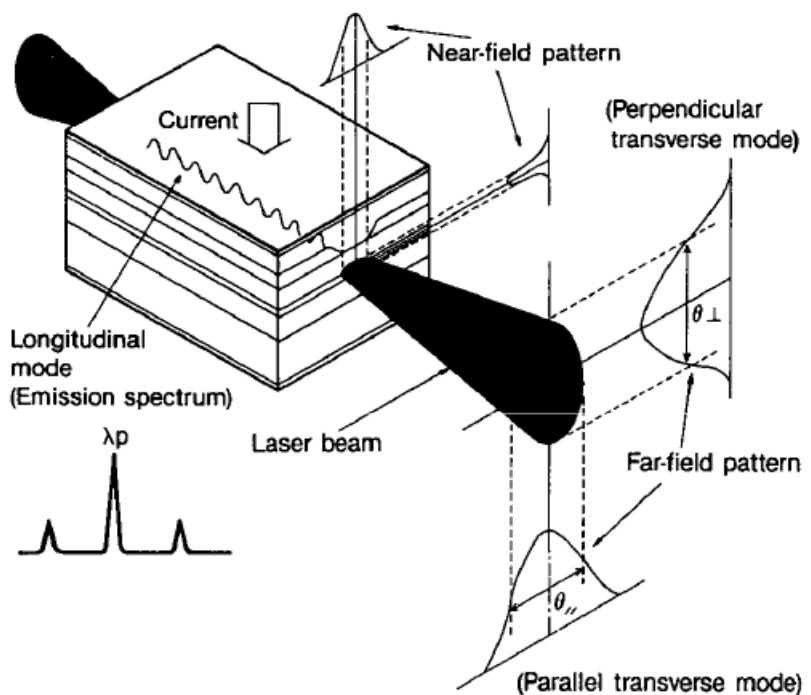


Figure 2. Schematic view of a laser diode chip.

SCHEMATIC STRUCTURE OF VISIBLE LASER DIODES

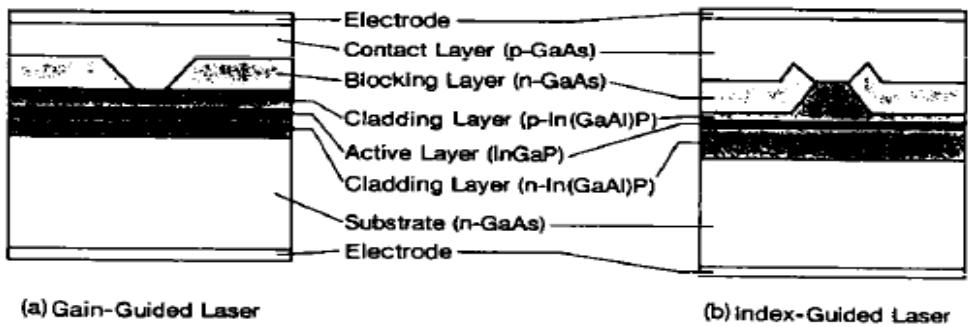


Figure 3. Schematic picture of the internal semiconductor structure of a typical laser diode. This view is looking into one facet of the laser cavity.

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.)¹

II. Lasers with Grating Feedback or External Cavity Diode Lasers (ECDL)

A. Introduction

Bare diode lasers have two undesirable properties: 1) their linewidths ($\Delta\nu\sim50$ MHz) are large compared to the linewidths of atomic transitions (in our case $\Gamma\sim5$ 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.

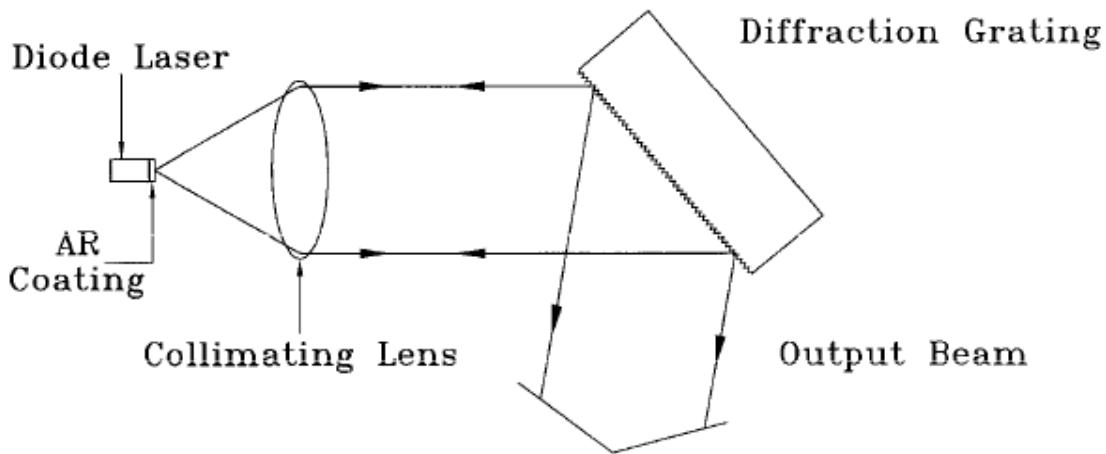


Figure 4. Basic configuration of the diode laser system.

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

¹ It is possible to get an approximate measure of the reflection coefficient, $R = 16.5\% \pm 5\%$. (See section A4-2 for details.)

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.

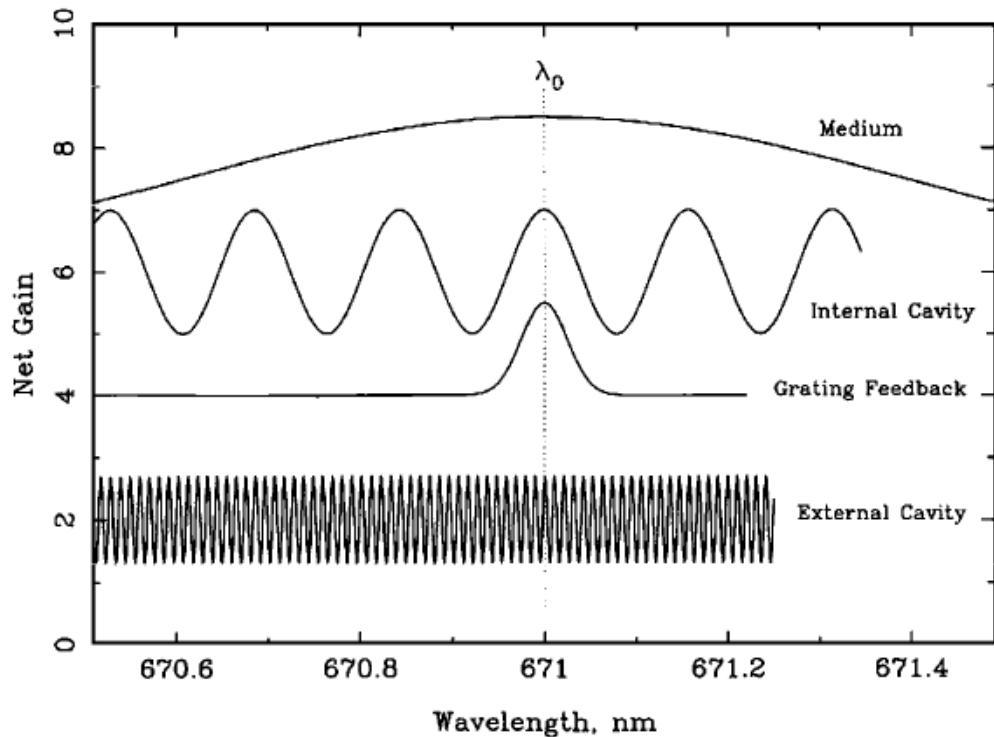


Figure 5. Schematic of the different contributions to the net optical gain of an arbitrary laser as a function of frequency. The curves are displaced relative to one another for clarity.

1. 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.

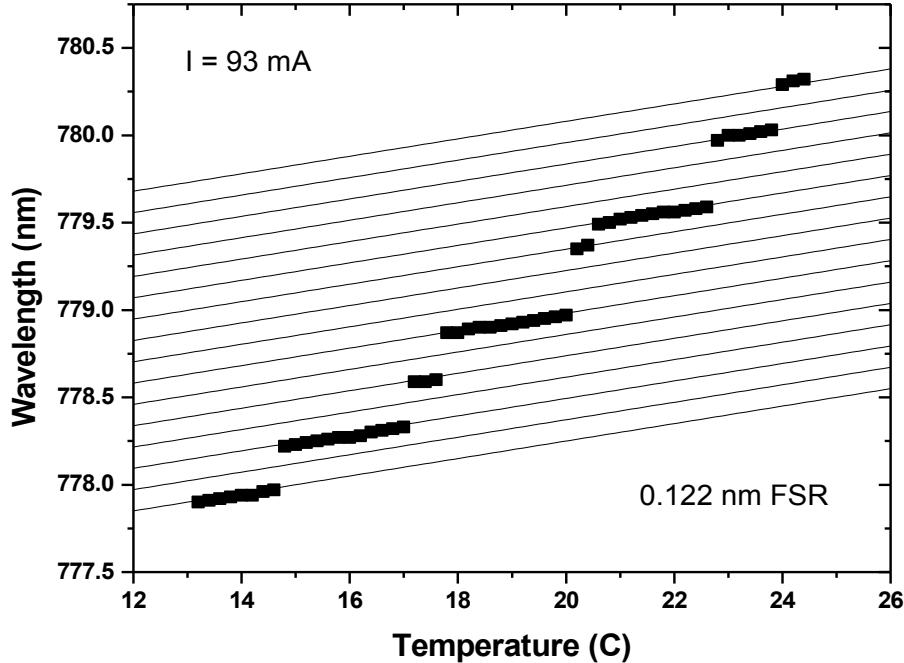


Figure 6. Output wavelength of a free-running (i.e., no external optical feedback) Sanyo DL-7140-200S diode laser as a function of diode temperature. (The behavior of other diode lasers is similar.)

2. 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 $\Delta\nu_{\text{FSR}} \approx 60 \text{ GHz}$ ($\Delta\nu \approx 0.122 \text{ nm}$). 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

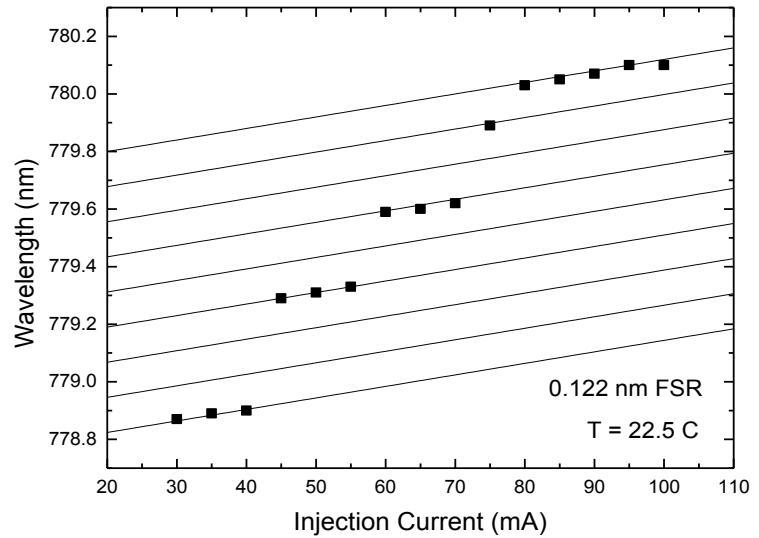


Figure 7. Free-running laser Wavelength versus Injection Current at a fixed temperature.

measured from the small scale slope the individual steps in Figure 6. Unfortunately, the temperature of the laser head cannot be changed very quickly. The thermal time constant of the laser head can be estimated to be on the order of 10 seconds.² The internal cavity modes will also change with the diode current. (See Figure 7.)

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 μ 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. 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 θ 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, Δv , will be given approximately by $v/\Delta v=N$, where v 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 $\Delta v \approx 70$ GHz. The position of this peak is determined by the grating L/R angle.

4. 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 $\Delta v_{FSR} = c/2L \approx 10$ 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 λ_0 (e.g. an atomic resonance line), the gain from each of the components should peak at λ_0 as shown in Figures 5.

² Estimated from the mass (≈ 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.

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 9 shows a series of pictures of the External and Internal cavity modes as the

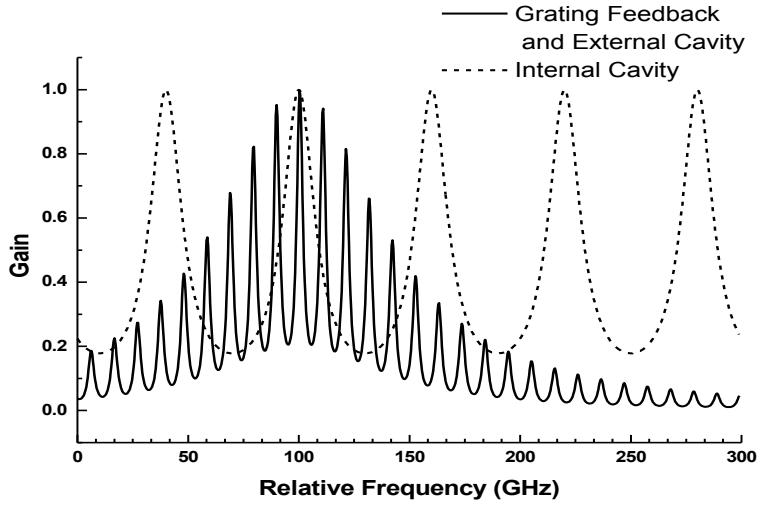


Figure 8. "Best guess" picture of internal cavity, grating feedback and external cavity modes in the laser.

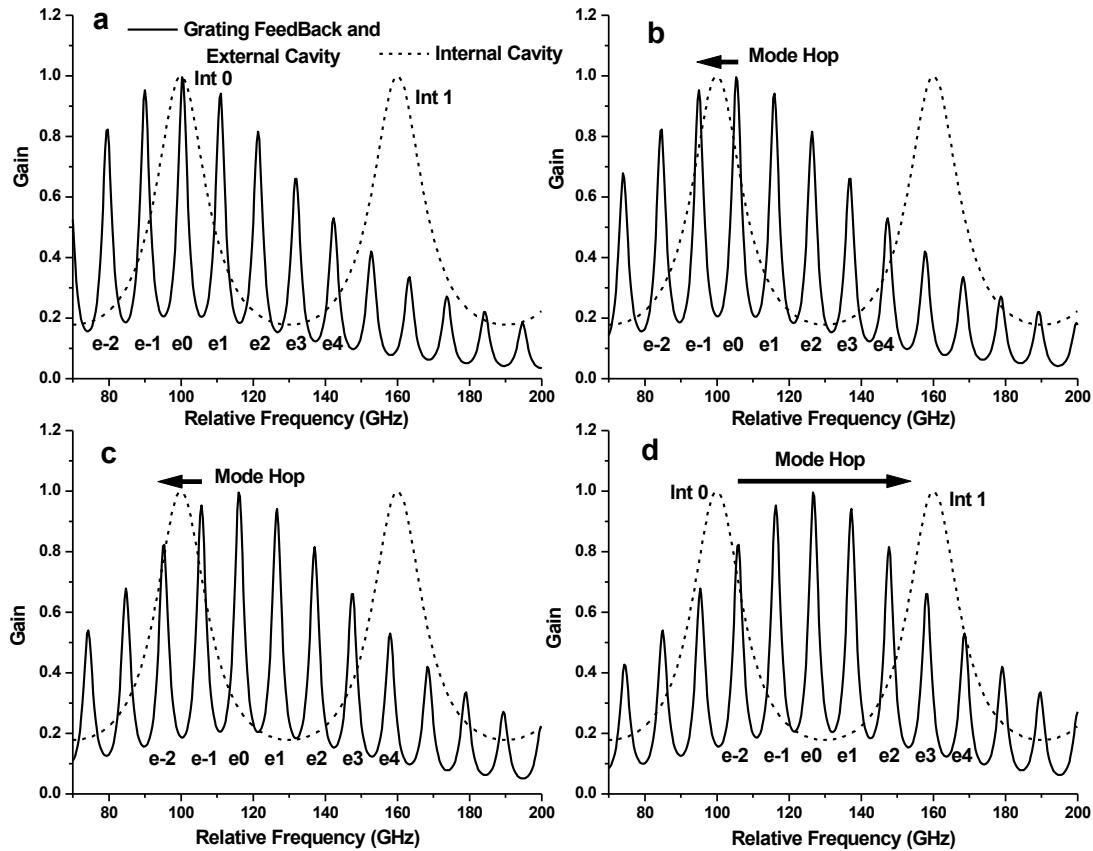


Figure 9. Series of graphs showing how the external and grating feedback mode shifts as the grating angle is changed.

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 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.

III. References

- Camparo, J. C. 1985, “The Diode Laser in Atomic Physics,” *Cont. Phys.* **26**, 443.
Möller, K. D. 1988, *Optics*, (University Science Books).
Wieman, C. E. and Hollberg, L. 1991, “Using Diode Lasers for Atomic Physics,” *Rev. Sci. Instrum.* **62**, 1.
Yariv, A. 1991, *Optical Electronics*, 4th edition (Holt, Rinehart and Winston).

Appendix 2: OVERVIEW OF THE INSTRUMENT

A. 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. 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 $10\text{ M}\Omega$ to $333\text{ }\Omega$ 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. Absorption Cell Assembly

The absorption cell assembly consists on 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. 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. Controller

While almost all functions of the apparatus are controlled by the modules on the front on 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.

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. 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.

Appendix 3: INITIAL INSTRUMENTATION CONFIGURATION AND STARTUP

1. Turn on the power strip at the rear of the optics bench. The TV monitor should illuminate.
2. Turn on the controller using the rocker switch on the right rear of unit. This will activate all units in the controller.
3. Turn on the oscilloscope.
 - a. Make sure the trigger is EXTERNAL and the mode should be NORMAL.
 - b. For both channels 1 and 2, the impedance should be set to 1 MΩ.
4. 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 established set-point temperature. 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.
5. Setting up the ramp generator and oscilloscope
 - a. 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 (see Figure 1 below). 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.
 - b. 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.
 - c. 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.)
 - d. 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. **Note: For each scan you will need to make further adjustments to the ramp generator and Piezo settings.**

Operating note: The PIEZO CONTROLLER drives a small piezoelectric stack that moves the optical feedback grating. This scans the laser frequency.

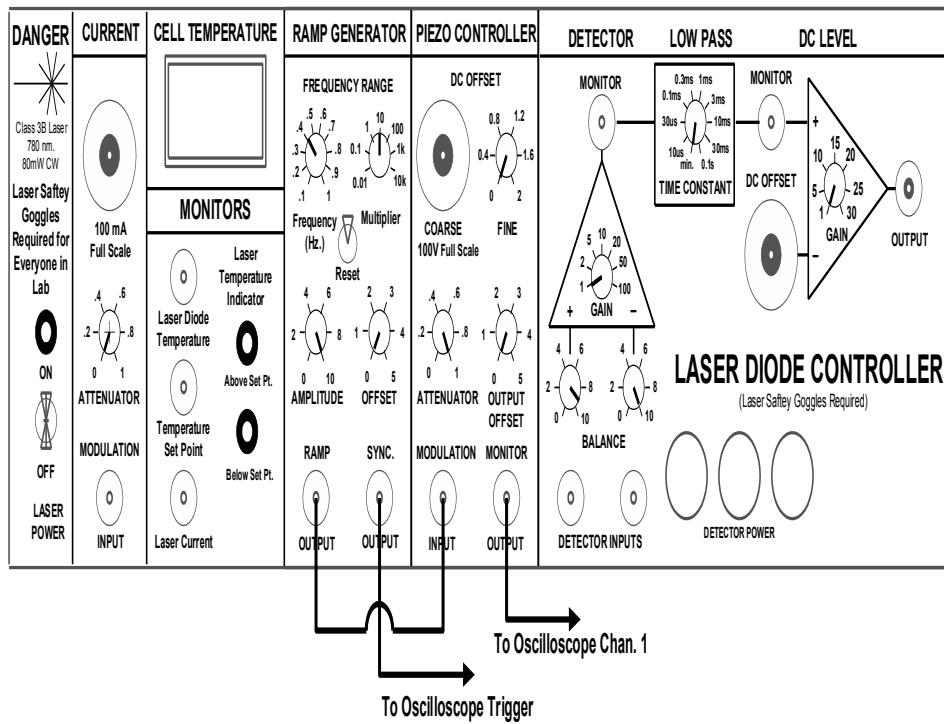


Figure 1. Modules showing connections for setting the frequency sweep.

6. 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 voltage corresponding to this optimal temperature is 2.636 volts.

- Check the Diode Laser temperature.
 - Use a voltmeter to read the TEMPERATURE SET-POINT in the MONITORS section of the controller chassis. This voltage should equal 2.636 ± 0.003 volts
 - 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.
- CHECK THAT EVERYONE IN THE ROOM IS WEARING SAFETY GOGGLES.
- Set the laser CURRENT potentiometer fully counterclockwise (low current) then turn the LASER POWER switch on. **NEVER TURN ON THE LASER POWER SWITCH UNLESS THE POTENTIOMETER IS FULLY COUNTERCLOCKWISE. Doing so can damage the laser.**
- Slowly rotate the potentiometer clockwise. This increases the laser diode current. While monitoring the current with a DMM, raise the current up to the level specified in the lab handout. The DMM should be set to read volts, and the conversion is $1v = 10\text{ mA}$.
- Check the TV monitor. You should see a flashing white light in the Rb cell. This is the fluorescence of Rb. If you do not see fluorescence OR you are unable to raise the diode current to the specified level, consult your TA or the lab staff.

7. Photodiode hookup and scope adjustment

- a. 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, 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.
- b. Adjust the position and height of the PD so that it intercepts the laser beam coming from the Rb cell. Use the IR viewing card to find the beam and optimize the PD position and height. Use the maximum gain on the PD that does NOT saturate it.

Appendix 4: RECORDING AN OSCILLOSCOPE SCAN

To record an oscilloscope screen image, like the one shown below in Figure 1, and store it on a flash drive, follow the steps below.

1. Insert a flash drive into the front USB port of the oscilloscope.
2. The oscilloscope display should show the image you wish to save.
3. Press the SAVE/RECALL button.
4. Turn the Action knob (uppermost knob closest to the display) until you see the top two menu items “Action Save Image” and “File Format BMP”.
5. Press the printer button and wait as the bit map is saved. This will take several minutes. A clock with hands will appear while the data is being saved. When the clock disappears the data has been saved and you can remove your flash drive.
6. Before continuing, check that the image was correctly saved to your flash drive. Make sure the date and time stamp are correct.
7. For further information regarding the saving of images, select the menu item “About Saving Images”.

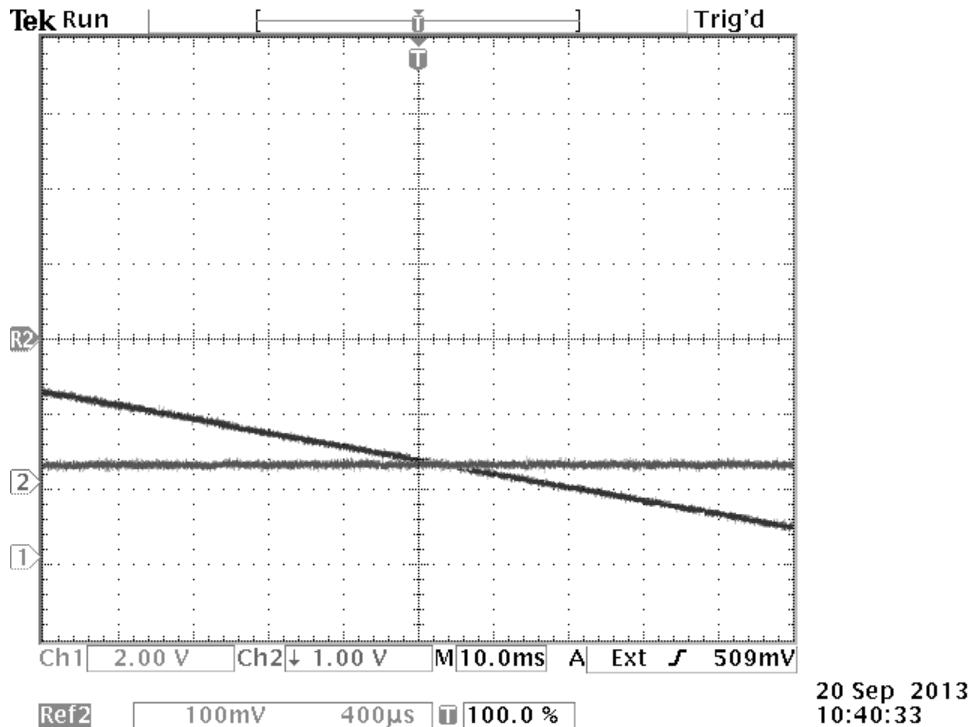


Figure 1. Scan showing date and time stamp

Appendix 5: THEORY OF SATURATED ABSORPTION

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.

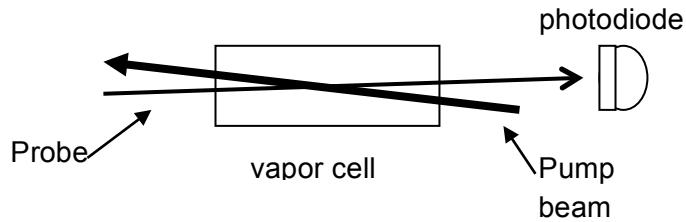


Figure 1: The basic saturated absorption spectroscopy set-up.

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 Γ of the transition (for the Rb D lines $\Gamma \gg 6$ 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; t 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 $v \approx c\Delta\nu/\nu_0$, 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.

There zero velocity 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 ν_1 and ν_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.

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 $g2$.

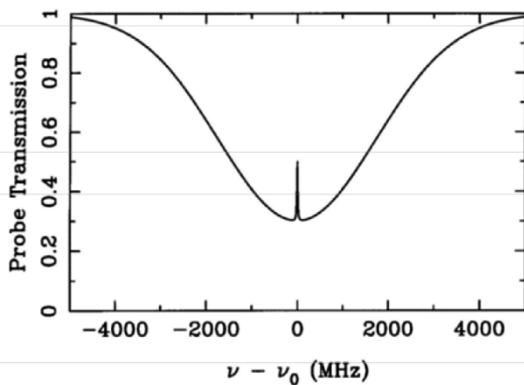
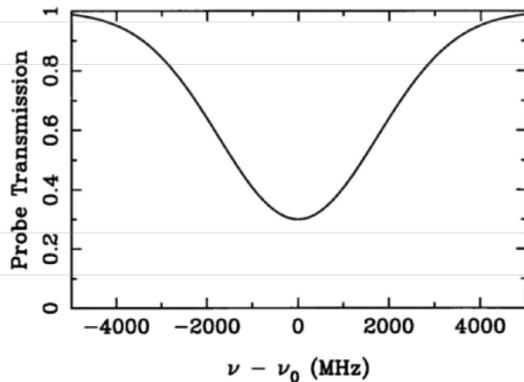


Figure 2. Absorption spectra for 2-level atoms, without (upper) and with (lower) the pump beam. If you think about it a bit more you will see there are two velocity classes of atoms for which this is true – atoms moving toward the pump laser, and away from it.

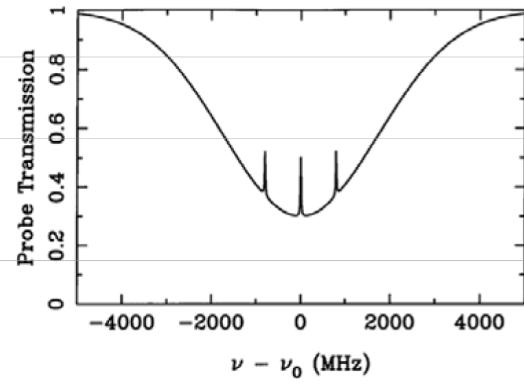


Figure 3. Saturated absorption spectrum for atoms with a single ground state and two closely spaced excited states.

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.

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 $e^{-t(v)}$, and $\tau(v)$ is the optical depth of the vapor.
2. The contribution to $\tau(v)$ from one velocity class of atoms is given by $d\tau(v, v) \sim (P_1 - P_2)F(v, v)dn(v)$ where P_1 and P_2 are the relative populations of the ground state and excited state, respectively ($P_1 + P_2 = 1$). $dn \sim e^{-mv^2/2k_B T}dv$ is the Boltzmann distribution for v along the beam axis, and

$$F(v, v) = \frac{\Gamma/2\pi}{(v - v_0 + v_0 v/c)^2 + \Gamma^2/4}$$

is the normalized Lorentzian absorption profile of an atom with natural linewidth Γ , including the Doppler shift.

Putting this together, the differential contribution to the optical depth, for laser frequency v and atomic velocity v is

$$d\tau(v, v) = \tau_0 \frac{v_0}{c} (P_1 - P_2) F(v, v) e^{-mv^2/2k_B T} dv .$$

The overall normalization comes in with the τ_0 factor, which is the optical depth at the center of resonance line, (i.e., $\tau_0 = \int d\tau(v_0, v)$ with no pump laser, integral is over all velocity classes).

3. The populations of the excited and ground states are given by

$$P_1 - P_2 = 1 - 2P_2 \text{ and } P_2 = \frac{s/2}{1+s+4\delta^2/\Gamma^2}$$

where $s = I/I_{sat}$ and $\delta = v - v_0 - v_0 v/c$. I_{sat} is called the saturation intensity, which is clear if you consider the formula for P_2 above with $\delta = 0$. As $I/I_{sat} \rightarrow \infty$, P_2 saturates at 1/2.

The saturated intensity is given by

$$I_{sat} = \frac{2\pi^2 hc\Gamma}{3\lambda^3}$$

For the case of Rb, $\Gamma \gg 6\text{MHz}$, giving $I_{sat} \gg 2 \text{ mW/cm}^2$.

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

$$\dot{P}_1 = \Gamma P_2 - \alpha I(P_1 - P_2) \text{ and } \dot{P}_2 = -\Gamma P_2 + \alpha I(P_1 - P_2)$$

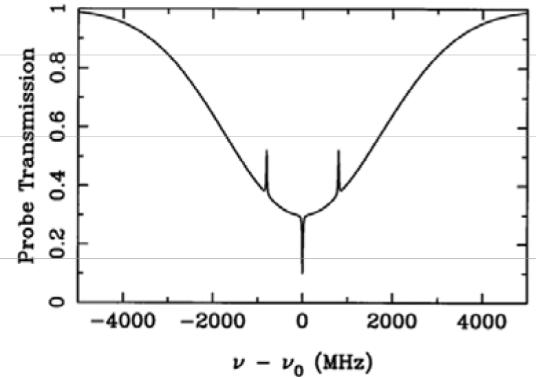


Figure 4. Saturated absorption spectrum for atoms with a single excited state that can decay into either of two closely spaced excited states.

where the first term is from spontaneous emission with Γ equal to the excited state lifetime, and the second term is from stimulated emission, including 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 ($I_{sat} \propto \Gamma$). 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).

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 τ_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."

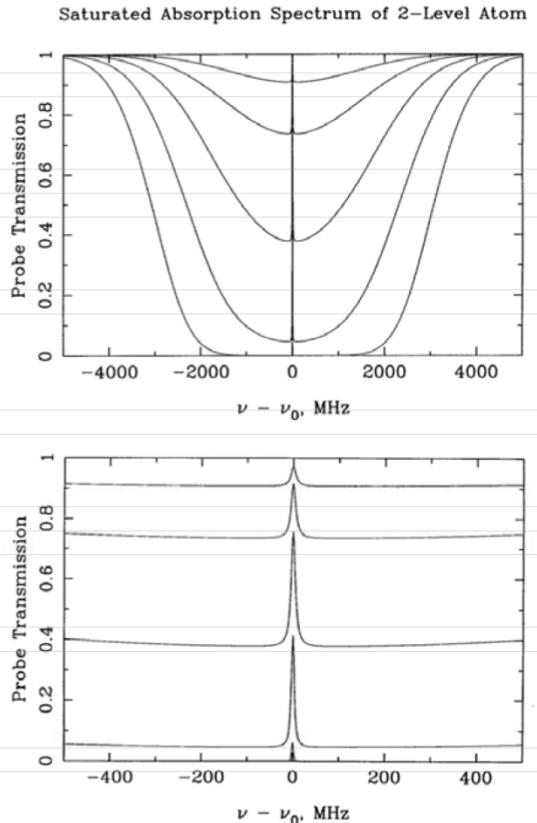


Figure 5. Calculated saturated-absorption spectra for two-level atoms, for $(\tau, I/I_{sat}) = (0.1, 10)$, $(0.316, 10)$, $(1, 10)$, $(3.16, 10)$ and $(10, 10)$. The two plots show the same spectra with the frequency axis at different scales. Note the overall Doppler-broadened absorption, with the small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

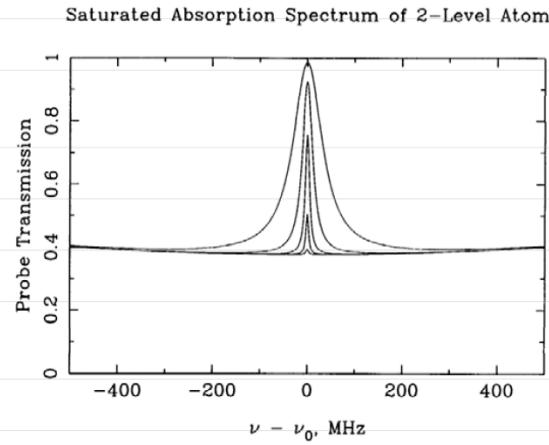


Figure 6. Calculated saturated-absorption spectra for two-level atoms, for $(\tau, I/I_{sat}) = (1.0.1)$, $(1,1)$, $(1,10)$, $(1,100)$ and $(1,1000)$. Note at large laser intensities, the saturated absorption feature is "power broadened" as the line saturates.

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 $\tau_0 = \int d\tau(v_0, \mathbf{v})$ when the pump laser intensity is zero, from the formula above. Hint: the integral is simplified by noting that $\Gamma \ll \Delta v_{Dopp}$.

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 $\alpha = \alpha(v)$ depends on the laser frequency, but not on the position inside the cell. (In this case, α^{-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 analogous to $e^{-\tau}$ above.

The objective in this problem is to work out what happens when the input laser beam is not weak, and thus you cannot assume the atoms are all in the ground state. In this case $\alpha = \alpha(v, x)$, 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 you should have $\alpha(v_0, x) = \alpha_0/(1 + s(x))$.

In the weak beam limit $I \ll I_{sat}$ this reduces to the 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 τ_0 . Check your expression by noting in the limit of finite τ_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., $s_{final} = s_{initial}/2$)?

Appendix 6: OBSERVING SATURATED ABSORPTION

A. Optical Plan

There are countless ways in which the optics could be configured to do observe the Saturated Absorptions Spectrum. A complete diagram of the configuration is shown below in Figure 1. (A different layout is used in the lab notes from Caltech, which are at the end of this manual.)

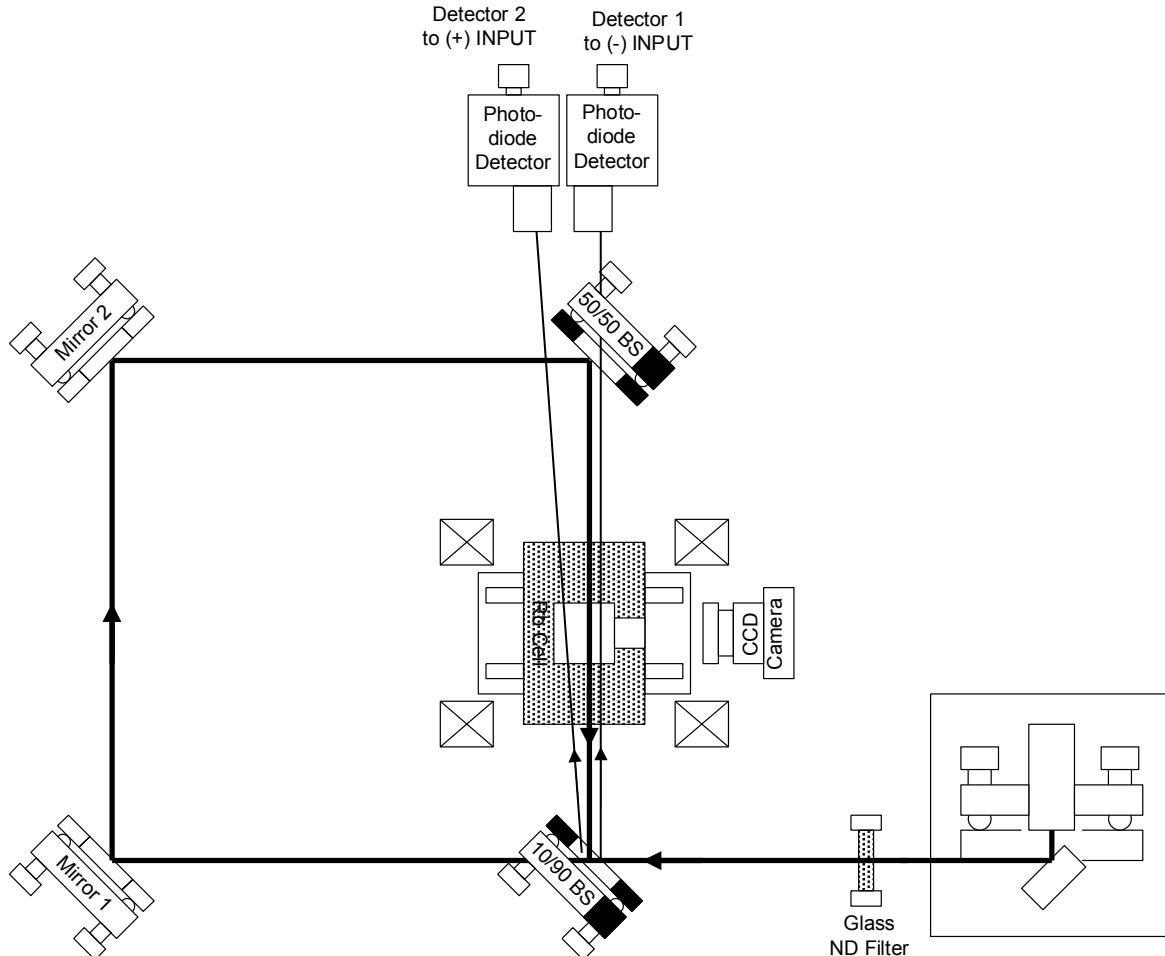


Figure 1. Complete saturated absorption spectrometer (SAS) setup.

B. Some Basics Before Beginning

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, shown in Figure 2, 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 Rb 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 3. (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**

We have used the 1° 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.

3. Now, add the two turning mirrors to the setup, as shown in Figure 4. Move the Beam Blocker to the new location shown.

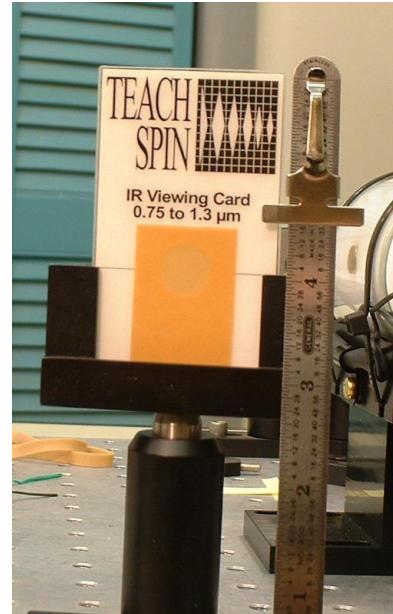


Figure 2. Viewing card for observing the invisible beam.

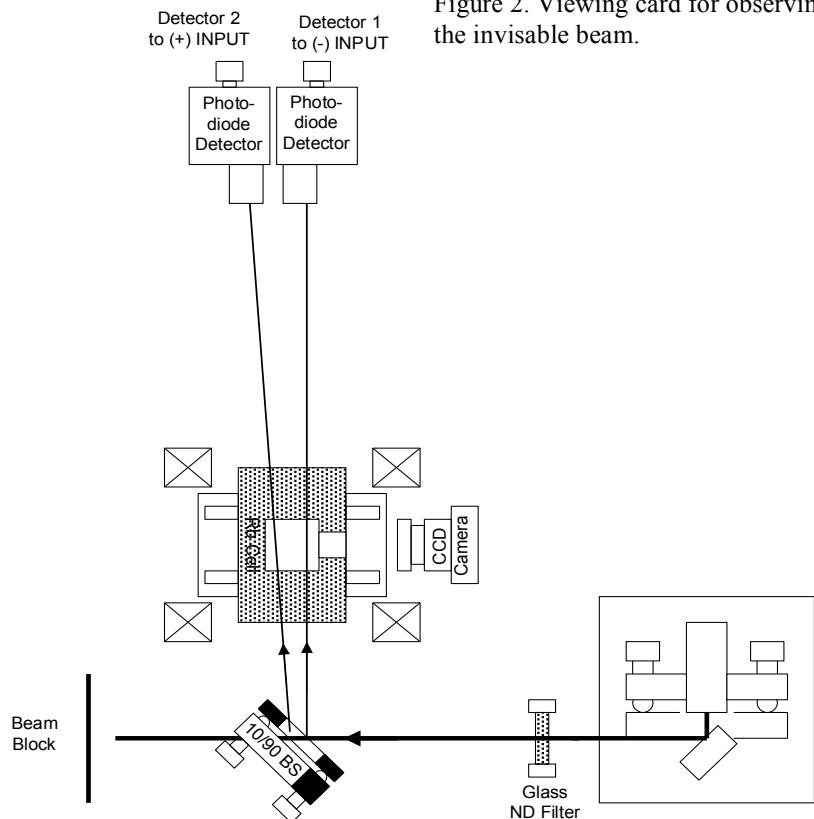


Figure 3. Start of SAS setup with 1° wedged beam splitter in place.

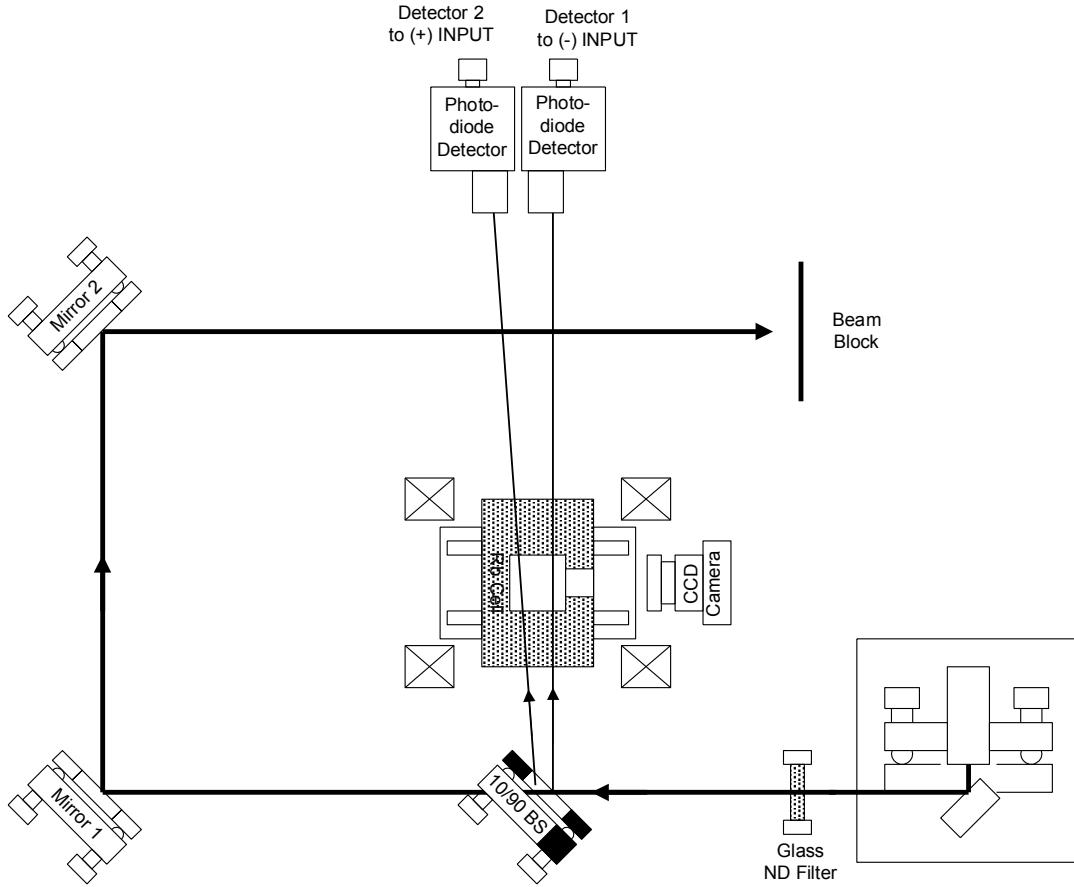


Figure 4. Turning mirrors added to setup.

D. Understanding the Functions of the Beams

We are now ready to add the important 50/50 beam splitter as shown in Figure 5. 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 5. 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.

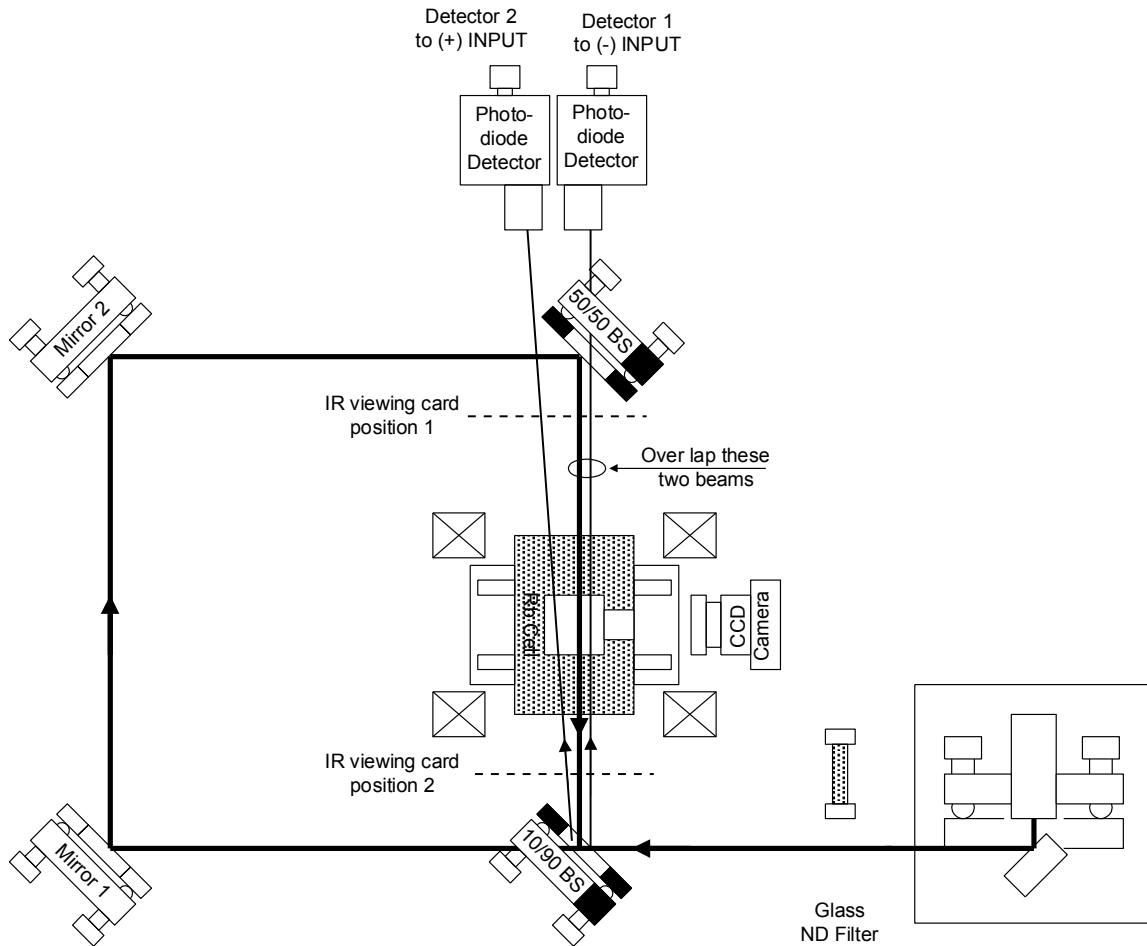


Figure 5. Aligning pump and probe beams.

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 6. 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.

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 7. 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.

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 to 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

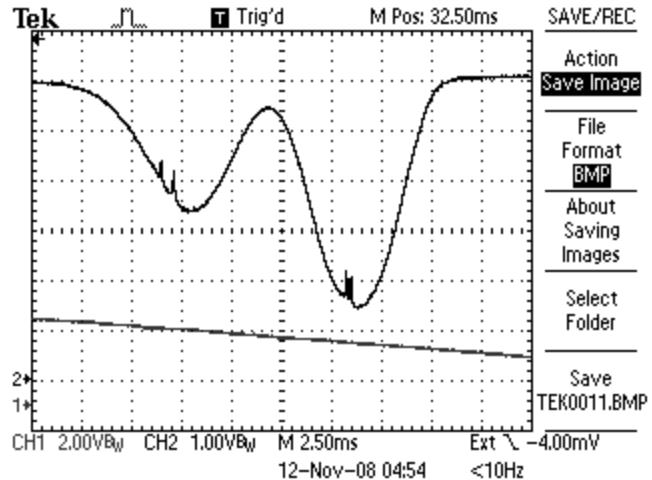


Figure 6a. Observation of SAS features. Beams are partially overlapped and some SAS signal is visible.

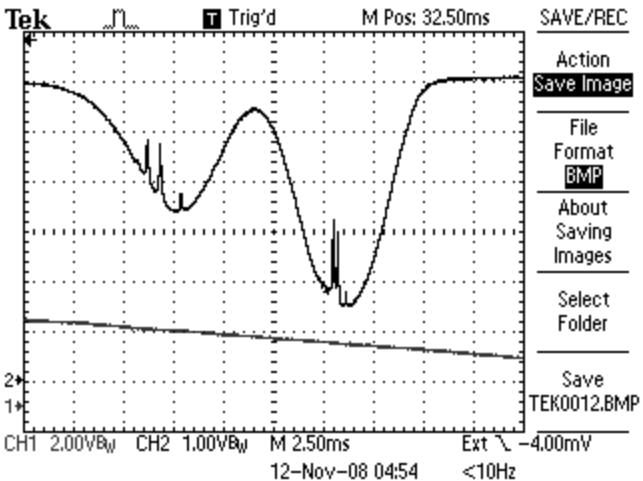


Figure 6b. Observation of SAS features. Signal after tweaking of mirrors and 50/50 beamsplitter.

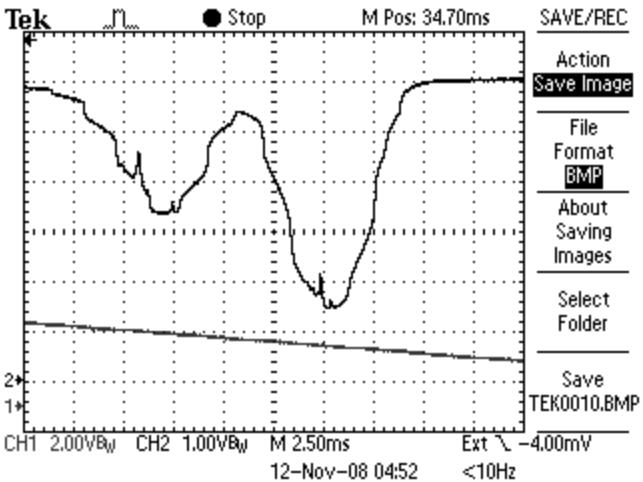


Figure 7. When the anti-parallelism is too close to perfect, there is feedback into the laser that corrupts the frequency sweep. The ‘staircase’ appearance of the absorption profile is the indication of this.

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 $1.0\text{ M}\Omega$ and Detector 2 a gain of $330\text{ k}\Omega$.)

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 like those in Figures 8a and 8b.

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.

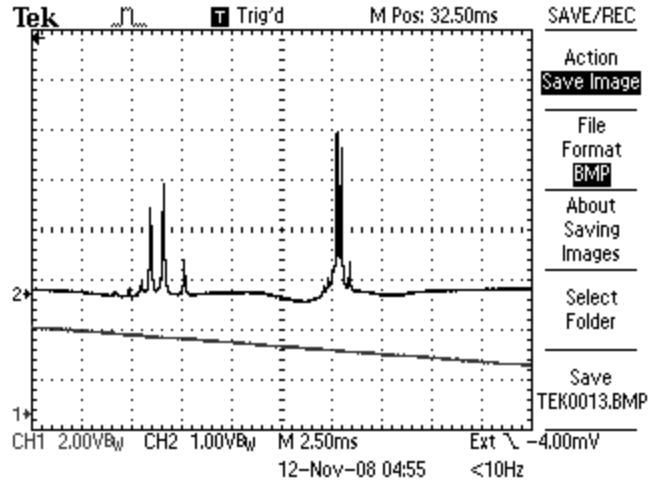


Figure 8a. SAS traces with background subtraction. ^{87}Rb F=2 and ^{85}Rb F=3.

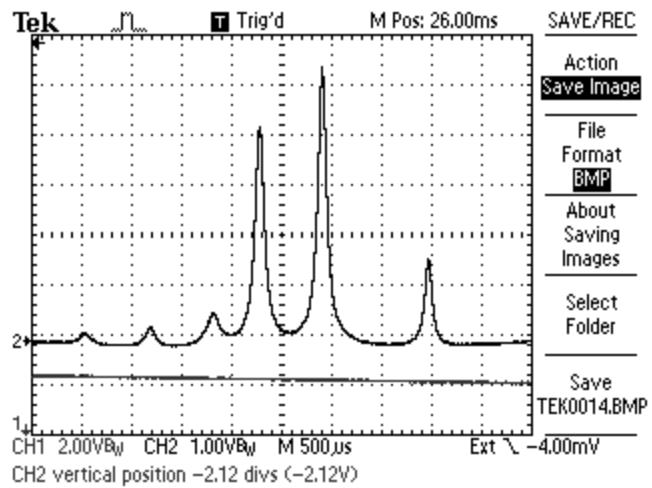


Figure 8b. SAS traces with background subtraction. Expanded view of ^{87}Rb F=2.