

## Appendix A

### Dichroic Atomic Vapor Laser Lock

#### A.1 Introduction

Lasers with stable frequencies are essential in many fields of research. In addition, they are used commercially in precision machining tools, gravimeters, and laser vibrometers. He-Ne lasers have been the industry standard for many years,[102] but they are bulky, energy inefficient, and have limited tube lifetime. Diode lasers offer an improvement in all these areas and moreover can be stabilized to atomic transitions. Typical methods of stabilization [103, 104] although practical in some laboratory settings, are not reliable enough for use in commercial equipment. Using a technique originally demonstrated with a LNA ( $\text{La}_{(1-x)}\text{Nd}_x\text{MgAl}_{11}\text{O}_{19}$ ) laser in helium [105] we developed a robust diode laser stabilization scheme that will be useful in both commercial instruments and research laboratories.

#### A.2 Diode Laser Frequency Stabilization

The frequency of a diode laser with grating feedback depends on the current, temperature, and external diffraction grating position. With the laser cavity in a Littrow configuration (see Fig. A.1), the output beam reflects off the grating, while the first-order beam diffracts back into the laser diode. The optical feedback from the grating is spectrally narrowed and peaked at a frequency that can differ from the bare diode central frequency. Thus this feedback narrows the laser linewidth to  $<1$  MHz and forces the central frequency to nearly that of the feedback signal. To tune the laser central frequency, the grating is tilted by applying a voltage to a piezoelectric transducer (PZT). Over time, the central frequency will drift because of temperature, current, and mechanical fluctuations. This drift can be reduced by stabilizing the laser to an external reference. In addition, small, rapid fluctuations in laser frequency, which contribute to the laser linewidth, can be reduced by rapidly controlling the diode laser current.

In one popular method of stabilizing the diode laser frequency, some of the output light is sent into a saturated absorption spectrometer. The diode laser frequency is then locked to either the side or the peak of the narrow saturated absorption features, [103, 104, 106] shown in Fig. A.2. These narrow lines offer the advantage of a steep slope, where the slope is the change in the fractional absorption signal with laser frequency. Side-locking to this slope is accomplished by electrically controlling the PZT

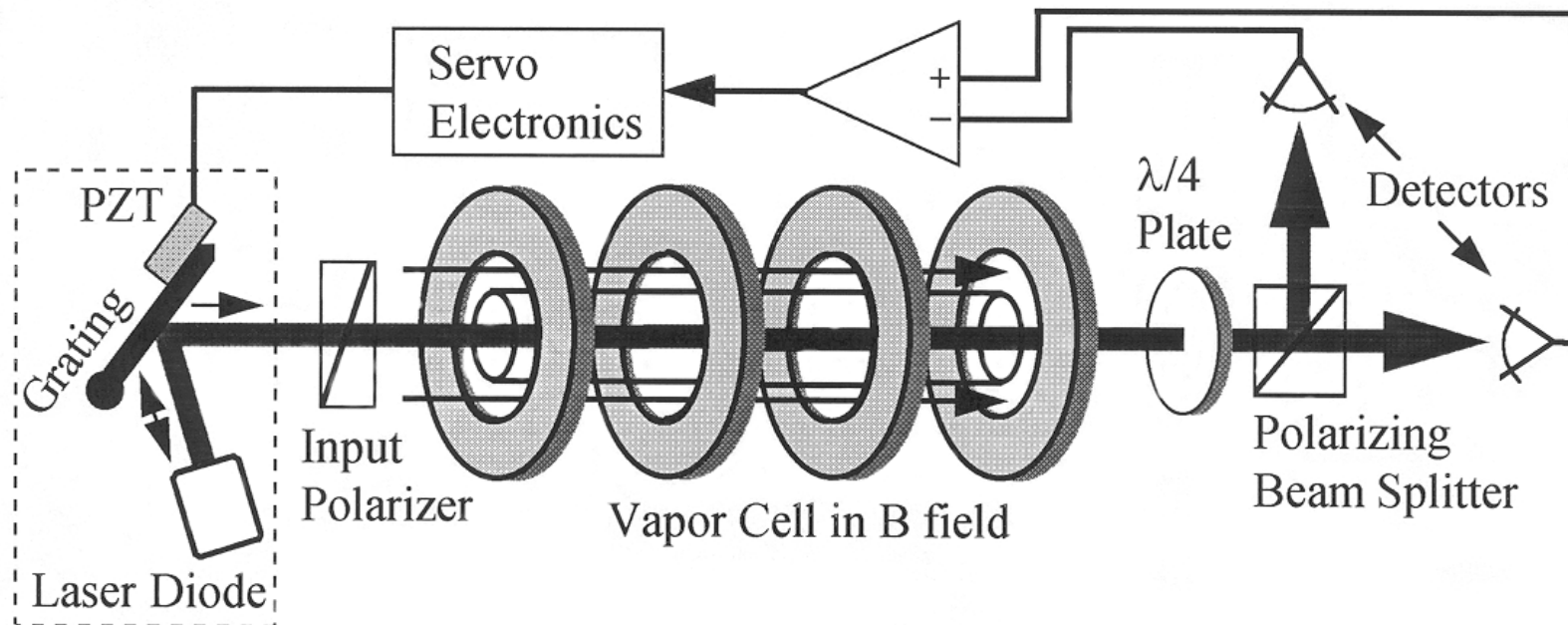


Figure A.1: Schematic of a DAVLL system. Here we show the entire beam passing through the lock, but in actuality, only a small amount of power is picked off from the main beam and enters the locking apparatus.

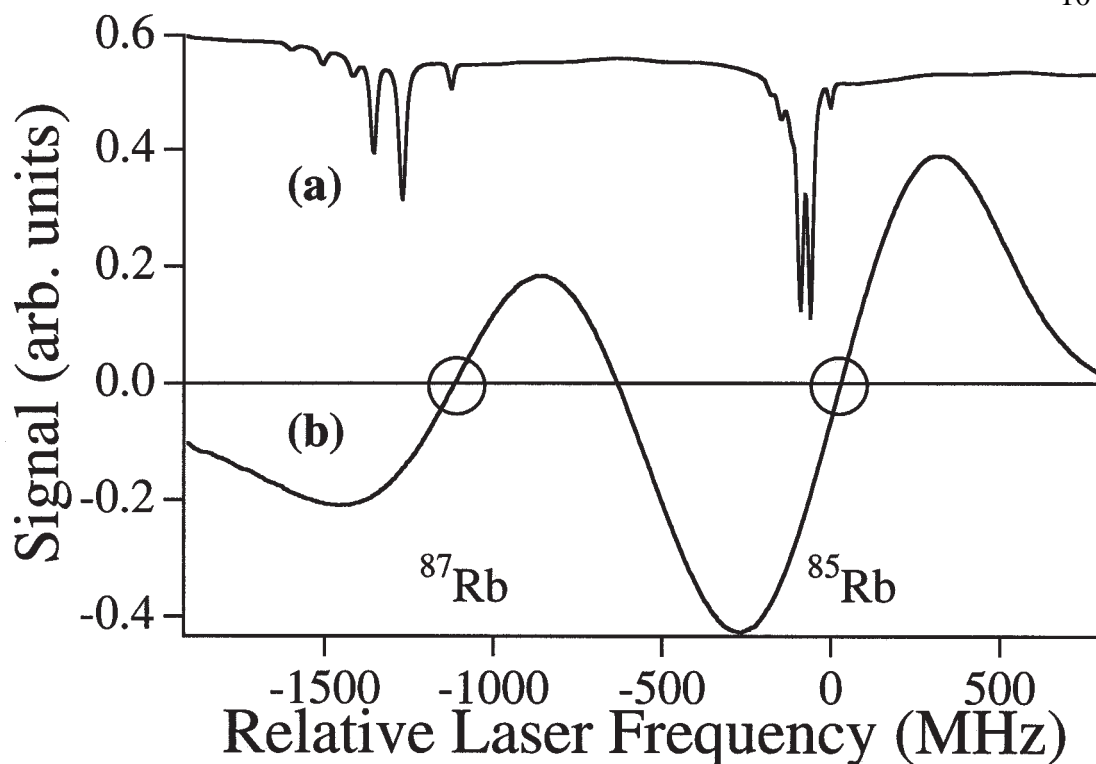


Figure A.2: Oscilloscope trace of (a) the signal from a saturated absorption spectrometer and (b) the DAVLL signal, as the diode laser is scanned across Rb resonances with the PZT. A laser can be locked to either of the two circled zero crossings of the DAVLL signal. These features are due to the  $^{87}\text{Rb}$   $F' = 2 \rightarrow F' = 1, 2, 3$  and the  $^{85}\text{Rb}$   $F = 3 \rightarrow F' = 2, 3, 4$  transitions. The frequency of the lock point can be tuned optically by rotating the quarter-wave plate, or electronically by adding an offset voltage to the signal.

voltage so that the saturated absorption signal is maintained at a particular level. However, a disadvantage of side-locking is that fluctuations in beam alignment and intensity will alter the lock point and cause drift in the laser frequency. Peak-locking is less sensitive to these fluctuations, but has its own disadvantages related to phase-sensitive detection: Either the output of the laser is modulated directly or expensive electro-optic components are used to modulate only the light entering the spectrometer. A further disadvantage of both peak and side locks is their small capture range, which prevents them from recovering from perturbations that shift the laser frequency by more than  $\sim 30$  MHz.

### A.3 The Dichroic-Atomic-Vapor Laser Lock Signal

To overcome the aforementioned disadvantages with the conventional locks, we developed a dichroic-atomic-vapor laser lock (DAVLL). This technique employs a weak

magnetic field to split the Zeeman components of an atomic Doppler-broadened absorption signal and then generates an error signal that depends on the difference in absorption rates of the two components. The subtraction technique minimizes the frequency drifts that are due to changes in line shape and absorption that typically limit the utility of Doppler-broadened absorption features for frequency stabilization. The DAVLL lock offers the advantages over saturated absorption: large recapture range, simplicity, low cost, and no need for frequency modulation.

As shown in Fig. A.3(a), a Doppler-broadened absorption feature is detected when a laser beam (with wave vector  $\mathbf{k} = k\hat{z}$ ) passes through a Rb vapor and the laser's frequency is scanned across a transition. In the absence of a magnetic field, we obtain the same signal regardless of the laser polarization (c). However, if a uniform magnetic field ( $\mathbf{B} = B\hat{z}$ ) is present and the laser is circularly polarized ( $\epsilon = \hat{\sigma}_+$ ), the central frequency of the absorption feature increases [Fig. A.3(b)]. If the laser has the opposite polarization ( $\epsilon = \hat{\sigma}_-$ ) [Fig. A.3(c)], the central frequency decreases. By subtracting the two absorption profiles [Fig. A.3(d)], we obtain an antisymmetric signal that passes through zero and is suitable for locking.

A DAVLL signal with a steep slope causes the lock to be less sensitive to noise sources that mimic laser frequency changes, such as laser intensity noise. A rough comparison with a typical saturated absorption setup in our laboratory shows that the DAVLL slope is comparable with that of the saturated absorption lines. This may seem surprising at first, because the linewidths of the saturated absorption lines (FWHM -20 MHz) are much smaller than those of the DAVLL lines (-500 MHz peak-peak) [Fig. A.2(b)]. However, the heights of the saturated absorption features range from  $\sim 1/3$  to  $1/30$  of the on-resonant Doppler-broadened absorption fraction, whereas the DAVLL signal height is twice that absorption fraction. By approximating the slope as the linewidth divided by the signal height, we estimate that the slope of the largest saturated absorption peak is only four times bigger than the DAVLL slope.

The slope of the DAVLL signal is also affected by the magnetic field. The separation of the two Zeeman-shifted absorption peaks must be large enough to give a sizable capture range, but small enough to give a large slope through the unshifted resonance. In addition, the Zeeman-shifted absorption peaks broaden with increasing field, because the various transitions contained within one Doppler-broadened feature shift different amounts. We found that 100 G maximizes the slope, and therefore represents the best compromise between increased separation and increased broadening. However, the dependence of slope on the magnetic field is not strong, so if  $B$  is varied by a factor of 2 it should not significantly alter the lock performance.

#### A.4 Apparatus

A schematic of the diode laser and optics used to generate the DAVLL signal is shown in Fig. A.1. The SDL 780 nm diode laser is tuned by use of a diffraction grating, as described above. The output beam from this laser passes through a beam splitter, and a small amount of power is split off to be used for locking. After passing through a small aperture, the resulting beam passes through a linear polarizer. Pure linear polarization

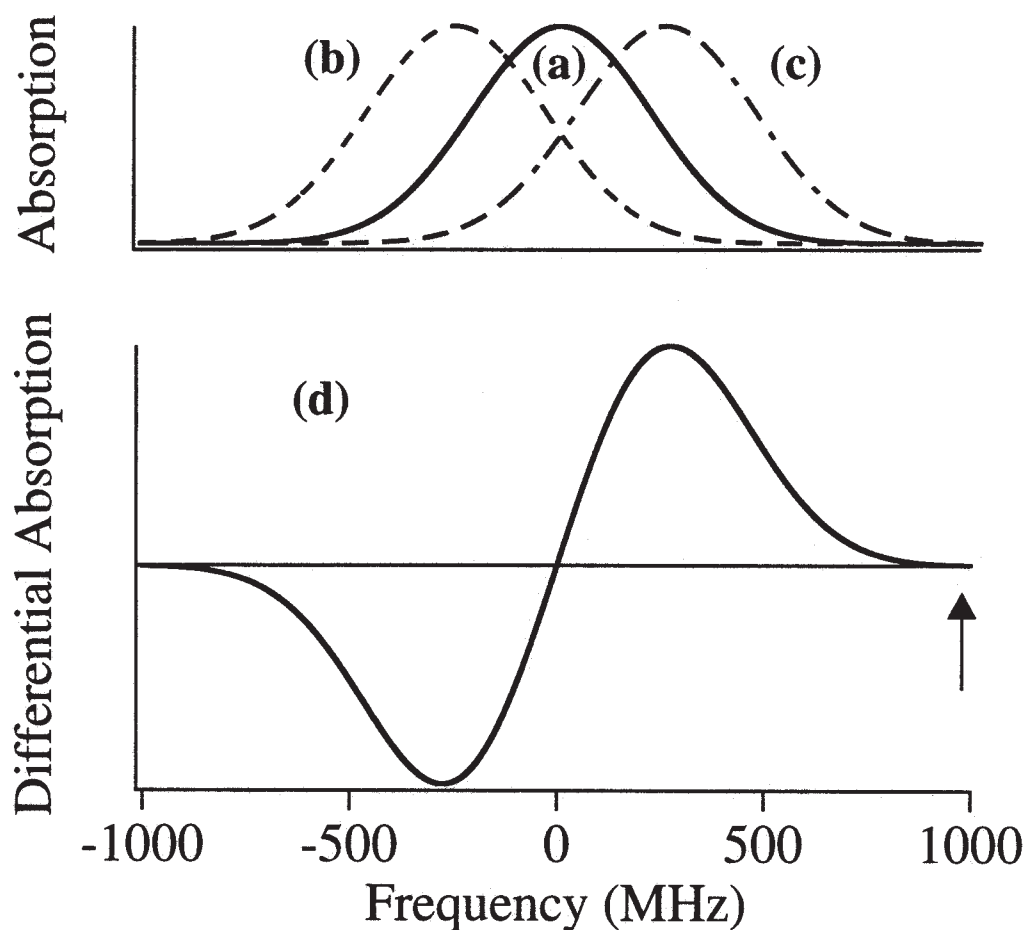


Figure A.3: Origin of the DAVLL signal shape. (a) A Doppler-broadened transition in Rb in the presence of no magnetic field. (b) The same transition, Zeeman shifted in a 100 G magnetic field, when circularly polarized light is incident on the vapor. (c) The same as (b), but with the opposite circular polarization. (d) The difference between (c) and (b) giving the DAVLL signal. In this idealized case, the arrow indicates that the off-resonant signal is zero.

is equivalent to a linear combination of equal amounts of two circular polarizations. This beam (2.5-mm diameter, 0.5 mW) next passes through a cell-magnet combination, consisting of a glass cell filled with Rb vapor and a 100 G magnetic field. The magnet is made of rings of rubber-embedded permanently magnetic material, spaced appropriately and glued together concentrically around the glass cell.<sup>1</sup> To generate the DAVLL signal, the absorption profiles of the  $\hat{\sigma}_+$  light must be subtracted from that of the  $\hat{\sigma}_-$ . To accomplish this, after exiting the cell, the two circular polarizations are converted into two orthogonal linear polarizations by passing through a quarter-wave plate. Then the two linear polarizations are separated by a polarizing beam splitter, and the resulting two beams are incident on two photodetectors whose photocurrents are subtracted. As the frequency of the laser is scanned across an atomic transition, an antisymmetric curve is generated, as shown in Figs. A.2 and A.3. The diode laser is then locked by feeding back a voltage to the PZT so that the DAVLL signal is maintained at the central zero crossing.

We align the optics by orienting the fast axis of the quarter-wave plate at  $45^\circ$  to the axis of the output polarizing beam splitter, so that equal intensities are incident on the two photodetectors when the laser is far detuned ( $>1$  GHz) from the Rb resonances [see Fig. A.3(d)]. The DAVLL system is least susceptible to drifts when the off-resonant signal gives no net photocurrent, and the lock is therefore very near the center of the unshifted resonance, as shown in Figs. A.2 and A.3. We tuned the locked laser frequency either by adding an electronic offset or by rotating the quarter-wave plate. The latter optical method changes the frequency by weighting one circular polarization more heavily than the other. This type of offset is more stable than the electronic offset because the lock point is always at a zero in net photocurrent, which occurs when the powers incident on the two photodetectors are equal. Thus with optical offsets, the lock point maintains its insensitivity to laser intensity fluctuations.

## A.5 Characterization of Frequency Stability

To monitor the frequency stability of the laser lock, we stabilized two separate lasers each to their own DAVLL system. We locked them to the same Doppler-broadened feature ( $^{85}\text{Rb } F = 3 \rightarrow F'$ ) with different optical offsets, typically approximately 25 MHz apart. A portion of the light from each laser was combined at a beam splitter and copropagated onto a fast photodetector (125 MHz). The resulting beat note, corresponding to the difference between the two laser frequencies, was fed into a high-speed counter. By reading the counter every 5 s, a computer monitored the laser stability over periods ranging from 12 to 38 h.

In this way, the difference between the two laser frequencies was monitored over many days, under different conditions. The beat frequency was stable to 2.0 MHz peak-peak while the temperature of the laboratory, and therefore of the optical components,

<sup>1</sup> We used the material with part number PSM1-250-3X36C from the Magnet Source, 607-T S. Gilbert St., Castle Rock, Colo. 80104, 1-800-525-3536. Although uniformity is not critical to stability, we minimized variations to 5% along the field axis of symmetry by spacing the inside rings closer together than the outer ones.

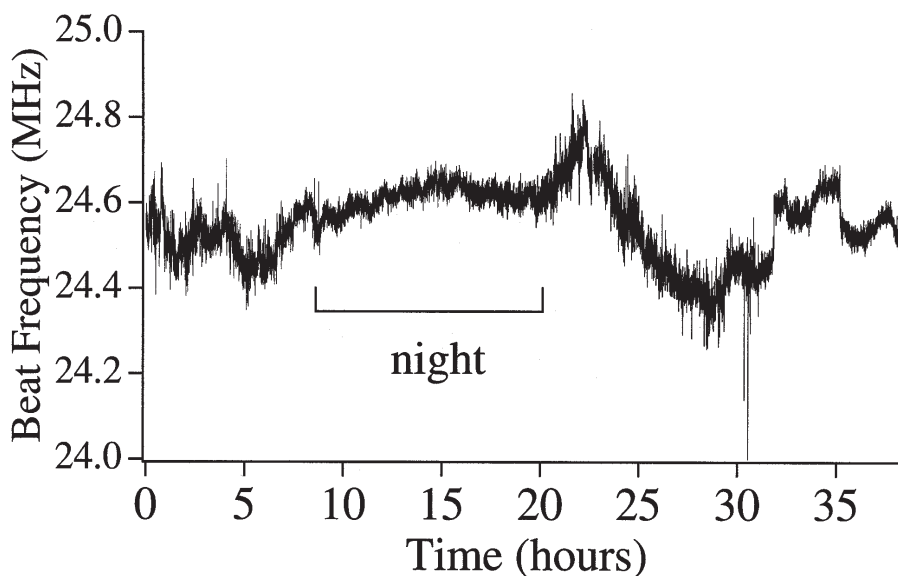


Figure A.4: Measured beat frequency between two DAVLL systems over a 38 h period. Variations in the beat frequency indicate the limits of the laser stability to be approximately 500 kHz peak-peak. These data show a stability of 27 kHz rms during an 11 h period at night when environmental factors such as room temperature and air currents are more stable. The discontinuities at the end of the run are due to incomplete shielding of the detection photodiodes from room lights. The run was stopped when a laser mode hopped, but after we adjusted the current to return the laser to the proper mode, it returned to the same frequency.

varied a couple of degrees throughout the day. When the cells (with attached magnets) were enclosed in a copper pipe and crudely temperature stabilized, the stability improved to 500 kHz peak-peak over 38 h, as shown in Fig. A.4. The cell-magnet combinations have measured dependences of 1.0 MHz/°C and 1.7 MHz/°C. We attribute this drift to a temperature-dependent birefringence of the cell windows, because the lock point is more sensitive to birefringence than to any other parameters. This is expected and observed, as discussed below. To confirm that optical offsets are more stable than electronic, we used an optical offset to tune one laser 120 MHz away and found that the drift rate was still comparable. When similar frequency offsets were applied electronically, the drift increased to 3 MHz peak-peak.

If the two lasers drift in a correlated manner, then the difference frequency remains constant so the above measurement is insensitive to it. To confirm that this was not occurring, we measured the stability of one DAVLL system by beating it against a second diode laser that was locked to a peak of a saturated absorption feature. Because the physics of the two locks is quite different, we expect drifts in the two systems to have different dependencies. In this case, we observe a stability of 200 kHz peak-peak over 12 h, which is consistent with the result previously described. From this we conclude that the two DAVLL systems were not drifting in a correlated manner, and

the stability of the beat frequency can be interpreted as the stability of the absolute frequency.

The frequency stability of the lock can also be predicted without comparing two separate systems. We can convert the stability of the off-resonant signal level (Fig. A.3) to an equivalent frequency stability by multiplying the fluctuations in photocurrent by the slope of the central resonant DAVLL signal. This calculation reliably predicts the frequency stability of the locked system and is therefore a simple, useful diagnostic. The agreement between the predicted and measured stability also indicates that the primary source of drift is changing birefringence of the optical components, because birefringence equally affects the signal levels both on and off resonance. As a final testament to the lock's stability, we used these lasers to maintain a Rb magneto-optic trap for many days without adjusting the lasers that were locked to DAVLL systems.

The above results were obtained by use of zero-order glass/polymer retarders, calcite Glan-Thompson input polarizers, and calcite Wollaston prism beam splitters. Comparable stability was also found when we used less expensive optics, including a plastic film polarizer, a plastic film retarder ( $\lambda/4$  at 540 nm), and a single calcite crystal (used as a polarizing beam splitter). In contrast, we found that some dielectric polarizing beam-splitting cubes give a large temperature dependence.

The DAVLL lock was found to be robust because of the very broad locking signal. In fact, we applied mechanical perturbations to the optical table as high as the table's damage threshold (including banging on the table with a hammer) and were unable to knock the lasers out of lock. The lasers jumped once every couple days, apparently because one of the lasers jumped to a different mode of the laser chip. These jumps were usually attributable to temperature drifts in the laser chip, but could occasionally be caused by a fast electromagnetic pulse such as that produced by our turning on a large nearby argon-ion laser. These types of mode hops are not observed in diodes with good antireflection coatings because the chip resonances are greatly suppressed. Therefore a DAVLL system constructed with such diodes would likely never lose lock.

## A.6 Conclusion

We have shown that the DAVLL lock provides an effective method for stabilizing a diode laser to a very broad, stable atomic reference. In comparison with saturated absorption locks, this system stays locked for much longer periods of time and requires fewer optics, less electronics, and less laser power. It can also be quite compact and inexpensive. This simple, robust stabilization scheme should work for a number of atomic and molecular species at a variety of wavelengths and is an appealing option whenever a continuous stable laser frequency is desired.