# Appendix B

# Stabilization of a Diode Laser at an Arbitrary Frequency

## B.1 Introduction

We describe a general technique for stabilizing a diode laser to an arbitrary wavelength. This involves the use of a stable diode laser locked to an atomic transition at a different wavelength, and a low-finesse scanning Fabry-Perot cavity. The resulting lock is very robust and tunable. Therefore this lock can be employed in situations where no atomic or molecular absorption lines exist.

This development was motivated by the Fr MOT described in Chapt.3. For that trap, two lasers needed to be stabilized to two different transitions, one at the $D_2$ transition and the other at the $D_1$. This is more challenging than locking to the corresponding lines in Rb because no stable isotopes of Fr exist, and therefore a Fr absorption cell is not an option. While molecular iodine lines exist near the $^{221}$Fr $D_2$ line, none are available near the $D_1$.

The cavity lock was therefore developed to meet some unusual demands. We knew the frequency of the $^{221}$Fr $D_1$ line only to within about 100 MHz, so our lock reference had to allow for a large scanning range. Because we had access to a $\lambda$-meter with precision of a few MHz, long-term (day-to-day) stability was not particularly necessary. However, a robust lock was essential, because we needed to find both laser frequencies simultaneously by fixing the $D_1$ diode laser and scanning and the $D_2$ laser. If the laser frequently lost lock, we would never find the Fr laser frequencies.

Thus we devised a scheme that offered all of the above benefits with relatively simple components. In short, a commercial scanning Fabry-Perot cavity was used to transfer the stability of a diode laser locked to a Rb line (at 780 nm) to a diode laser near the Fr $D_2$ line at 817 nm.

## B.2 Description

A schematic of the lock is shown in Fig. B.1. The idea is relatively straightforward. First a diode laser at wavelength $\lambda_1$ is stabilized to a readily accessible atomic transition. A beam from this laser is combined at a beam splitter (B.S.) with a beam from another laser at $\lambda_2$, the wavelength of interest. Following the beam splitter, a polarizer (Pol.) and quarter-wave retarder ($\lambda$/4) provide some optical isolation from the light that reflects off the cavity. The combined beam is then focused into a Fabry-Perot cavity with mirrors that reflect at both wavelengths. The power transmitted through the cavity is partially collimated with another lens before it strikes a diffraction grating (D. G.) and diffracts into two separate beams, each of which is collected with a lens and focused onto a separate photodetector. This allows the transmitted power at each wavelength to be monitored separately. To lock the length of the cavity to $\lambda_1$, the power transmitted through the cavity at $\lambda_1$ is monitored, and this signal is fed back to the cavity PZT to control the length. This effectively makes the cavity a length standard, equal in length to a half-integral number of wavelengths ($\lambda_1$).

The frequency of the second diode laser is in turn locked to the cavity at $\lambda_2$. To do this, the transmitted power at $\lambda_2$ is monitored by an additional photodetector. Then the signal is fed back to the second diode laser to stabilize its frequency to the side of the transmission peak of $\lambda_2$s. In this way the stability of the first laser can be transferred to the second laser via the cavity. In addition, $\lambda_2$ can be tuned in a controllable way by making small changes to the frequency of the first laser. The cavity length will change, and therefore $\lambda_2$ will change by nearly the same amount as $\lambda_1$ of the second laser's lock point will also change by nearly the amount that the first laser was adjusted.

This scheme will only work, however, when the cavity transmits both wavelengths. This condition is of course not met at every cavity length, and in fact becomes less likely as the cavity finesse increases. As an example, consider the case for $\lambda_1$ = 780 nm and $\lambda_2$ = 817 nm. The transmitted power as monitored by the two photodetectors is shown in Fig. B.2 for these wavelengths. One can see in Fig. B.2 (a) that there are only a limited set of cavity mirror spacings for which power at both wavelengths will be transmitted. Fig. B.2 (b) and (c) show enlarged portions of (a). The distance one must translate the rear cavity mirror in order to observe coincident fringes depends on the two wavelengths and the finesse of the cavity. If the two wavelengths share a large least common denominator, then only a few fringes separate coincident fringes. For example, when $\lambda_1$ = 500 nm and $\lambda_2$ = 600 nm, then one must only scan 6 fringes at $\lambda_1$ or 5 at $\lambda_2$ in order to observe exact coincidence. In general, however, coincidence is only approximate, and depends on the width of the cavity resonance, or fringe. This fringe width is given by the cavity free spectral range (FSR) divided by the finesse $F$.

The number of fringes that separate coincident fringes can be easily calculated using a simple computer program, as shown in Fig. B.3. This simple algorithm, written in IDL,[1] will calculate the number of fringes that separate coincident fringes. The only input parameters consist of the two wavelengths and the finesse of the cavity. We have not been able to write down a simple analytical expression for the results of this routine, but one may certainly exist. For $\lambda_1$ = 780 nm and $\lambda_2$ = 817 nm, $n_1$ = 22 ($22 < F < 260$), $n_1$ = 265 ($260 < F < 850$) and $n_1$ = 780 for larger $F$.

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[1] written by Kurt Miller

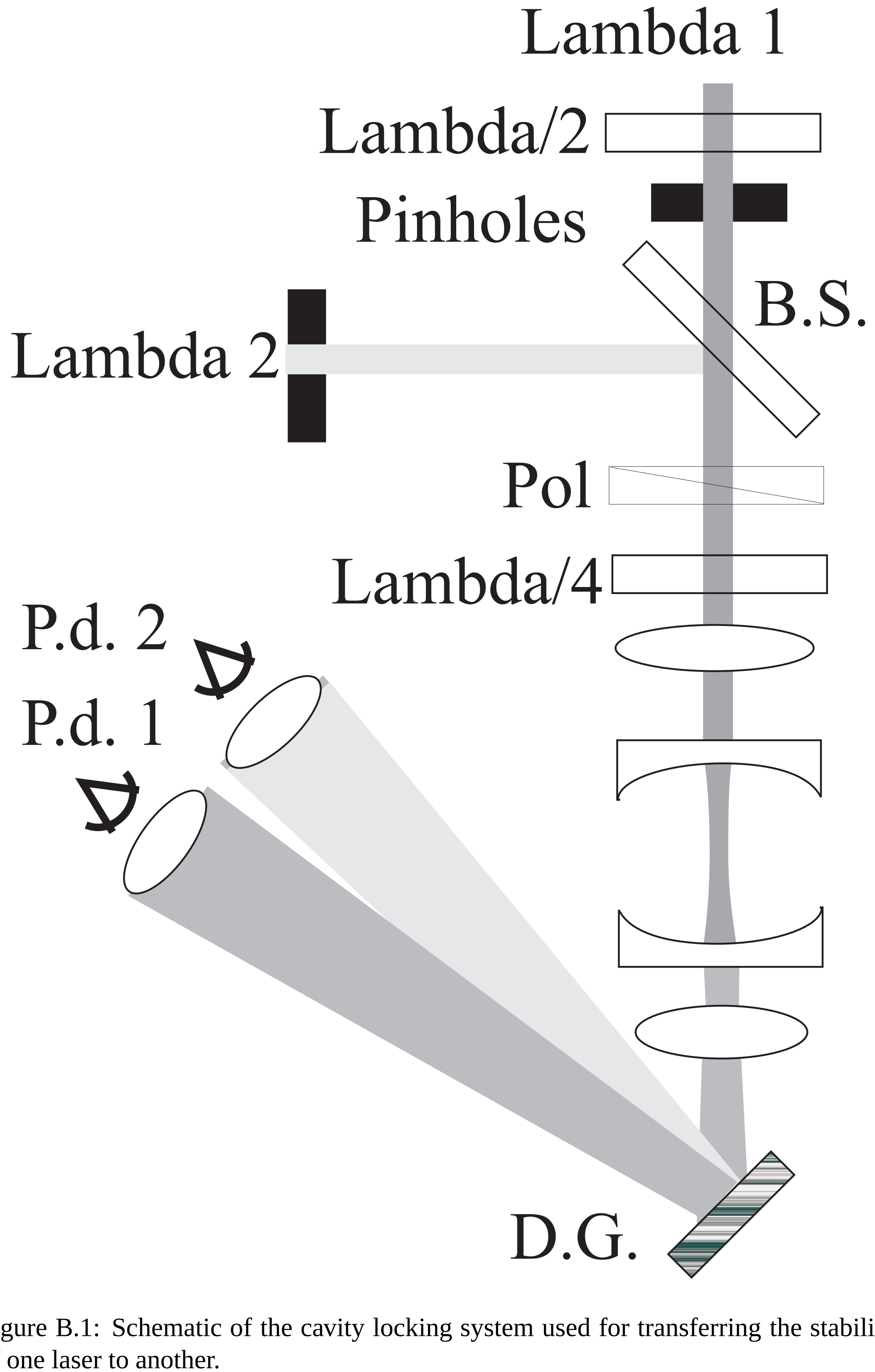

Figure B.1: Schematic of the cavity locking system used for transferring the stability of one laser to another.

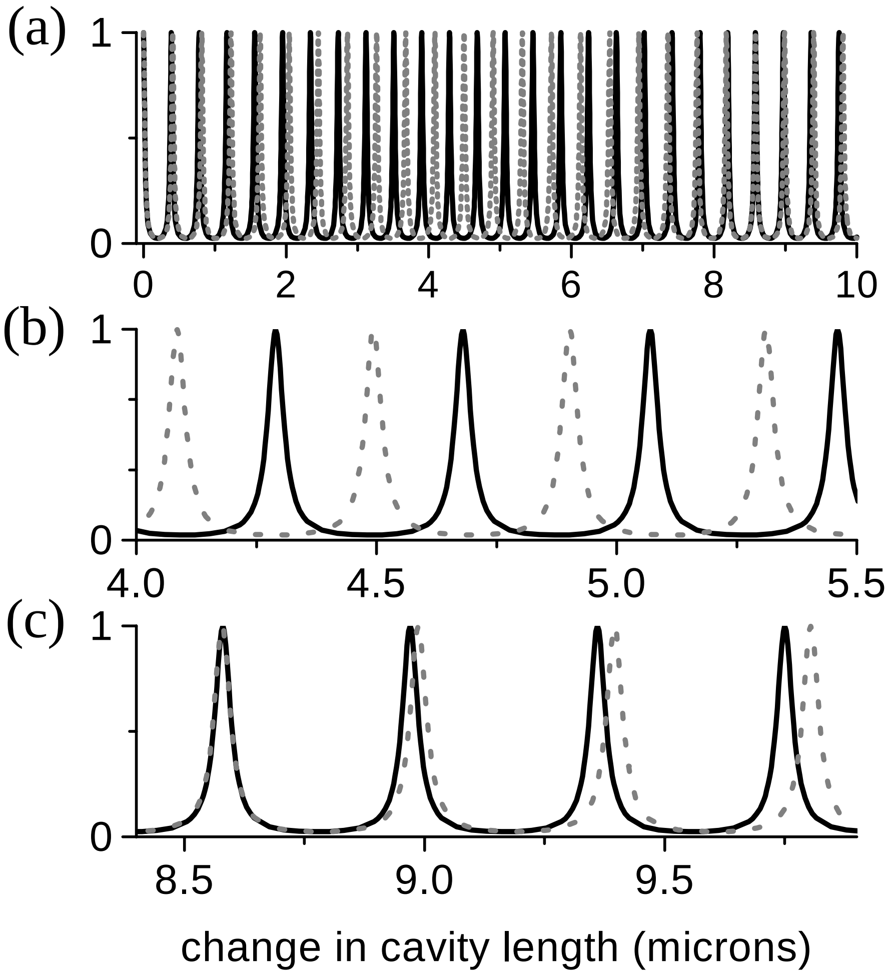

Figure B.2: Fractional transmission (calculated) of a cavity with a finesse of 40 for two different wavelengths. The dotted line represents the transmission of 780 nm, while the solid line represents 817 nm. Sections of plot (a) are enlarged below to show regions in which fringes are not coincident (b) and where fringes are coincident (c).

```
PRO cavity
;initialize
    n1          = 0L
    lambda1     = 780D
    lambda2     = 817 D
    F           = 130D
    flag        = 0

while (flag eq 0) do begin
              n1 = n1 + 1
              n2 = n1 * (lambda1/lambda2)
              if ( abs(n2-round(n2)) lt (1/F) ) then flag = 1
endwhile

print, ’n1=’,n1, ’ n2=’,n2

END
```

Figure B.3: A simple computer algorithm (written in IDL) to calculate the distance one must change the length of the cavity (in units of cavity fringes) between coincident maxima in cavity transmission. Input parameters include the 2 wavelengths (lambda1 and lambda2) and the finesse of the cavity (F). The output parameters, n1 and n2, represent the number of fringes (for each wavelength) through which the cavity must scan before two fringes coincide at the same length, to within the width of the fringe.

## B.3 Implementation

### B.3.1 Components

The diode laser at 780 nm was stabilized to the Rb $D_2$ transition using the DAVLL scheme described in Appendix A and Ref. [70]. In fact, the requirements of insensitivity to disturbances motivated the development of the DAVLL lock. The output of this stabilized laser then entered the scanning Fabry-Perot cavity. The voltage applied to the PZT of the cavity was electronically controlled by monitoring the transmission of the 780 nm light through the cavity, and side-locking to one of the cavity fringes.

The SDL laser at 817 nm was employed without an external cavity, in order to extract the most power possible for the Fr MOT. As a result, up to 80 mW were sent to the trap from the 100 mW nominal output diode. The frequency of the diode was controlled by applying a DC voltage to the servo input of the current supply. Thus the voltage was used to tune the current of the diode laser. A small amount of power from this laser was sent into a $\lambda$-meter, as described in Chapt. 3. It had a precision of a few MHz, and therefore allowed the frequency of the 817 nm diode to be precisely determined. Without active frequency stabilization, the frequency drifted at 32 MHz/hr or more.

The cavity we used was a commercially available Tropel scanning Fabry-Perot cavity. The mirror set we used was not particularly good at 817 or 780 nm, and as a result, the cavity finesse was small, typically about 60. We used a high frequency, high voltage amplifier built in the JILA electronics shop to drive the PZT of the cavity. The amplifier's high frequency response allowed us to use it in a servo loop to control the cavity length without inducing more phase shift than that inherent in the PZT-mirror spring-mass system alone. The position of the rear mirror could also be coarsely controlled by rotating the mirror mount so as to screw the mirror in and out.

### B.3.2 Procedure

Once both lasers are optimally aligned into the cavity, the following procedure is employed to stabilize the frequency of the 817 nm diode laser. First, the 780 nm diode laser is locked to the zero-crossing of Fig. A.2, where it is least susceptible to drift. Then the 817 nm laser is tuned to the desired frequency by adjusting both its temperature and current while monitoring the $\lambda$-meter. A saw-tooth ramp applied to the high-voltage amplifier sweeps the cavity across several fringes, while the output of each photodetector is monitored on an oscilloscope as simulated in Fig. B.2. By simultaneously monitoring the fringes, the cavity can be adjusted such that the cavity is nearly confocal and the fringes are therefore as symmetric as possible. Even so, the fringes are often not completely symmetric. Then small turns of the screw are applied to find a pattern of coincident and nearly coincident fringes, as shown in Fig. B.2 (c).

Once the correct coincident fringes are found, the cavity is locked to the side of the transmission fringe observed by photodetector 1. At this point, one must recheck the frequency of the 817 nm laser, to ensure that it has not drifted too far, and if necessary, relock the cavity to a different fringe of the 780 nm diode. One must also keep in mind the desired tuning range of the 817 nm laser when selecting the cavity fringe. At last, the 817 nm diode frequency is side-locked to the transmitted power detected by photodetector 2. This frequency can then be scanned by changing the set point voltage of the DAVLL-locked diode laser.

### B.3.3 Polarization

As a note, we also attempted to separate the two wavelengths using polarization instead of wavelength. In this scheme, the two wavelengths enter the cavity with opposite polarization, and are then separated at the output with a polarizing beam splitter. This method might prove useful in cases where $\lambda_1$ and $\lambda_2$ are too close together to make the diffraction grating useful. Unfortunately, this technique is very sensitive to slight mirror birefringence, especially for high finesse. This made it more difficult to eliminate cross-talk between the two polarizations, as discussed below. Therefore, the remainder of this Appendix will deal with the wavelength separation.

## B.4 Results

The cavity lock performed very well throughout the Fr experiment. The robust behavior of the DAVLL lock has already been discussed. During the experiment, it essentially never lost lock. The 817 nm diode laser lost lock when it mode hopped, and this occurred every couple days, due to the unfortunate relative inaccessibility of our transition to our diode. The lock would also jump when the table was bumped too hard, because the cavity was sensitive to mechanical perturbations. Day-to-day, however, the cavity was also quite stable. Once the length was set, the coincident fringe would consistently be found at the same voltage, $\sim$200 V.

One possible limitation to the stability of the lock would be cross-talk between the two lasers. This would occur if some light detected by photodetector 2 was at $\lambda_1$ and vice versa. This leakage was less than 0.3%, implying that at least 99.7% of the light striking photodetector 2 was at $\lambda_2$.

Finally, all evidence indicates that the laser was stable to within a few MHz for hours. We were able to maintain a Fr MOT for hours at a time, and the MOT should be sensitive to changes of 3 MHz or less, especially operating with limited repump power as we were. The $\lambda$-meter readings were also stable to within its resolution.

## B.5 Conclusion

In conclusion, we successfully transferred the stability of the DAVLL lock to an additional diode laser via a cavity. This technique has minimal technological requirements, including a low-quality diffraction grating and a low-finesse cavity. It allows for controlled tuning over a wide range of laser frequencies, up to several hundred MHz. Therefore this locking scheme is generally applicable to a large number of wavelengths for a variety of applications.