Laser Stabilization

Kevin Cox

Advisor: Jun Ye

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1 Introduction

Over the past fty years, lasers have become one of the most valuable tools for studying physics. Monochromatic, phase coherent laser light can be used for experiments which were impractical or impossible with traditional light sources. Of course, since the laser's invention, fundamental limitations on a laser's freqency stability and phase coherence time have been recognized [1]. Yet, most lasers are limited by technical noise sources such as vibrations, temperature uctuations, and thermal noise of the resonator mirrors. This instability limits a laser's usefullness for applications such as precision spectroscopy, measurements of physical constants, and atomic clocks. For this reason, signi cant research continues in the eld of laser stabilization. The Ye goup at JILA is currently endeavoring to achieve a laser with linewidth below .5 hertz. This result will match the best laser stability ever recorded and increase the precision of the group's strontium atomic clock. In this paper, I will report on this experiment and the progress made during a ten week period with the group. Furthermore, this paper will serve as a brief introduction to the Pound-Drever-Hall method of laser stabilization which is commonly used in ultra-stable laser systems.

2 Laser Stability

A common and useful way to characterize a laser's frequency noise is by its spectral density. The spectral density of frequency variations is de ned as

$$S_v \quad \frac{\nu^2_{r.m.s}(f)}{b}[Hz^2/Hz]. \tag{1}$$

Where b is the bandwidth of the frequency noise, and $\nu^2_{r.m.s.}$ is the \power" of the frequency excursions at a given frequency (note the peculiar units Hz^2/Hz). The frequency spectral density of a laser is the cause of its linewidth, ν, and lineshape. Of course, the lineshape of a laser is the same as saying the spectral density of optical power, S_e. Given a constant frequency spectral density over a bandwidth b, if the noise bandwidth, $b < \quad \nu_{r.m.s.}$, then the lineshape is Gaussian. If $b > \quad \nu_{r.m.s.}$, the lineshape will be Lorentzian. In general, a laser's lineshape is a convolution of the two. [2] In either case, the linewidth is proportional to the amplitude of the frequency modulation, $\nu^2_{r.m.s}$.

$$\nu \; / \; S_v(f) \tag{2}$$

Is it accurate to assume the frequency variations of the laser are uniform? The answer is, sometimes. The careful physicist must calculate S_e from the laser's autocorrelation function [3]. Yet, in general, common noise sources contribute to the noise over known frequency ranges. Figure 1 shows a plot of limiting noise sources over a 100kHz bandwidth for the current clock laser setup.

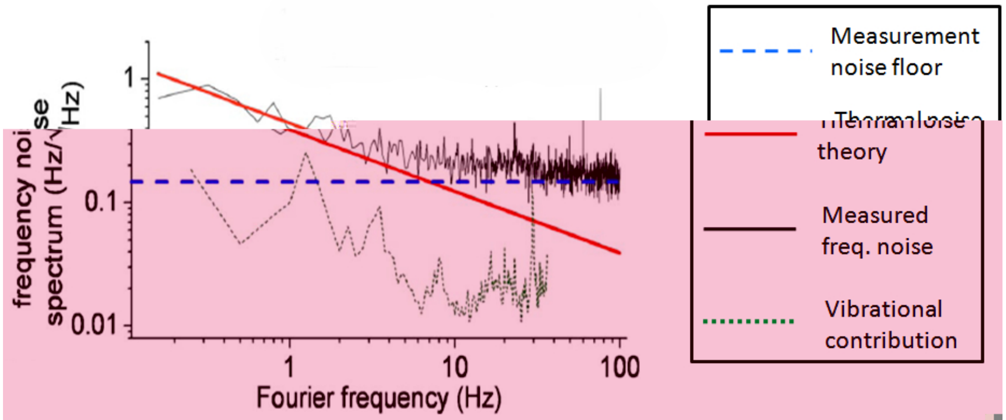

Figure 1: Spectral density of frequency fluctuations for a 698nm laser stabilized below 1 kHz. Thermal noise is the dominant noise source at low frequencies and dominates the instability of the laser.

From Figure 1, we see that the limiting factor to laser stability is thermal noise. This thermal noise is caused by fundamental fluctuations in the mirror substrate (Brownian motion) at nonzero temperatures. The job of the physicist stabilizing a laser is to decrease this noise spectral density as much as possible over a large bandwidth. To do this, Fabry-Perot cavities and feedback control techniques such as the Pound-Drever-Hall (PDH) method are used.

3 Fabry-Perot Cavities and PDH Stablization

Fabry-Perot (FP) cavities are useful for stabilizing a laser because they act as a constant frequency reference. More precisely, FP cavities resonate at distinct frequencies governed by the relation,

$$\omega = nc/2L, \tag{3}$$

where n is an integer and L is the length of the cavity. This equation is easy to understand using wave optics. If the laser frequency agrees with the condition of Equation 3, for each pass through the cavity the electromagnetic field, the light will constructively interfere.

More complete descriptions can be found in a good optics book [4]. For a cavity with perfect mirrors, the resonant condition is exact. However, if the mirrors have loss{and they always do{then the cavity has resonant peaks with width, $\delta\nu$ centered around the resonant frequency in Equation 3. In fact, the linewidth of the cavity is best characterized by the cavity's nesse. Finesse is the most useful quantity used to characterize an FP cavity.

$$F = \frac{\omega_{FSR}}{\delta\nu} \tag{4}$$

where ω_{FSR} is known as the free spectral range of the cavity and is de ned by the frequency spacing between cavity resonances, $c/2L$. The nesse of a cavity is solely dependent upon the optical losses as light travels between the mirrors. Cavities with a nesse of over 100,000 are used to construct ultra-stable lasers with linewidth below one hertz.

The goal of the physicist stabilizing lasers is to compare his laser's frequency with that of the cavity and use a feedback system to correct for the error. The laser transmission through an FP cavity is shown below in Figure 2.

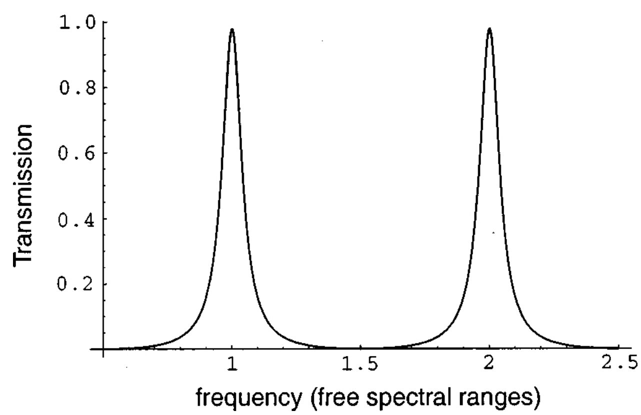

Figure 2: Transmission coe cient from a Fabry-Perot cavity.

A simplistic way to lock the laser frequency would be to measure the laser transmission from the cavity in order to lock the frequency to some point detuned slightly from resonance. One would not lock directly on resonance with this method since the transmission signal is symmetric around this point. The feedback system would not know which direction to apply a correction. For this reason the range of a suitable error signal is limited to one side of the transmission signal. More importantly, this method is flawed because the error signal would be sensitive to amplitude noise in the laser as well as frequency noise. Pound-Drever-Hall stabilization addresses both of these problems.

The golden idea of PDH stabilization is to modulate the laser's frequency and monitor the laser's reflection from the FP cavity in order to obtain a more useful error signal. This error signal is obtained by measuring the amplitude and phase of the reflected light. There is no device which can directly measure the phase of an oscillating electric field, but the PDH method gives us a simple and clever way to make the measurement. For a FP cavity with no losses, the reflection coefficient for the electric field is given by,

$$F(\omega) = \frac{r(exp(i\frac{\omega}{\Delta\nu_{fsr}}) - 1)}{1 - r^2 exp(i\frac{\Delta\nu_{fsr}}{\omega})}. \tag{5}$$

For a laser modulated with a modulation amplitude, β, the electric field can be expanded as a series of Bessel functions and written [5],

$$E(\omega) = E_0[J_0(\beta)e^{i\omega} + J_1(\beta)e^{i(\omega+\Omega)t} - J_1(\beta)e^{i(\omega-\Omega)t}] \tag{6}$$

Where ω is the laser frequency, Ω is the modulation frequency, and J_0 and J_1 are the Bessel function coefficients of the series expansion. Equation six shows how modulating the electric field creates an incoming wave which appears in frequency space as a large carrier with two sidebands. How can we conceptualize this new modulated laser interacting with the FP cavity? The system simply behaves as if three waves were interacting with the cavity: The carrier with frequency, ω, and the two sidebands with frequencies $\omega + \Omega$ and $\omega - \Omega$. The reflected light is this electric field with each term multiplied by the reflection coefficient at the corresponding frequency. The magnitude of the electric field squared is the power of the reflection signal.

$$P = P_c jF(w)j^2 + P_s[jF(\omega + \quad)j^2 + jF(\omega \qquad)]j^2 \tag{7}$$

$$+ 2\sqrt{P_c P_s} Re[F(\omega)F \quad (\omega + \quad) \tag{8}$$

$$F(\omega)F \quad (\omega \qquad)]cos \quad t + Im[F(\omega)F \quad (\omega + \quad) \tag{9}$$

$$F(\omega)F \quad (\omega + \quad)]sin \quad t + (2 \quad terms) \tag{10}$$

This is measured in a photodetector. The important terms in this measured signal are those that oscillate at the frequency . The goal is to demodulate this oscillating term to measure the factor in front which contains the error signal. This can be done with either the sine or cosine term. The solution is found by combining the re ection signal with a pure sine oscillation from the local oscillator. We then have an electronic signal which contains,

$$Im[F(\omega)F \quad (\omega + \quad) \tag{11}$$

$$F(\omega)F \quad (\omega + \quad)]sin \quad t \quad sin \quad t \tag{12}$$

The constant term out in front is the error signal, $E(\omega)$, and the sine sqaured term becomes

$$sin^2(\quad t) = 1 \quad cos^2(\omega t) \tag{13}$$

Aha! By mixing the two sines together, we have created a demodulated term with the error signal. Experimentally, the rest of the measured signal is thrown away with a low pass lter. Also, in real setups, the phase of the two sine terms is never necessarily equal, so a phase shifter is used to create the correct error signal shown below in Figure 3.

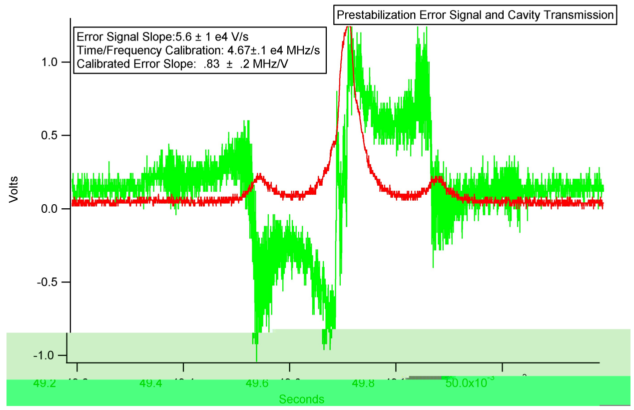

Figure 3: Measured error signal from a cavity with F=1000. The red trace shows the measured optical carrier with sidebands.

Now that a useful error signal has been produced, the laser frequency is controlled using standard feedback methods.

4 Technical Considerations

The slope of the error signal around resonance, shown in Figure 3, is very nearly [5]

$$E \qquad \frac{4\sqrt{P_c P_s}}{\pi \quad \nu} \tag{14}$$

where P_c and P_s are the power of the laser at the carrier frequency and sideband frequencies respectively. ν is the cavity linewidth. So, cavities with higher nesse have a larger sloped error signal compared to the noise of the system. This allows for greater control. Cavities with relatively lower nesse, perhaps 100 or 1000, are usually limited by quantum shot noise at the photodetector in the PDH con guration. Since the slope of the error signal is not as large as that of the ultra-high nesse cavities generally used, the shot noise uctuations limit the sensitivity of the setup to smaller frequency deviations of the laser.

Another technical consideration is mode matching to the FP cavity. Traditional FP cavities with planar mirrors are rarely used in practice because they are quite sensitive to misalignments. Cavities with spherical mirrors are pre ered. The standing waves of this type of cavity are actually Gaussian beams [4]. The lasers being used must be focused correctly so that the beam divergence matches the radius of curvature of each mirror.

If a laser is locked to a cavity, uctuations in the cavity length contribute to noise just the same as inherent laser frequency uctuations. Because of this, all FP cavities used for laser stabilization must be precisely temperature controlled and constructed of materials with low thermal expansion coe cients. Temperature control becomes an important technical aspect to consider when constructing a laser stabilization setup.

Lastly, PDH stabilization su ers from a sensitivity to so-called \Residual Amplitude Modulation" (RAM). When our laser is frequency modulated at frequency , amplitude modulation is introduced at the same frequency. This spurious RAM will be recieved on the photodetector as a term with $sin(\; t)$ oscillation and will be demodulated into the error signal. As the RAM changes amplitude over time, possibly with variations in temperature, the baseline of the error signal can uctuate. For lasers locked to high nesse cavities, this can be a serious problem. The best solution currently known is to prevent RAM from leaking onto the signal.

5 Experimental Setup: 40cm Cavity

The Ye labs strontium atomic clock has achieved an overall uncertainty of 1 10^{-16}. The linewidth of the clock laser is .5 hertz. Despite this fact, laser stability is still the limiting factor in the precision of the atomic clock. Earlier in this paper, Figure 1 showed us that the limiting factor for this stability is currently thermal noise. One way to reduce the contribution of this noise is to design a longer cavity. Indeed, this is one of the ways that a new 40cm cavity stabilization system can improve the current clock laser stabilization. This cavity, which is currently being setup for integration into the strontium clock, is shown below in Figure 4. The new 40 cm cavity is expected to have a factor of 10 increased insensitivity to thermal noise. This is in part due to the increased length of the cavity.

Also, the mirrors of the 40cm cavity are coated with fused silica substrate instead of the ultra low expansion (ULE) coating, the coating on the current fabry perot cavity. Fused silica exhibits lower thermal noise than ULE material.

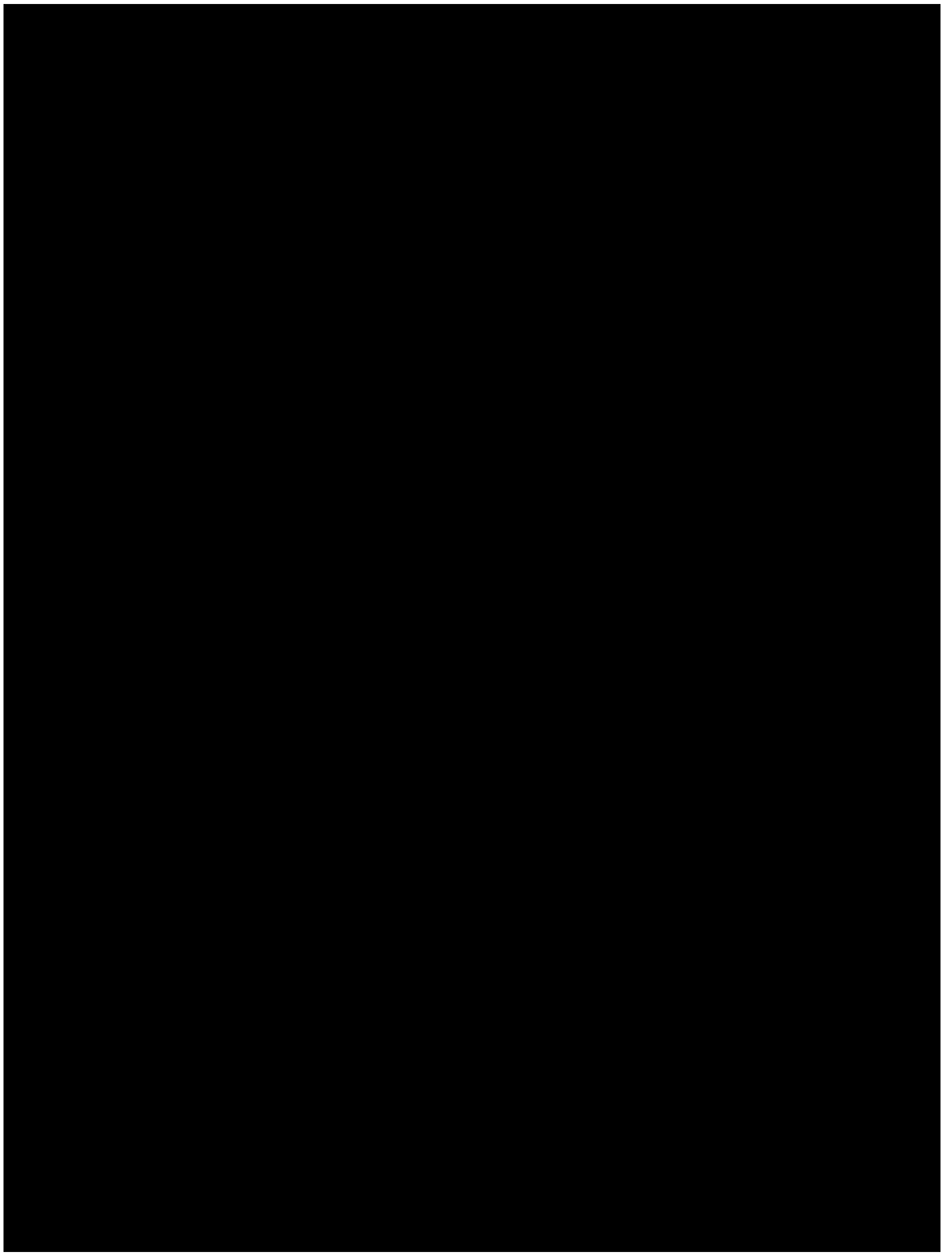

Figure 4: 40cm fabry-perot cavity made of ULE material with fused-silica mirrors.

The Pound-Drever-Hall locking scheme discussed above will be used to create a 698nm stable laser system with this optical cavity. However, before the diode laser can address the super-cavity, it must be \pre-stabilized" to a linewidth around 1kHz. This was accomplished with a smaller optical cavity with a linewidth of 2.8MHz and a nesse around 1000. A diagram of the experimental setup for PDH locking is shown below in Figure 5 [5].

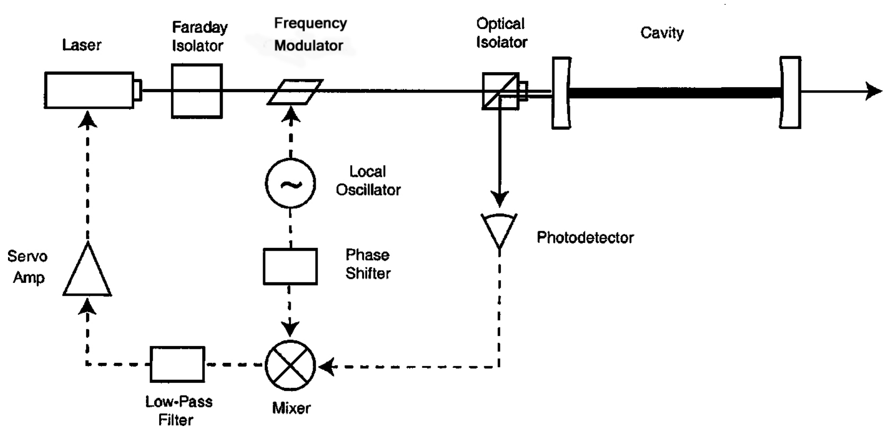

Figure 5: Schematic for a PDH setup. The re ection signal from the optical cavity is detected and combined with the local oscillator signal in order to demodulate the error signal.

From this setup, the spectral density was measured using a Fourier Transform machine. The extrapolated linewidth of the laser was 550 $200Hz$. The stabilization lock was seen to have a bandwidth of nearly 2.5MHz which is typical for a PDH locked laser.

6 Conclusion

The current atomic frequency standard created by the strontium clock in Ye labs has reached a total uncertainty of 1 10^{-16}. This uncertainty is less than the national standard{the Cs ion clock housed at the National Institute of Standards and Technology (NIST). By creating a more stable laser system, lasers will be able to probe the narrow transitions in strontium even more precisely. The current laser stabilization system uses a vertically mounted 7cm Fabry-Perot cavity with a nesse around 200,000 [6]. A new system, consisting of a 40cm horizontal cavity with comparible nesse is currently being integrated into the atomic clock system. The 40cm cavity is expected to have a factor of ten less sensitivity to thermal noise, or thermal uctuations in the mirror substrate. My 10 week project project was to setup the prestabilization of the 698nm laser to a prestabilization cavity. After the prestabilization, the laser's stability will be comparable with the 40cm cavity's linewidth. The prestabilization achieved a linewidth near 550hz, a very suitable stability which will allow further stabilization to the 40cm cavity.

References

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