

Pound Drever Hall Stabilization with Thermally Modulated Cavities

- Acknowledgements
- Introduction
 - Lasers & need to stabilize
 - Pound Drever Hall locking
 - Use for atomic physics, projects in the Simon Lab
- Design and Testing
 - Design of the first cavity
 - Multiple iterations & changes in materials used
 - Designing a locking scheme
 - Heating laser and focusing challenges
- Results
 - How to test bandwidth/maximum performance
 - Bandwidth measurements
 - Current use in the Simon Lab
- Outlook
 - Applications in PDH locks that utilized piezos to lock cavities to resonances
 - Improvements
 -

Questions (addressed in meeting w/ Jon):

- References: Simon lab papers for connection to physics in Simon lab?
 - Siegman
- How much background necessary? I talked about lasers, pound drever hall locking, thermal stuff, and really not much else.
 - We use dfb lasers, right?
- Relationship to physics in the Simon lab?

LaTeX: Overleaf package

Bring in LIGO as a reference

Use microwaves to heat: pick a material with absorption depth of something that absorbs microwaves resonantly w/ absorption depth about three times thickness of cavity uniform heating

Abstract

This thesis will explore the design, construction, and implementation of an optical cavity that is Pound Drever Hall (PDH) locked to resonance with a laser. PDH locking is a well-understood technique employed almost universally in laser physics, as well as more notably at LIGO [1]; the novelty of this project is in the method used to lock the optical cavity to resonance with laser. PDH locking of a cavity to a more stable object is often achieved with a piezoelectric transducer (piezo), that can be integrated into a cavity design such that its voltage-controlled expansion and contraction corresponds to a lengthening or shortening of the cavity. This allows the the length of the cavity to be precisely tuned to satisfy the conditions for a particular laser mode to pass resonantly through the cavity. In this work, I design a cavity that will use its own thermal expansion as a point of access to laser-cavity resonance, forgoing the use of a piezo as a locking element. The Simon Lab has already integrated such a thermal expansion-based feedback loop into a piezo PDH lock on an existing experimental cavity, where the addition of the thermal control mitigates piezo woes stemming from long-term piezo control voltage drift. By constructing a cavity out of materials that respond quickly and strongly to thermal impulses and heating it with a powerful infrared laser, I demonstrate a degree of control over cavity length sufficient to stably PDH lock the cavity to resonance with the laser over both short and long time scales, facilitating future research into effects that require strong coupling of laser light to matter inside an optical cavity.

Introduction

Relevance to Physics Research

The benefits of controlling cavity length with its temperature are particularly relevant to research into topics in cavity quantum electrodynamics. The strength of interactions between light and matter are characterized by a coupling constant $g = \left(\frac{\mu^2 \omega}{2\epsilon_0 \hbar V} \right)^{1/2}$ which depends on the electromagnetic mode volume V and the dipole matrix element between electronic states μ . Strong interactions between light and matter are appealing both as an avenue for exploring new physics and as a tool with a broad range of applications [2], and efforts to increase this coupling strength often focus on reducing the mode volume. Designing a cavity to have a small mode volume generally results in a decrease in stability of its resonance with light. Often, it becomes necessary to employ methods beyond the typical PDH approach in order to stabilize these cavities. One such method is configuring a PDH lock to feed back on the position of the cavity mirrors using thermal expansion of the objects they are mounted to. This type of thermal feedback has previously been employed to stabilize fiber Fabry-Perot cavities [3], high-finesse on-chip microcavities capable of hosting magnetically trapped atoms [4], and asymmetric cavities that host Yb atoms and are capable of high coupling strengths [5]. Recent research efforts in the Simon Lab towards characterizing topological matter have also relied upon a twisted, four-mirror cavity stabilized using thermal feedback [6,7]. Near-unstable cavities may also have applications in the detection of neutral atoms, as in [8]. As a result, the development of a method for controlling cavity mirror position has applications in a variety of areas.

Lasers

The need for a source of coherent, frequency-stable light is ubiquitous in modern AMO physics research. Any attempt to efficiently couple light to electronic dipole transitions in atoms requires a light source capable of producing photons in a sufficiently narrow range of energies close to the transition energy. Most often this light source is a laser, and while there are many different kinds of lasers, I will give a simplified explanation of how they work that sufficiently motivates my work towards stabilizing them for this project.

The most common type of laser is a diode laser, which consists in its most basic form of a layer of undoped semiconducting material sandwiched between a layer of p-type semiconducting material and a layer of n-type semiconducting material. By applying a voltage in the correct direction, the resulting electric field moves excess holes in the p-type semiconductor and excess electrons in the n-type semiconductor into the undoped (intrinsic) region. Once in sufficiently close proximity within the intrinsic region, an electron and a hole can combine to momentarily form a bound state called an exciton before annihilating and releasing a photon with the same energy required to displace them from their original states in the n-type and p-type semiconductors. This process on its own does not produce nearly as many photons as it is possible to generate with this device. By fabricating the semiconductors in a certain way and placing reflective surfaces on two sides of the intrinsic region, photons produced in combination events may remain in the resulting Fabry-Perot cavity for a period of time before exiting. While inside the cavity, these photons may participate in a process known as stimulated emission, in which the presence of a photon nearby an electron-hole pair can initiate their instantaneous annihilation, bypassing the exciton state and generating a second photon with identical phase, polarization, and wave vector. It is this stimulated emission process that generates the photons that form coherent laser light.

Such a laser is prone to a variety of environmental factors that prevent the energies of the photons they generate from being identical, and the energies of the photons produced form a spectrum. Photon energy differences result from in the initial state energies of electrons and holes before they combine. In any material, the likelihood of a state being occupied depends on the ratio of the state's Boltzmann factor to the partition function. At room temperature, electrons in a semiconductor may occupy different states with energies determined by their momentum, resulting in a range of different energies released upon combination with a hole. Slight changes in temperature can also shift the entire range of frequencies produced. In the same manner, vibrations in the semiconductors can cause similarly substantial changes in photon energy. As a result, lasers are often temperature controlled in order to stabilize their frequency. However, temperature control occurs relatively slowly, and often perturbations in laser frequency occur on much faster time scales. In order to ensure that even fast changes changes in laser frequency are eliminated, it is necessary to employ external frequency measurement and fast feedback.

Pound Drever Hall Locking

The basic strategy of Pound Drever Hall (PDH) locking involves collimating the laser, mode matching it to an optical cavity consisting of two partially reflective dielectric mirrors, and then measuring the intensity of the light reflected off the cavity with a photodetector. The effect of the optical cavity on the propagation of the light is to introduce boundary conditions at the mirror surfaces. These boundary conditions are a result of Maxwell's equations, and have the effect of permitting only an integer number of wavelengths of light to exist between them. The result is that the laser light will only travel through the cavity if this condition is satisfied; there are many ways to do so that depend on the cavity size, the angle of entrance of the beam, and its wavelength. For this section, however, it suffices to say that if the beam is appropriately aligned with the cavity, the intensity of the light reflected off the cavity will increase as the frequency of the laser light drifts further away from the resonance frequency. As a result, we have a signal that corresponds to the difference between the frequency of the laser and the resonance frequency of the cavity and that can be manipulated and fed back to the laser in order to tell it to change its frequency to be closer to resonance. A plot of this reflection signal against laser light frequency will look like an inverted peak around the resonance that drops off in magnitude on either side. As a result, as laser frequency drifts higher or lower than resonance, the magnitude will decrease. However, this means that the signal gives no information about in which direction to correct the laser frequency. In order to yield a signal that is asymmetrical about the resonance, or

equivalently one that can indicate how the laser frequency should be changed to match the resonance condition, a more involved technique is required. This method is called Pound Drever Hall technique.

Pound Drever Hall locking typically involves a phase modulator, a mixer, a proportional integral derivative (PID) controller, and a radio-frequency (RF) oscillator in addition to the laser, optical cavity, and photodetector. Following [9], the creation of the error signal will be derived assuming that the laser produces monochromatic light with magnitude $E_i = E_0 e^{i\omega t}$. Assuming that the length of the cavity is L , the reflectivity and transmissivity of the identical cavity mirrors as R and $T = \sqrt{1 - R^2}$, and recalling that reflection off a dielectric with a higher index of reflection incurs a π phase shift, we can write the magnitude of the reflected signal as

$$E_r = E_0 (R e^{i(\omega t + \pi)} + T R T e^{i(\omega t - 2L\omega/c + \pi)} + T R^3 T e^{i(\omega t - 4L\omega/c + \pi)} + \dots)$$

where the additional path length of the light making one round trip through the cavity is $\frac{2L}{c}$. The free spectral range of the cavity is defined as $\nu = \frac{c}{2L}$, and simplifying the infinite sum, we get

$$E_r = E_0 \left(\frac{R(e^{i(\omega + \omega/\nu)} - e^{i\omega t})}{1 - R^2 e^{i\omega/\nu}} \right)$$

The frequency response of reflection off the cavity is

$$G(\omega) = \frac{E_r}{E_i} = \frac{R(e^{i\omega/\nu} - 1)}{1 - R^2 e^{i\omega/\nu}}$$

The phase modulator or electro-optic modulator (EOM) is a device that makes use of the electro optic effect in order to induce a phase lag in the the laser light. The EOM is driven with an RF oscillator that adds a sinusoidal term to the phase of the beam. If $E_i = E_0 e^{i\omega t}$, and the EOM is driven with a signal of frequency Ω , then after the EOM, the magnitude can be described as

$$\begin{aligned} E_i &= E_0 e^{i(\omega t + \beta \sin(\Omega t))} \\ &\approx E_0 e^{i\omega t} [J_0(\beta) + 2iJ_1(\beta) \sin(\Omega t)] \\ &= E_0 [J_0(\beta) e^{i\omega t} + J_1(\beta) e^{i(\omega + \Omega)t} - J_1(\beta) e^{i(\omega - \Omega)t}] \end{aligned}$$

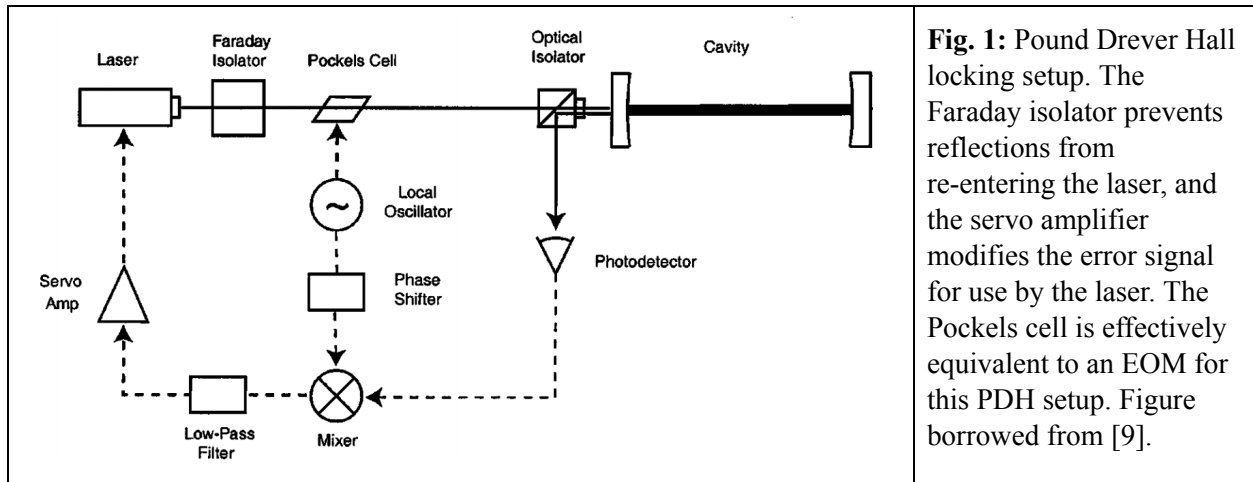
Evidently, passage of monochromatic light through the EOM yields two “sideband” frequencies offset by $\pm \Omega$ with amplitudes given by first order Bessel functions in addition to the original frequency component with reduced amplitude given by the zeroth order Bessel function. Plugging this into the frequency response function yields

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

The photodetector can only measure intensity, however, which is proportional to the square of the electric field. As a result, the detected signal has magnitude

$$\begin{aligned} I &\sim \left| J_0 \right|^2 |G(\omega)|^2 + \left| J_1 \right|^2 (|G(\omega + \Omega)|^2 + |G(\omega - \Omega)|^2) \\ &\quad + 2J_0 J_1 \text{Re}[G(\omega) G^*(\omega + \Omega) - G^*(\omega) G(\omega - \Omega)] \sin(\Omega t) \\ &\quad + 2J_1 J_0 \text{Im}[G(\omega) G^*(\omega + \Omega) - G^*(\omega) G(\omega - \Omega)] \cos(\Omega t) \\ &\quad + O(2\Omega) \end{aligned}$$

The relevant phase information is contained in the $2J_1 J_0 \text{Im}[G(\omega) G^*(\omega + \Omega) - G^*(\omega) G(\omega - \Omega)]$ term. In order to extract this term, we can multiply the entire signal by the modulation signal $\beta \sin(\Omega t)$. This is accomplished using a mixer, which is an electrical component that takes in two signals and outputs a rescaled version of their product.



The result of this multiplication of the modulation signal and the photodetector signal is the sum of a DC component containing the desired term and another component that oscillates with frequency 2Ω . Using a low pass filter, one can extract just the desired term, which has the desired antisymmetric shape about the resonance frequency. As a result, the PDH method makes it possible to extract an error signal from the laser's reflection off the optical cavity. This signal indicates the direction in which the laser frequency needs to be adjusted, and can be appropriately manipulated in order to serve as a feedback signal for the laser.

Feedback Loops and PID Control

Provided with a way to measure the difference between the desired laser frequency and the detected laser frequency, it becomes necessary to send some version of this signal to the laser that can tell it how to adjust its frequency. Depending on the type of laser is in use, a number of laser parameters may be chosen to be tuned to adjust frequency. However, in the Simon Lab, we use distributed feedback (DFB) lasers that can be easily and finely tuned with a control voltage that alters the current supply to the diode and shifts the frequency of light produced. As a result, our error signal should be converted into a voltage proportional to the frequency offset. The challenge is to design a circuit that modifies the error signal to generate a voltage V_{mod} that allows the laser to respond to changes in frequency on an appropriate time scale and with an appropriately sized change in frequency. For example, if the laser were only able to change its frequency at a rate $d\omega/dt$, a V_{mod} that oscillates too quickly will result in no change in frequency. Similarly, if V_{mod} is too small or too large, the laser will tend to over- or undershoot its frequency target, resulting in oscillatory frequency behavior or no change at all.

The standard approach to generating an effective V_{mod} is to use a proportional, integral, derivative (PID) controller. Such a controller creates a V_{mod} that is the sum of three components. The proportional term $V_p = K_p e(t)$ is directly proportional to the error signal $e(t)$, and serves to directly reduce any measured frequency offset. The integral term $V_i = K_i \int_0^t e(t) dt$ integrates the error signal in time. Thus, if there is a frequency offset that persists in time despite correction by the proportional term, the integral term will reduce the offset more and more with time, by an amount proportional to the integral over time of the difference between the target and measured frequencies. The derivative term $V_d = K_d \partial_t e(t)$ is proportional to the derivative of the error signal and has the effect of smoothing out rapid changes in V_{mod} that may cause instability in laser frequency. These three components taken together are generally sufficient to reduce the deviations of some object from a set point, and create a control signal.

$$V_{mod} = V_p + V_i + V_d = K_p e(t) + K_i \int_0^t e(t) dt + K_d \partial_t e(t)$$

The constants K_p , K_i , K_d are tuned in order to produce a control signal that changes the laser frequency in just the right amount in response to some frequency offset. The tuning of these parameters has been studied extensively, and there are a number of tuning methods. One of the most basic, and the one employed in this project, is Ziegler-Nichols method. This approach uses numeric ratios to determine the values of K_p , K_i , and K_d [10].

Thermal Expansion

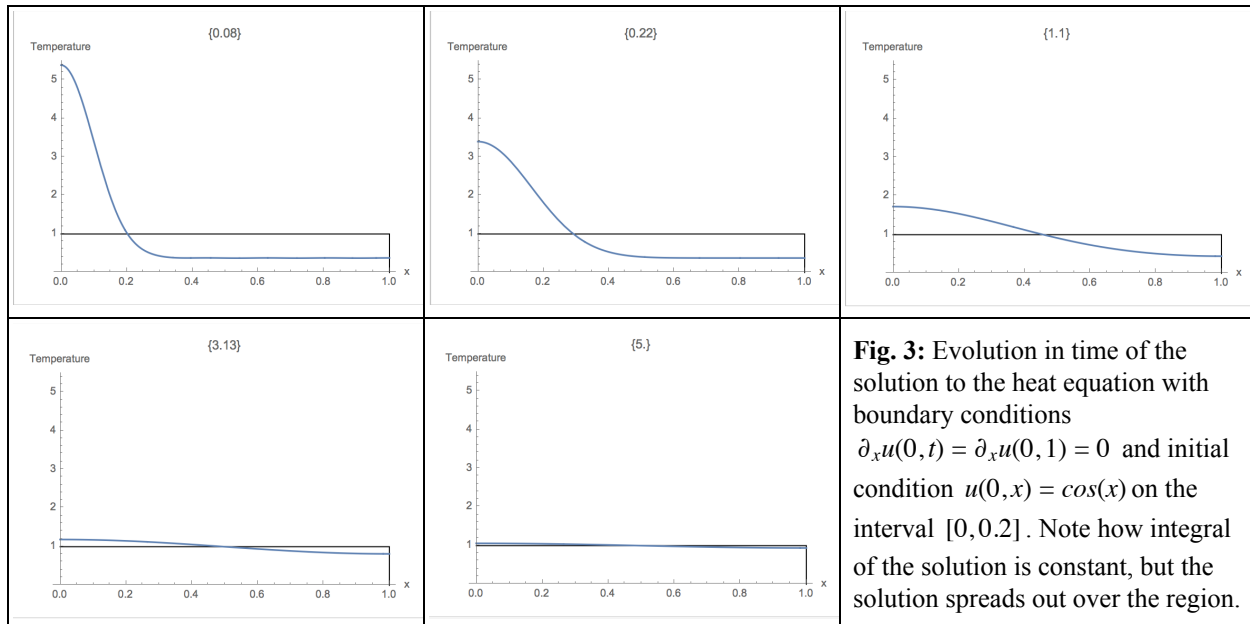
The goal of this project is to design an optical cavity that can quickly and reliably change its length in order to maintain resonance with a laser. This is accomplished by shining an infrared laser onto the side of the cavity to heat and cool it; increases and decreases in infrared power lengthen and shorten the cavity respectively. In order to maintain resonance with the original laser, it is necessary for the cavity to be able to heat up and change its length quickly enough to filter out environmental perturbations that may change its length and disrupt resonance with the laser. The primary criterion for a successful cavity is the speed of its response to perturbation, or equivalently, at how high of a frequency the cavity can make corrections to its length. In order to design a cavity whose length will be changing based on its temperature, it is essential to understand how the temperature of an object affects its size. For any uniform object, expansion in one dimension is characterized by the coefficient of thermal expansion $\alpha_e = \frac{1}{L} \frac{dL}{dT}$ of the constituent material. This coefficient describes the relative change in length of an object per change in temperature. Provided with this information, it is necessary to understand how the temperature of an object changes in response to heating. The theory of the absorption of infrared photon energy of metals is interesting yet unenlightening in this case, as the amount of heat energy absorbed scales with the power of the infrared beam. The question relevant to cavity design is about how heat moves throughout the material that makes up the cavity. For one-dimensional heat transfer, this process can be modeled by the heat equation:

$$\frac{\partial u}{\partial t} = \alpha_D \frac{\partial^2 u}{\partial x^2}$$

where u is the temperature and α_D the thermal diffusivity, defined as $\alpha_D = \frac{k}{\rho c}$, where k is thermal conductivity, ρ the density, and c the specific heat. Solutions to the heat equation are characterized by a fundamental solution $H(x, t) = \frac{1}{\sqrt{4\pi\alpha_D t}} e^{-|x|^2/4\alpha_D t}$, and for an initial heat distribution $u(t = 0, x) = u_0(x)$,

solutions are $u(x, t) = \int_{-\infty}^{\infty} u_0(y) H(x - y, t) dx$. For a one-dimensional medium of thickness L that exists

from $x = 0$ to $x = L$, and whose initial heat distribution is a delta function $u_0(x) = \delta(x)$ at its surface, the solution to the heat equation spreads out over the object as time progresses, mimicking how heat diffuses. The solution involves an exponential function with a rate constant that depends on α_D . Consequently, the speed at which the temperature of the object equilibrates increases with α_D .



The importance of this fact has to do with thermal expansion in non-uniformly heated bodies; if an object is rigid and is heated in just one plane of its volume, it cannot expand because the rest of the object resists this motion. In order for the entire object to expand, it is necessary for heat to distribute throughout it. This is why the thermal diffusivity is important; the rate at which the cavity can expand when heated depends on the thermal diffusivity. Notably, however, the thickness of the material is also a key factor in the rate at which thermal expansion can occur. Heat diffuses throughout a thin object quicker than a thick one, and so picking a material that optimizes both thermal diffusivity and thickness (or rather, thinness) will maximize the rate at which an optical cavity heated with infrared photons can expand and contract in response to environmental perturbations.

Design and Testing

Overview

This project consists of three parts. The first part is designing the locking cavity. The cavity is designed to maximize the frequency with which it may appreciably change its length in order to account for perturbations to cavity length. The bandwidth of an object generally refers to the range of frequencies in which it operates, and so the higher the maximum frequency of response, the higher the bandwidth of the cavity. Building a high bandwidth cavity is a balancing act between building a cavity that can expand rapidly but is also rigid enough to not be subject to mechanical noise from the environment that may shake it enough to displace the mirror by an amount that will result in a disruption in the locking signal. There are a number of ways to go about this. First, one might try to maximize the thermal diffusivity of the cavity body without much regard for the thickness of the cavity. There are a number of materials with high thermal diffusivities; amongst these are aluminum, copper, and pyrolytic graphite. Generally, the same materials that have high coefficients of thermal expansion also have high thermal diffusivities. However, pyrolytic graphite consists of sheets of hexagonally ordered carbon bound by Van der Waals forces, and has an extraordinarily high thermal diffusivity in the plane parallel to these sheets. Another approach is to try to minimize the thickness of the cavity walls. Thinner walls allow faster heat diffusion and a higher bandwidth; however, they also reduce structural rigidity and a higher chance that the mirrors glued to it will move from their set positions, disrupting the carefully set condition on inter-mirror distance and negating the potential improvement in bandwidth.

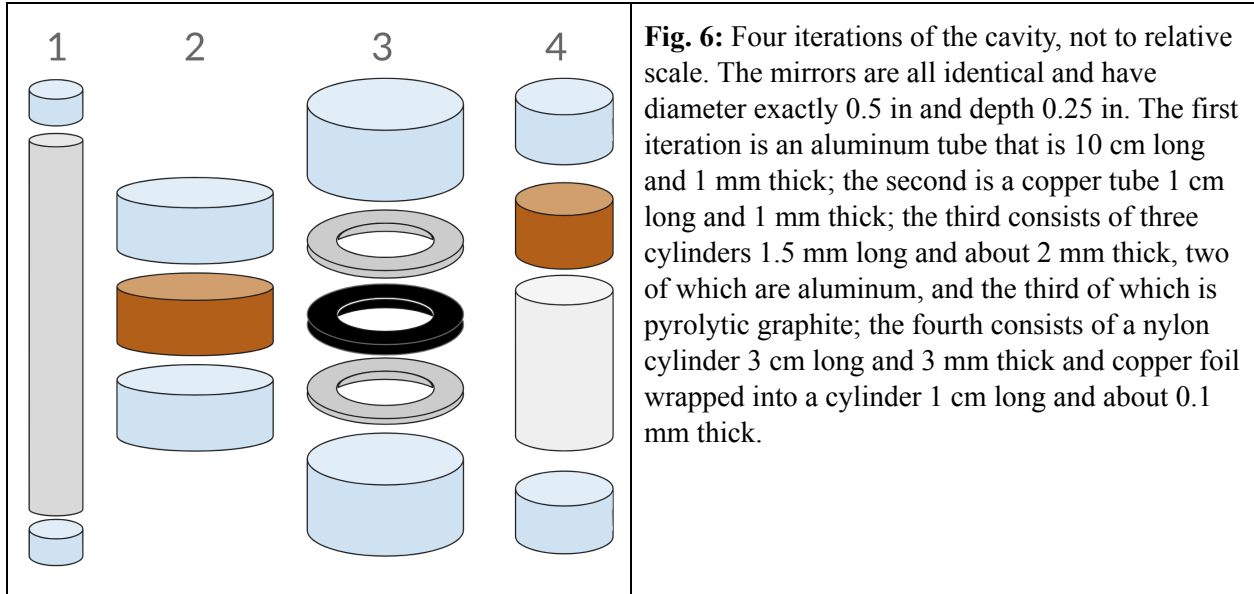
The second part of the project involves measuring the bandwidth of the cavity. There are a number of different ways to approach this, but the most reliable bandwidth measurements for this cavity were made by sinusoidally varying the power of the heating laser shining on the cavity's side. A measure of the cavity length is obtained by PDH locking a laser to the cavity; the feedback signal sent back to the laser will vary sinusoidally as the cavity length and thus the necessary laser frequency for resonance changes. By driving the cavity with higher and higher frequency heating laser modulation, we will be able to determine at what heating laser frequency the locking signal (corresponding to cavity length) will be reduced by half. This frequency is determined to be the cutoff frequency of the cavity, and is equivalent to the bandwidth.

The final part consists of designing a locking scheme that will allow the cavity to be locked to a laser. The PDH technique described above is for locking a laser to a cavity. In order to lock a cavity to a laser, the feedback signal needs to be sent to the heating laser so that it can change the intensity of light focused on the cavity, changing the cavity temperature and correspondingly its length. The locking scheme for this PDH lock will be more complex than one locking a laser to a cavity.

Cavity Construction

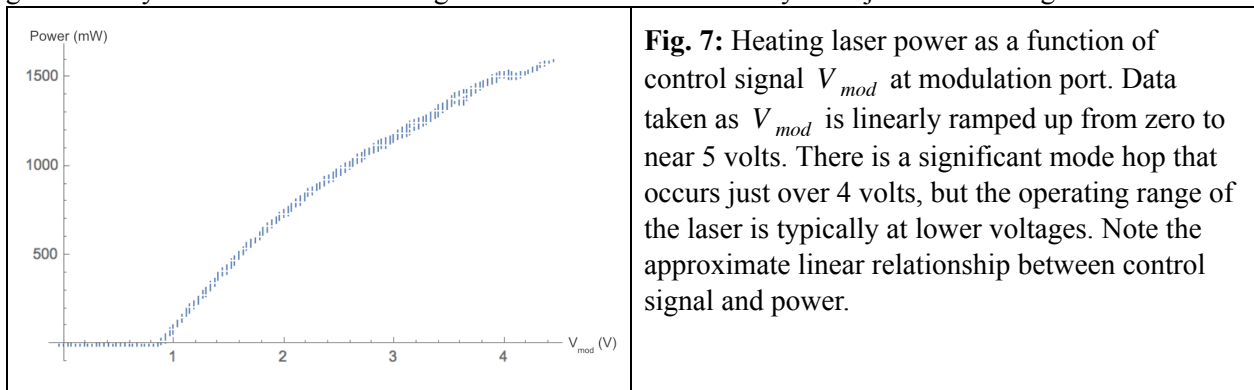
There have been four iterations of the cavity. Each is built out of raw materials that I machined into their respective forms in the student machine shop.

The first is a long, aluminum tube painted with a paint called Berkeley black, which is a thermally conductive, thermal shock-resistant, low-coefficient of thermal expansion epoxy mixed with carbon black. This paint was spread over the tube, and two fused silica output coupler mirrors glued to the end with TorrSeal epoxy. Heating was achieved by shining a 1.6 W, 980 nm laser at the side of the cavity. This cavity was limited in how quickly it could expand by the time it took for heat to diffuse through the thickness of the cavity walls. The second cavity was built out of a much shorter copper tube, the desired effect being to limit the diffusion of heat lengthwise along the cavity in favor of it propagating around the circumference so as to minimize warping and increase the rate at which the whole cavity could heat up and expand. The third cavity was constructed using a small, square piece of pyrolytic graphite cut into a ring shape and sandwiched between two aluminum rings of similar proportions. Two mirrors were glued to the end of this object to make a cavity, and the heating laser shines on a thin patch of exposed carbon. The fourth cavity was built by machining a nylon rod into a cylindrical shape and wrapping a piece of thin copper foil around it so that a small section of the foil stuck out above the nylon. By gluing one mirror to the exposed nylon end and another just to the edge of the copper foil, I created a two-mirror optical cavity. The heating laser shines on the part of the foil that sticks up above the nylon and that is glued to the cavity.



Heating Laser

The heating laser was purchased from eBay and emits light at 980 nm at a power of 1.6 Watts. Light is generated by a series of diodes arranged in a line and collimated by an adjustable rotating lens.



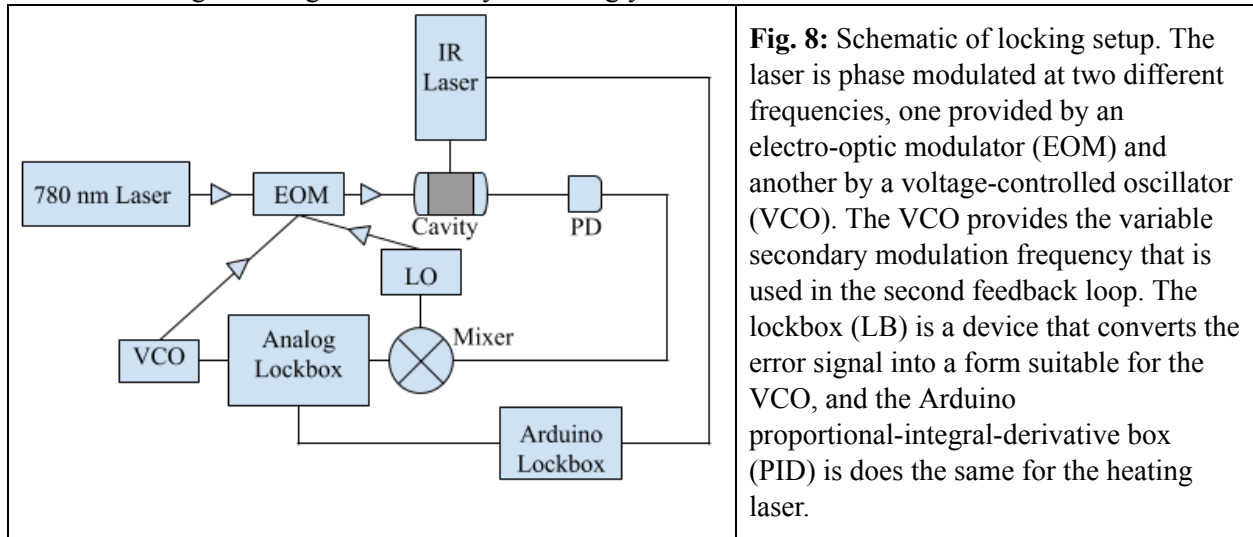
To induce temperature changes in the cavity, the heating laser beam was collimated and focused onto a small patch on the surface of the cavity that was painted black to minimize reflection off the metallic surface.

Locking Scheme

In my work, the goal is to use the lock the cavity to the laser rather than vice versa. The appropriate Pound Drever Hall setup needs to measure the length of the cavity instead of the frequency of the laser light, and the feedback signal should be sent the the heating laser that changes the cavity length instead of the laser. However, there is a problem in that the length of the cavity is not an easy value to measure. The obvious choice is a piezoelectric transducer, which converts changes in length to a voltage. However, piezos, while responsive to fast modulation, are subject to significant drifts in voltage that makes them poor indicators of exact lengths. As a result, I introduced a second Pound Drever Hall feedback loop that locks another more easily measurable quantity to cavity length in order to be able to feed back on the cavity length. This second quantity is the frequency of another EOM-generated laser sideband. As discussed previously, a sideband is an additional frequency spectrum feature of a laser's output that is created by phase modulating the laser. The result of phase modulation is a series of additional frequency

components at frequencies offset from the original frequency by the modulation frequency, with amplitude given by the Bessel functions.

In my setup, this secondary modulation frequency is the variable that the feedback of the first Pound Drever Hall loop is sent to. Essentially, when the cavity changes in length, and the amount of light transmitted through it reduces, and the location of a sideband in frequency space changes slightly. The position of this sideband is thus an indicator of cavity length. The result of this is that the position of this sideband can be used as a feedback signal in a second Pound Drever Hall loop, where the signal corresponding to this sideband position is mixed down with another oscillator that is used to modulate the cavity length. The amount by which this sideband deviates from a set position is then used as an error signal for cavity length, which is passed through another PID controller and then sent to the heating laser in order to change the length of the cavity accordingly.

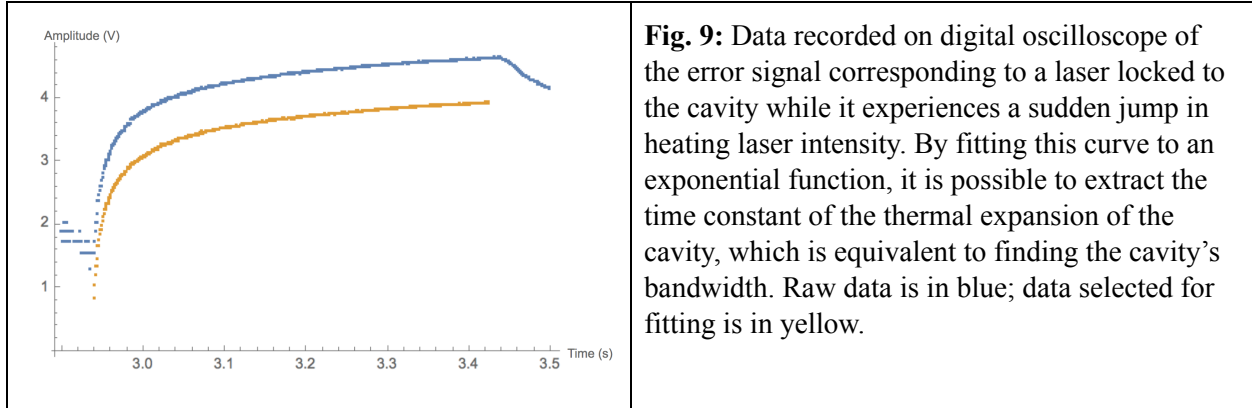


Results & Discussion

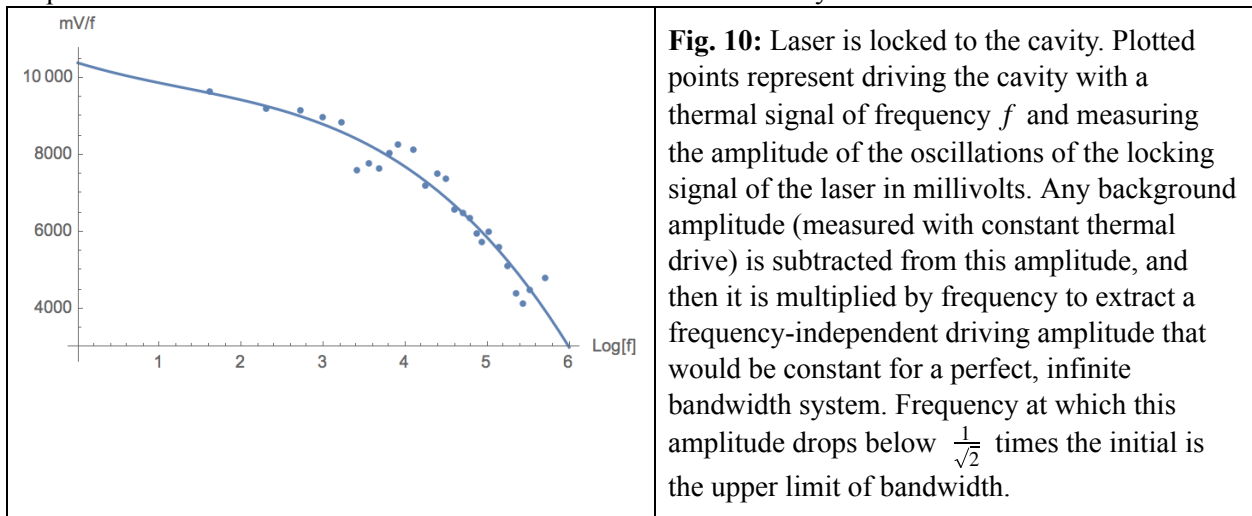
Testing Cavity Bandwidth

In order to see that the length of the cavity can be changed reasonably quickly using just its temperature, I first set up the cavity to have laser light pass through it, and then image the cavity output on a CCD camera. For a fixed laser frequency output, observation of the series of Hermite-Gauss modes that propagate through the cavity at different cavity lengths due to changing cavity resonance conditions gives a clear visual indication that the heating laser is indeed changing cavity length. In order to measure how good the heating modulation is for a Pound Drever Hall locking scheme, or equivalently, how quickly the heating laser can change the cavity length, I measured the bandwidth of the cavity. The job that the cavity is performing is changing the distance between two mirrors in order to maintain resonance with a stable laser. A higher frequency of operation of this setup is equivalent to the cavity being able to respond to environmental perturbations that occur faster, such as a small fan motor shaking an optical table, or a single sharp jolt the optical table. These kinds of perturbations cause a brief displacement in the position of the mirrors that leads to a disruption of laser-cavity resonance, which is what the cavity is designed to filter out. Measuring the bandwidth of the cavity is equivalent to checking on how short a timescale the cavity can change its length in order to cancel out such perturbations. There are several approaches one can take to measuring bandwidth.

One option is measuring $1/e$ expansion time of the cavity. This consists of fitting data corresponding to the length of the cavity to an exponential curve as the heating laser is suddenly turned on. The characteristic time of this expansion is an estimate for the shortest amount of time that the cavity can respond in a reasonably fast way to environmental perturbations. The limitation of this method is that the cavity is made of a variety of materials that all have different characteristic expansion times, and selecting the data that corresponds to only the fastest response of the cavity length the the heating laser impulse is tricky and often misleading.



Another option is heating the cavity with a sinusoidal signal and measuring the frequency at which the amplitude of the response decreases by $1/e$. This method provides a better measure of how well the cavity will work in the way it was intended, as in the Pound Drever Hall locking scheme, the cavity will be responding to quick changes in heating laser intensity in response to perturbations of distance between cavity mirrors. The bandwidth of the cavity is estimated to be the frequency of heating laser modulation at which the proportion of cavity length to driving frequency drops below the value I measure at very low frequencies. This was the method I used to determine the stated cavity bandwidth of 90 Hz.



In both of these methods, a further challenge consists in noise stemming from ambient vibrations. In fitting the data that I collected, it was sometimes necessary to filter out a significant 50-60 Hz noise component present in our lab. This was done by taking data, reversing the polarity of the data signal, taking more data, and then taking the difference of the two data sets. Another thing that I took into account during the bandwidth measurements was the time it took for the heating laser to ramp up to a set value. However, this process was relatively fast and ended up not being significant enough to make a difference in my calculations.

Arduino PID and Locking Performance

Provided with a value for the bandwidth of the cavity, it is possible to begin designing a “lockbox” that will convert the error signal from the PDH setup into a useful control signal V_{mod} . In a typical PDH setup for locking a cavity to resonance, a piezo can respond very quickly to changes in applied voltage so it is commonplace to use an analog circuit—a ‘lockbox’—to create the control signal. The advantage of analog lockboxes is their bandwidth; the rate at which an analog lockbox paired with a piezo can make changes in cavity length is limited in the kHz range by lockbox electronics. However, because a typical analog lockbox cannot slow the rate at which it measures frequency offsets, much of the control signal it generates will be filtered out by the slow response of the cavity. Instead, I use a digital system that permits easy manipulation over the rate of corrections made to the control signal. Using a microcontroller called an Arduino Uno, I make use of the built-in analog-to-digital conversion feature in order to produce a control signal that is updated on a time scale similar to that of the bandwidth of the cavity. Another benefit of the microcontroller lockbox is that tuning of the PID coefficients is fast and easy—all that needs to be done is to change the values of variables in the code I wrote that tells the Arduino to convert the analog error signal into a control signal. Using this approach, I was able to demonstrate locking of the cavity I built to resonance with the laser at a bandwidth of 50 Hz.

Outlook

It has been shown that thermal control of an optical cavity can be used to PDH lock an optical cavity to resonance with a laser. Adding this type of feedback loop into a piezo PDH lock can improve the long term performance of the original piezo lock. This work may be useful for stabilizing concentric and otherwise near-unstable optical cavities in the service of minimizing mode volume and maximizing the strength of interactions between laser light and matter inside the cavity.

One way in which this work may be extended and improved upon is by building a cavity out of a material that can be heated by resonantly absorbing microwave photons. In this case, there is no need to wait for heat to diffuse throughout the cavity in order for expansion to occur; the uniformity of the heating for resonant microwave absorption may relieve the response of the cavity from heat diffusion delay. To maximize the rate of heating, the thickness of this cavity should have a thickness smaller than the attenuation depth of microwave radiation but large enough to remain mechanically stable. By appropriately controlling the microwave radiation used to heat, this method may be used to improve upon the results of this project.

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