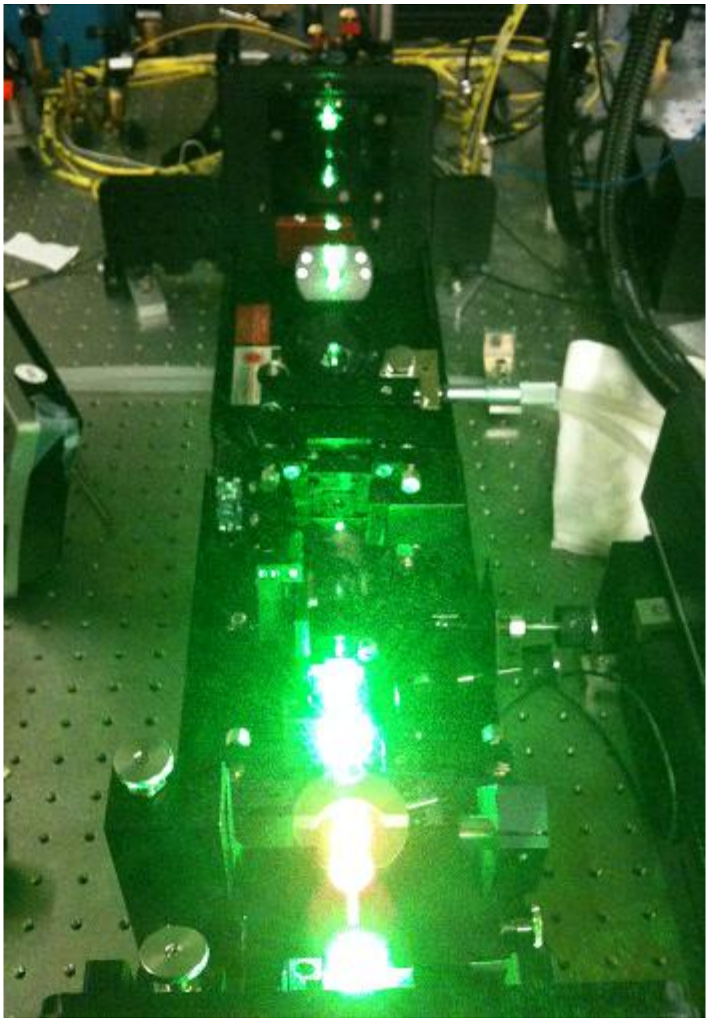
Stabilized Reference Cavity and Laser Lock



Andrew Cavers
Tenny Gao
Rudy Lam

Project Sponsor:
Dr. Kirk Madison

Project 1152
Engineering Physics 479
Engineering Physics Project Laboratory
The University of British Columbia
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EXECUTIVE SUMMARY

The “Stabilized Reference Cavity and Laser Lock” project is intended to produce a laser which is locked to a cavity in order to produce a significantly smaller bandwidth (or, in optical terms, “linewidth”) than the laser could normally achieve. The project was undertaken by Tenny Gao, Rudy Lam, and Andrew Cavers between September 26 2011 and January 10 2012.

The overall goal of the project was to couple light from an 899-21 titanium sapphire ring laser (Ti:Sapph) into a cavity and use the transmission intensity through the cavity as error feedback to lock the laser to a specific frequency. The overarching tasks required to reach this goal were to assemble the Ti:Sapph laser, characterize the cavity, and test the quality of the laser lock.

The deliverables of the project were:

1. Buying or building control electronics which allow the Ti:Sapph to be controlled by a user and by a feedback signal from a cavity. Deliverable A was found to be unnecessary, as a control electronics box (or "lockbox") was provided by the sponsor to control the laser. It was later found that this lockbox was broken in some way and required repair.
2. Assembling and bringing the disassembled 899-21 laser in the sponsor's lab into narrowband lasing. This deliverable was unattainable because although the 479 group brought the 899-21 laser into broadband lasing, the component required for narrowband lasing (the inter-cavity assembly, or ICA) could not be mounted into the laser and allowed to lase at the same time. The team ultimately resorted to locking another, identical Ti:Sapph laser in the sponsor's lab.
3. Locking the titanium sapphire ring laser onto a cavity, which in turn must be locked onto a frequency comb laser. Deliverable C was found to be impossible without replacing the initial cavity selection with a more stable cavity. The cavity the 479 group attempted to lock to was found to drift as quickly as 100 MHz a minute, endlessly.
4. Using an acousto-optic modulator to further correct the signal of the cavity-locked laser, using feedback from the cavity. Deliverable C was impossible to even initiate without Deliverable B complete.
5. Optionally, decreasing the line width of the laser further. This could be done by designing a new cavity to produce a more sensitive error signal and then adjusting the elements which rely on the cavity to control the laser’s line width so that they can accept the new signal. Obviously, this deliverable was not reached by the 479 team.

All of the components for the project, other than the titanium-sapphire ring laser, will need to be purchased by the ENPH 479 group from outside vendors. The group will rely on the budget of the sponsor’s (Dr Kirk Madison) lab.

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Introduction

<u>Background and Significance of Report</u>

In theory, lasers produce monochromatic light (light that has a single wavelength). However, this is not true in practice. In reality, lasers produce light that has a wavelength range of hundreds of nanometers, which is approximately equivalent to frequency bandwidth of GHz magnitude.

The project sponsor, Dr. Madison, wishes to use these lasers to excite dilithium (Li-Li) into specific energy states. However, in order for atoms to transition between energy states, the energy that is put into the atoms from an external source (which in this case is the laser) must be exactly equal to the difference in energy between the two energy states. Otherwise, the atoms will either be excited into a different energy level or no transitions will occur at all.

The figure below shows the energy transitions that Dr. Madison wishes to achieve:

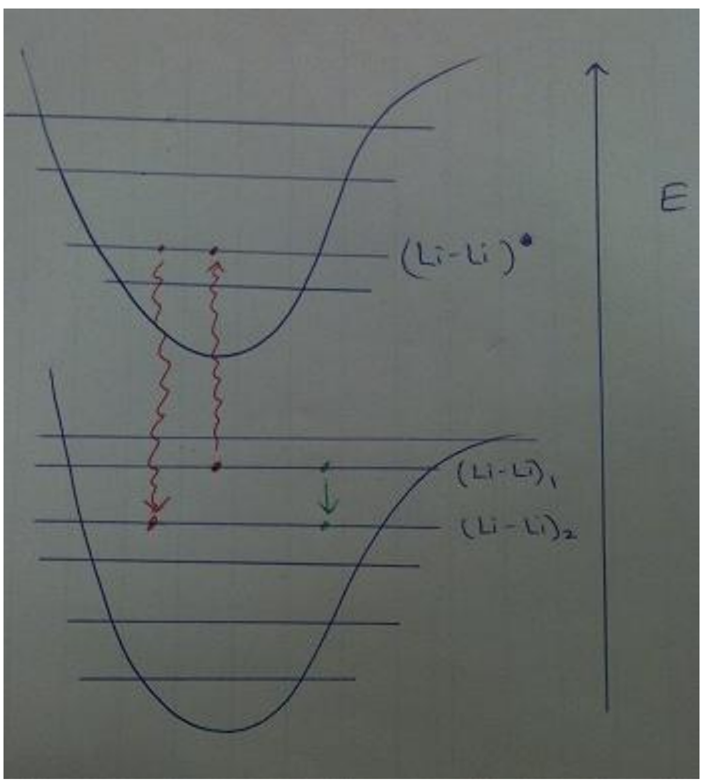


Fig 1: Energy Transition Diagram

The energy transition shown in green is what is ultimately desired. However, to achieve this in practice, the laser must cause the dilithium atoms to transition between energies as shown in red. Excitation to a higher energy level must first occur, and then the energy drop to the desired level will occur. Both transitions will ultimately be done by the laser.

Laser locking has been investigated repeatedly in the past. There are numerous papers that describe the setup and apparatus used to achieve tight locks, such as the paper by Hansch and Couillaud. However, this project is sufficiently different in that the sponsor does not want a novel method for achieving the tightest lock possible. Instead, he wants to achieve a sufficiently tight lock that is needed to excite dilithium atoms given the apparatus in his lab.

Project Objectives

The project objectives stated here are directly lifted from the proposal.

1. To deliver a lasing Ti: Sapphire 899-21 ring laser that successfully lases without the internal cavity. This objective can easily be verified simply by checking whether the laser emits light or not. We will deliver this by September 30.

2. To deliver a lasing Ti: Sapphire 899-21 ring laser that successfully lases with an internal cavity. This objective can be verified by creating an intensity vs. frequency plot of the laser as it leaves the cavity. If the plot shows evidence of fringes, even wide fringes, then the internal cavity successfully tunes the laser to a degree. We will deliver this by September 30.

3. To create a reference cavity that has a linewidth of 500 kHz and a center frequency shift of less than 2.5 MHz. The linewidth achieved can be verified by making an intensity vs. frequency plot and by mathematically analyzing the plot by measuring the width of the fringes. The center frequency shift can be verified by measuring the frequency with greatest intensity over time. We will deliver this by December 7, 2011

4. To design and create the optics that couples the light into the cavity. This objective can be verified by measuring the output error signal from the cavity to see if the laser is successfully coupled with the cavity. We will finish this by November 20, 2011.

5. To create and set up the PID controller. This will lead to assembling the entire system together (with the optics) so that laser locking can be achieved. To verify whether the PID controller functions or not, a signal generator can simulate an error signal input into the PID controller and an oscilloscope can read the output from the PID controller to see whether the expect behavior of the controller if achieved or not. We will deliver this by December 7, 2011.

6. To create the electronics needed to control the internal cavity within the laser. This objective can be verified by coupling the electronics with the cavity. Instead of controlling the length of the cavity with the manual knobs, the electronics will be used. We can feed voltages into the electronics via a signal generator and observe whether the correct change in the length of the cavity is observed. This will be completed by December 7, 2011.

7. To assemble the entire project and produce a laser with a line width of at most 500 kHz, centered around a wavelength between 650 and 950 nm. This will be finished by December 7, 2011.

8. Optionally, to further improve the line width of the laser to at most 10 kHz. This may not be completed, but would be finished by January 10, 2012.

Scope and Limitations

The scope of the report will be to cover the two main parts of the project. The first part will examine the performance of the titanium: sapphire laser that the 479 group assembled. This is significant because half the time period of the project was dedicated to assembling the Ti: Sapph and optimizing its output intensity. The second part of the report will examine the results of the laser-locking setup by the 479 group. This section includes the characteristics of the cavity used such as its finesse and drift, which influenced the quality of the lock and ultimately led to the team's failure to ever fully lock the laser. This section will also include the methods the team used to partially lock the laser, and their results.

There are limits to the scope of this report. This report does not explain the operation of the Ti:Sapph laser's components, and only provides rough descriptions of their functions and how they fit into the laser's beam path. Since the laser locking system was ultimately never successful by the end of the project's timeline, there are significant limits on what this document can report on or recommend. The team is unable to recommend any approach for locking the laser using an acousto-optic modulator, as was originally planned. The team is unable to provide measurements on the quality of the lock, such as its linewidth. The team never achieved an accurate enough cavity to perform linewidth measurements on the Ti:Sapph laser when it was locked using the manufacturer's cavity and control system, either, so it is unable to provide measurements which could be used as benchmarks for later development on the Ti:Sapph's cavity lock system.

Organization

The report documents the progress made by the 479 team so that the project can easily be picked up by the next group to work on it, and recommends the next steps to take. The report is divided into “Introduction”, “Discussion”, “Conclusion”, “Project Deliverables” and “Recommendations”. Of these sections, the “Discussion” section is the largest and for clarity is organized into the “Theories”, “Methods”, and “Results” of the various branches of this project. The research and development involved in locking a laser resulted in mechanical design of a new cavity, characterization of the current cavity, various electrical components, and experiments in locking a laser. Each of Discussion's sub-sections is further divided into sub- sections based on subject. For example, the 'Theory' sub-section contains the PID controller theory, optical cavity theory, and laser lock theory to name a few.

Discussion

Theory

The purpose of this section is to review all of the background knowledge which was necessary throughout the project. This includes an explanation of the Ti:Sapph's beam path and components, the basics of optical cavities, mechanical design for a stable cavity, a discussion of the properties of Fabry-Perot optical cavities, an explanation of the function of the voltage adder and PI controller circuitry, and finally the theory behind locking a laser to an optical cavity.

Titanium: Sapphire Laser Operation (Ti:Sapph)

This section will briefly go over how the titanium: sapphire (abbreviated as Ti:Sapph) laser produces laser light. The laser is capable of generating laser light between 680 to 1025 nm, which corresponds to a bandwidth of approximately 128 THz [2]. This section will describe the path of the light as it exits from the pump and discuss briefly what the function of each component is. The figure below shows the path of the beam of light that has to travel within the Ti:Sapph in order for it to lase.

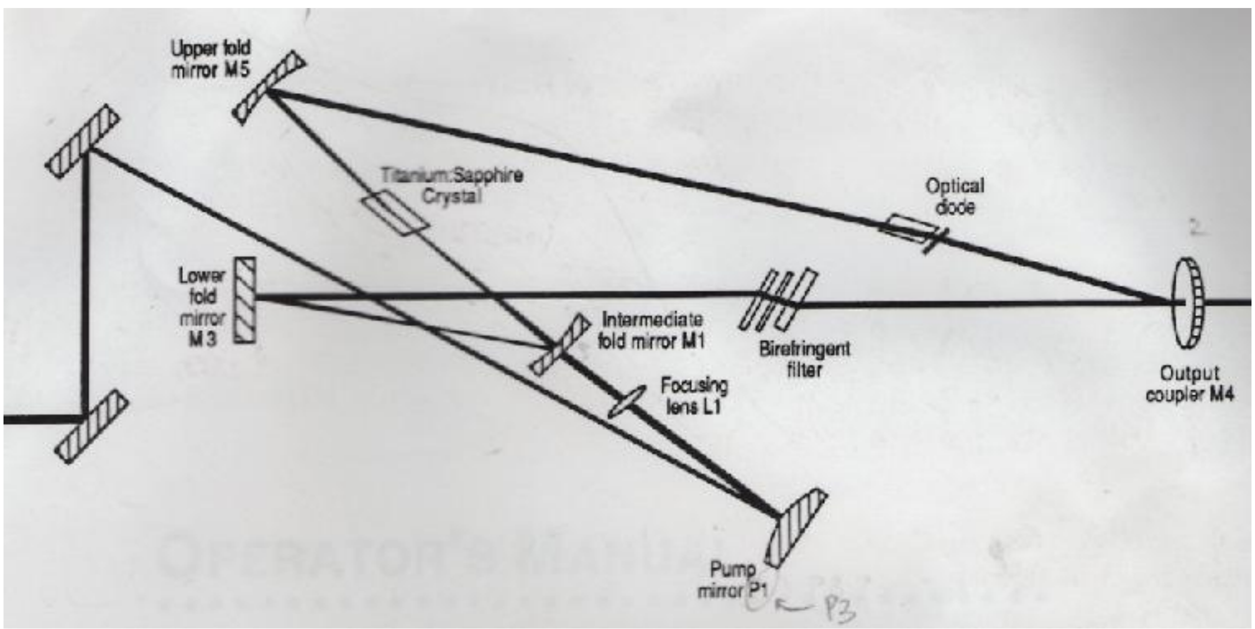


Fig 2: Path of laser beam in Ti:Sapph laser [2]

In order for the Ti: Sapph to lase at all, the light beam must hit every optic shown above at their centers. Otherwise, if the beam is misaligned at one segment, the succeeding beams would be off alignment, which would result in the laser failing to lase. Misalignment of the beam could also cause it to clip the edge of any of the optics shown above. This would cause a major attenuation in the output power of the laser.

Detailed instructions on how to align each of the optics and to get the laser to lase is given in the operator's manual for the Ti:Sapph. Thus, the exact procedures will not be listed in this section. This section will only outline the path of the beam as it travels through the Ti: Sapph laser and will provide the purpose of each of the components shown above [2].

The lower and upper periscope optics P1 and P2, the pump mirror P3, the intermediate fold mirror M1, the upper fold mirror M5, and the lower fold mirror M5 all serve the same general purpose: to reflect and therefore redirect the laser beam to the required path for operation. The upper fold mirror M5 is special in this case in that it splits the incident beam into two beams.

The birefringent filter enables the laser to lase broadband with a frequency bandwidth of 2 GHz. How it achieves this is beyond the scope of this report [2].

The optical diode is used to achieve unidirectional lasing. In other words, this diode is to ensure that the laser beam lases in one direction only. It achieves this using the Faraday effect and two polarizers between this material. Again, the theory behind how this optical diode works is irrelevant to the project and thus will not be discussed in further detail [2].

In order for the laser to lase narrowband, the intracavity etalon assembly (ICA) must be installed. It is shown in the figure below:

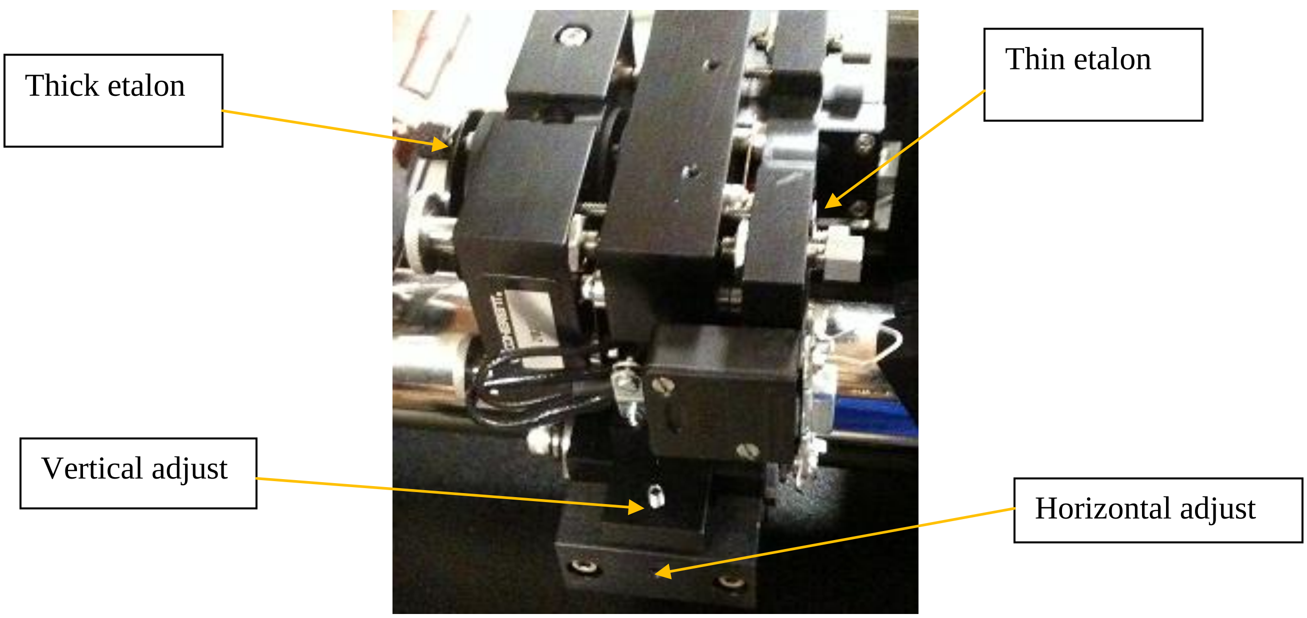


Fig 3: The intracavity assembly (ICA) is shown

The ICA consists of a coated thick and thin etalon that narrows the bandwidth of the laser to 10 MHz, which is defined as lasing narrowband [2].

The thin and thick etalons cannot be moved mechanically. A voltage must be applied to move them. Thus, in order to control the ICA and align the etalons to lase at narrowband, the control box must be connected to the ICA. The figure below shows the control box:

Fig 4: The control box for the ICA.

The theory behind how the ICA and control box work are beyond the scope of this report.

Basics of Optical Cavities

There are three further qualities of interest in an optical cavity: The finesse, linewidth, and Free Spectral Range (FSR). The linewidth and FSR are described graphically below, using plots of the cavity's response to a laser being scanned in frequency across the cavity's FSR. In order words, the laser's frequency is being slowly increased and the amount of light which is actually transmitted through the cavity at this frequency is plotted. The resonance peaks shown in blue in the Figures below are referred to later in this document as 'fringes'.

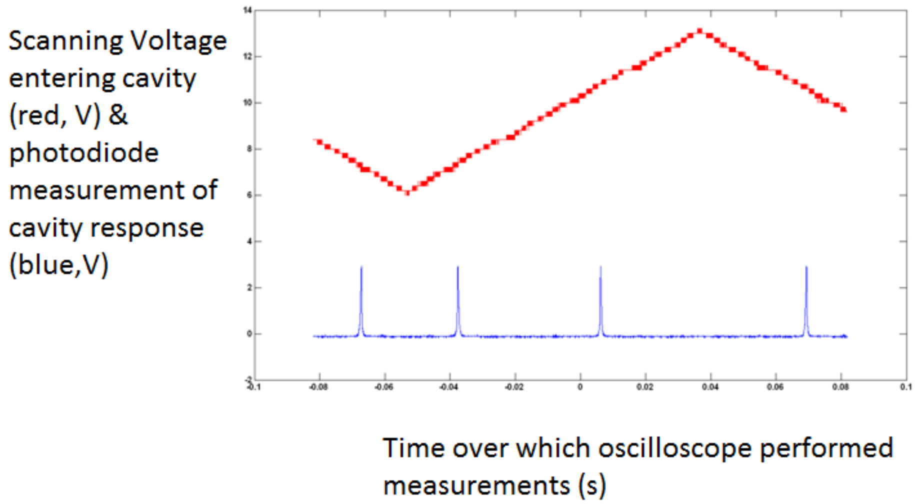


Fig 5: Oscilloscope traces of the voltage signal driving the cavity's piezo element (red) back and forth, and the photodiode voltage measurement of the cavity's resonance over this frequency scan.

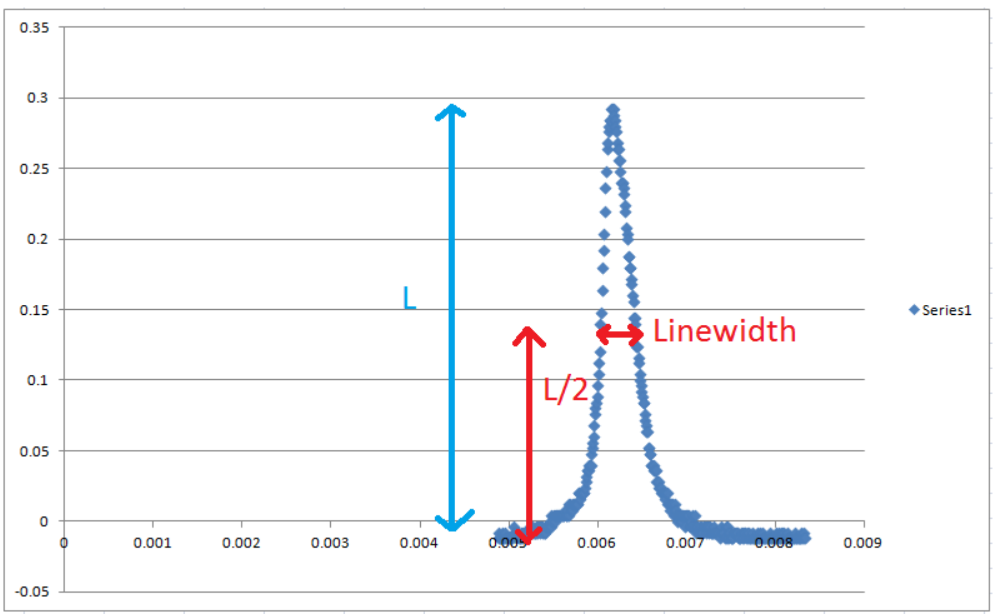


Fig 6: A zoomed-in version of a resonance peak shown in the Figure above, to illustrate linewidth.

The finesse is equal to the FSR divided by the linewidth.

Stable Cavity Design

This section relates some of the most important parameters such as finesse, linewidth and Free Spectral Range(FSR) to a cavity's physical properties and details the main environmental noise sources that influence the stability of a cavity. Material properties are explored for further evaluation of suitability to be used for a cavity.

<u>Relating the Finesse, Linewidth and FSR to A Cavity's Physical Properties</u>

To achieve laser frequency stability, a common method is to tune the laser output frequency to a resonance of an optical frequency reference cavity. Due to the fact that a reference cavity has no gain medium(optical gain within a laser), it can be made far more stable than the laser cavity. For example, a Fabry-Perot cavity, typically composed of two highly reflective mirrors mounted in a spacer, is commonly used for a reference cavity. The following parts of our report discuss the research performed on the design of a reference cavity and provide a recommendation on improving the stability of a current cavity in the optical lab.

In order to understand how to design a cavity with suitable finesse, linewidth and FSR for a particular project, it is necessary to understand how these quantities relate to the physical properties of the cavity. The equation below shows the relationships between these quantities as well as the reflectivity of mirrors (R).

$$\text{Finesse} = \text{FSR}/\text{Linewidth(FWHM)} = \pi * R^{1/2} / (1-R)$$

To narrow the laser bandwidth and achieve higher finesse, more reflective mirrors would be needed.

As the next step for cavity design, a cavity length needs to be specified. There are a certain number of factors to consider when specifying cavity length including acoustical noise, thermal noise, mechanical vibrations, etc. Two factors will be mainly discussed here in consideration of the cavity length specification, namely mechanical vibrations and ease of laser locking.

From mechanical perspective, the fractional length change is

$$\Delta L / L = 0.5 \rho L \alpha / E$$

Where $\Delta L / L$ is the fractional change of the cavity length, ρ is the density of cavity material, E is the Young's Modulus and α is the perturbing acceleration.

As shown in the equation above, a shorter cavity length would make the fractional change of length smaller and thus, lead to a more mechanically stable cavity.

A second factor to consider here will be the ease of the subsequent laser locking. Since the free spectral range is

$$\nu_{FSR} = C/(2L)$$

where C is the speed of light, and L is the cavity length.

It is obvious that the longer the cavity is, the smaller of value ν_{FSR} would be. As it can also be seen from Finesse = $\pi * R^{1/2} / (1-R)$, finesse is usually related to mirror properties and is independent of cavity length. Thus, the value of ν_{FSR} is proportional to the linewidth. The linewidth of a fringe is directly related to the ease of locking the laser as a steeper fringe would make it easier to lock the laser. A longer cavity length is thus desired.

Cavity Noise

To understand why the environmental noise will result in unstable peaks, the formation of a laser absorption line on a molecular level is investigated in this section.

Fig 7. shows a simple absorption spectrum of the iodine molecule.

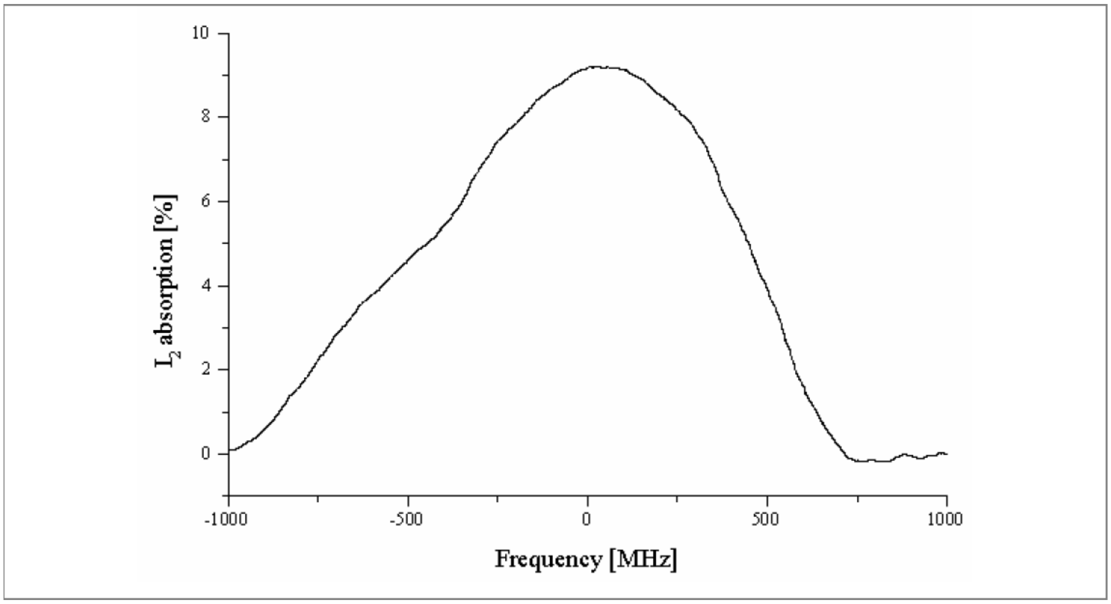


Fig 7. Courtesy Image of "Stabilizing a diode laser to an external reference, L.Willmann, 2003."

The absorption line is broad due to the Doppler effect, which is mainly due to thermal motion of molecules at room temperature. If the molecule is relatively stationary compared to the laser beam, the molecule will absorb the laser radiation at an exact resonance frequency ν_o. If a molecule has a relative movement from the laser beam, it can see either higher or lower frequency compared to the resonance frequency. The appearance of these frequency shifts is called the Doppler Effect. For a typical thermal velocity of 150m/s at 300K, the size of the Doppler shift is around $(0.5*10^{-6})* \nu_o$. [5]. As a result, molecules moving at different thermal speeds will absorb light over a range of frequencies and the absorption line as a function of laser frequency will have the shape shown in Fig 7.

Typical limits to cavity stability include vibration-induced cavity length fluctuations and thermal-mechanical noise of the passive cavity components[5]. By further system design, the relative noise impact can be reduced. To simplify selection of materials, two equations are used here to govern the basic design, from mechanical and thermal perspective respectively.

$$\Delta L / L = \alpha_L \Delta T$$

where $\Delta L / L$ is the fractional change of the cavity length, α_L is the thermal expansion coefficient of cavity material, and ΔT is the ambient temperature change.

System/material	Average α (°C^{-1} × 10^6)	Temperature range (°C)
β-Spodumene, $Li_2O \cdot Al_2O_3 \cdot 4SiO_2$	0.9	25–1000
β-Eucryptite, $Li_2O \cdot Al_2O_3 \cdot 2SiO_2$	−6.2	25–1000
Cordierite, $Mg_2Al_4Si_5O_{18}$	1.4	25–800
[NZP], $Ca_{3/4}Sr_{1/4}Zr_4P_6O_{24}$	0.6	25–1000
$NaZr_2P_3O_{12}$	−0.4	25–1000
Nb_2O_5	1.0	25–1000
Al_2TiO_5	1.4	25–800
$Zr_2P_2O_9$	0.4	25–600
Beryl, $Be_3Al_2Si_6O_{18}$	2.0	25–1000
SiO_2 glass	0.5	25–1000
SiO_2-TiO_2 glasses	0.05 to −0.03	25–800
Cu_2O-Al_2O_3-SiO_2 glasses	0.5	25–500
Zerodur	0.12	20–600
Invar	0.01	5–30
PMN, $Pb(Mg_{1/3}Nb_{2/3})O_3$	1.0	−100–100

Fig 8. Very Low Thermal Expansion Materials.[10]

And

$$\Delta L / L = 0.5 \rho L \alpha / E$$

where $\Delta L / L$ is the fractional change of the cavity length, ρ is the density of cavity material, E is the Young's Modulus and α is the perturbing acceleration.[6]

Since the fractional change of the cavity length is the main factor that contributes to the signal fluctuation, we need to minimize $\alpha_{L,}$ ρ and E when selecting cavity spacer materials. Listed below is a collection of materials for the cavity with their relevant paramters.

Material	Linear Coefficient(10^{-6}/^{o}C), $\alpha_{L, @20C}$	Young's Modulus(GPa)	Density(kg/m^3)
Aluminum	23	69	2700
Brass	19	100-125	8430-8730
Invar	1.2	137-145	8100
Steel	11	200	7850
Glass	8.5	50-90	2600

Table 1.

On one hand, in order to thermally improve cavity stability, we can both choose better materials with low thermal expansion coefficient and create a vacuum or mount an enclosure on top of the cavity to reduce ambient thermal fluctuation. On the other hand, we can pick up stiff materials with high Young's Modulus and we can also modify cavity mounting method to improve mechanical stability.

Materials such as Invar or ultra-low expansion glass are typically chosen. However, due to the limitation of availability in our lab, aluminum could used for testing the cavity. Aluminum is also a solid choice in consideration of its thermal expansion coefficients and Young's Modulus.

Another noted factor lies in equation 2 above, as the intention is to minimize $\Delta L / L$, the value of L is ieally desired, which is the cavity spacer length, to be kept as a minimum. However, as the cavity length continues to decrease, the free spectral range may become too large for measurement. Meanwhile, to maintain a reasonable resonance linewidth, there may be excessive power buildup to increase cavity finesse.

There are many different techniques used to make a reference cavity more stable, such as temperature stabilized enclosures, acoustic vibration isolation, vibration absorbing materials, etc. Some of these techniques can be very expensive and complicated to implement. Due to the limitation of project time, research has generally been focused on the mounting method of a cavity.

Fabry-Perot Cavity

The Fabry-Perot cavity was ultimately the type of cavity used to perform laser locking because it was provided by the sponsor. When properly aligned, the Fabry-Perot cavity functions as a resonator for any particular frequency of light. The exact alignment of the Fabry-Perot cavity, which is usually so sensitive as to require a piezo element to move it to a resonant position, determines the exact frequency at which the cavity responds. The following sections describe the behavior of the Fabry-Perot cavity and where resonance fringes can be expected.

General Description:

All Fabry-Perot cavities, at their most basic, consist of two highly reflective lenses which are planar on one side and convex on the other, and which are oriented so as to reflect each other's light. A longer description on the exact alignment of the mirrors is given below. (http://en.wikipedia.org/wiki/Optical_cavity) Most also include a stand on which the mirrors are mounted, and a coarse/fine adjustment to alter the distance between the mirrors. The fine adjustments are generally performed by a piezo element.

An example of a Fabry-Perot cavity is pictured below. The various components mentioned above are labeled below.

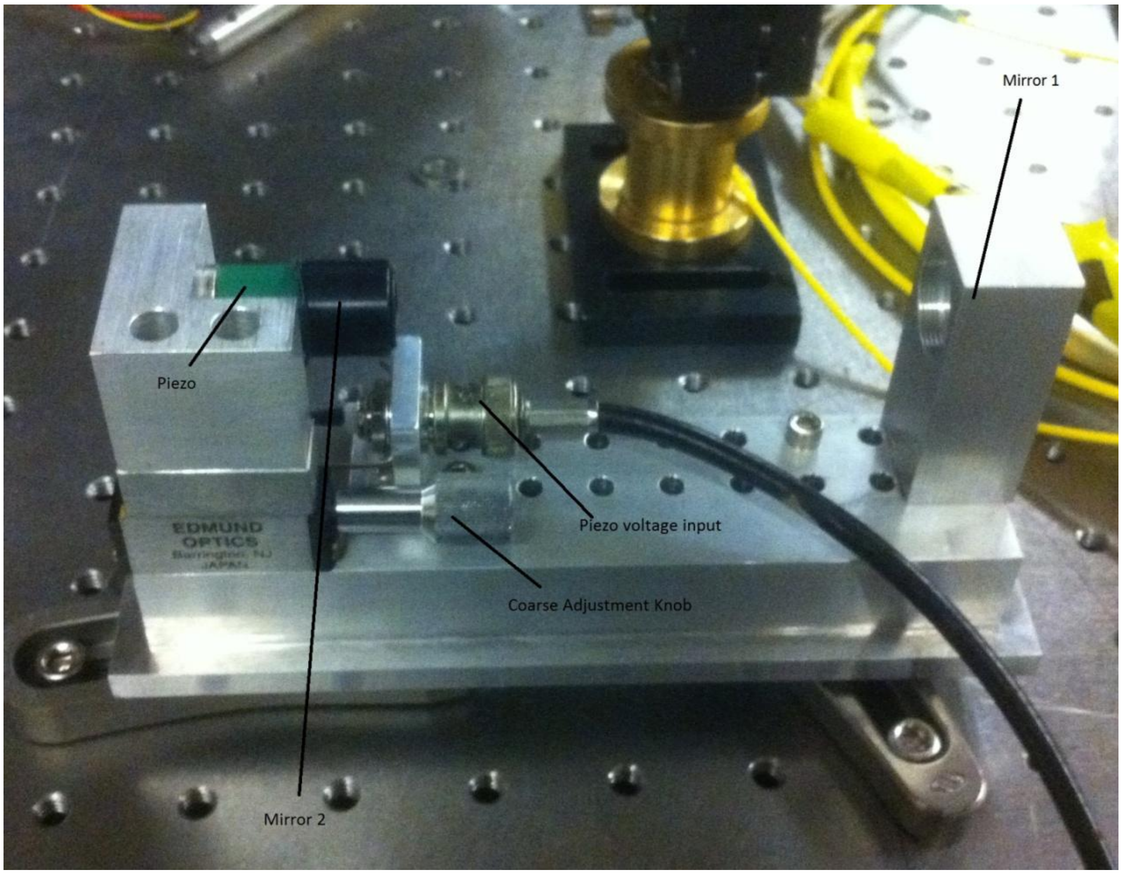


Fig 9: Fabry-Perot cavity

Resonance (Confocal Conditions):

The Fabry-Perot cavity is only able to act as a resonator when the lenses are in an approximately confocal configuration, and are trapping the light between themselves. A diagram of the confocal configuration is below.

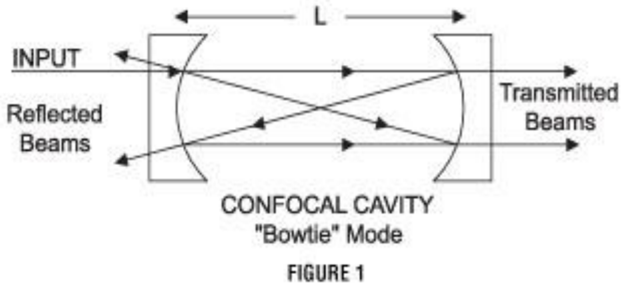


Fig 10: Diagram of confocal configuration.

Note the shape of both of the lenses; each is planar on the outside and convex on the inside. Here the quality of the mirrors determines the cavity's ability to trap light: If the lenses are more reflective they will block much of the light coming in but the light which does end up between the mirrors is trapped for, on average, a longer amount of time.

In order for the light to be trapped, the lenses must be in this confocal alignment however. The Figure above depicts the geometry of the confocal configuration. The radius of curvature of the inside edges of the convex mirrors must be equal to the distance between them.

Resonance in Confocal Configuration

When the cavity mirrors are in or close to a confocal configuration, laser light properly coupled into the cavity will constructively interfere with itself. The light inside the cavity can then only exist in a very discrete set of modes, and certain resonance properties described below such as linewidth, Free Spectral Range (FSR) and finesse, emerge from the properties of the cavity. Resonance only occurs for certain distances between the mirrors corresponding to the inputted laser's frequency, and are very intuitively equal to n/2 * (c/f) where n is a positive integer, c is the speed of light, and f is the frequency of the laser. The derivation of this property is the same as for any wave trapped between two points where it must be equal to zero, and boils down to the intervals at which a sine wave is zero on either end.

Voltage Adder Circuit

The voltage adder circuit is essential to locking the laser at a set frequency. The figure below shows the circuit diagram for the voltage adder:

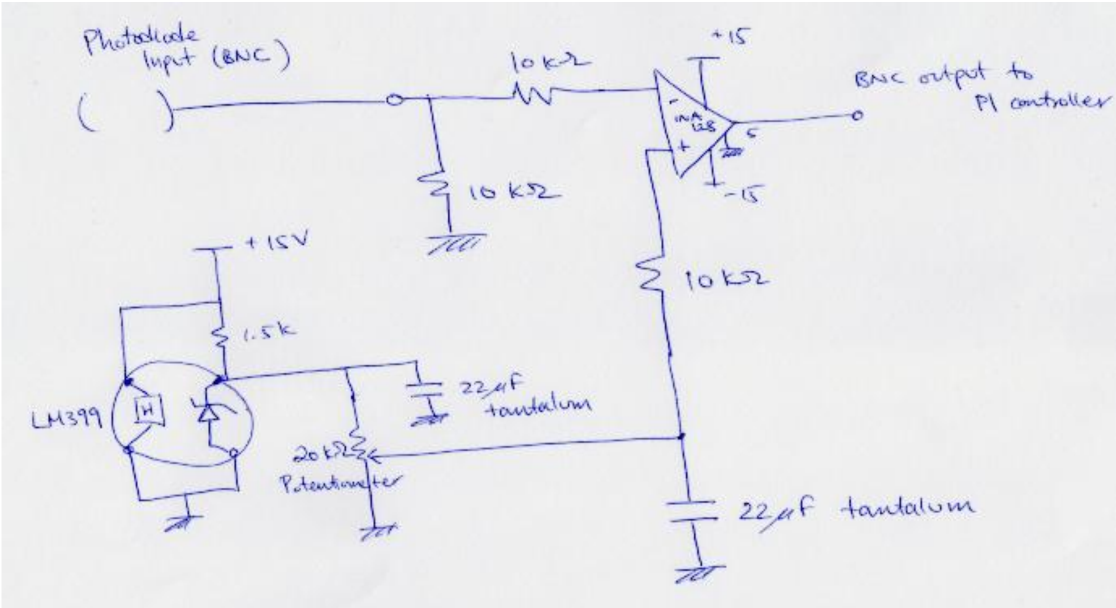


Fig 11: Circuit diagram of voltage adder circuit.

The function of this circuit is to take the voltage from the photodiode input, invert the signal, amplify it, and allows the zero point of the signal to be shifted as desired by the user. A plot of this circuit in operation is shown below.

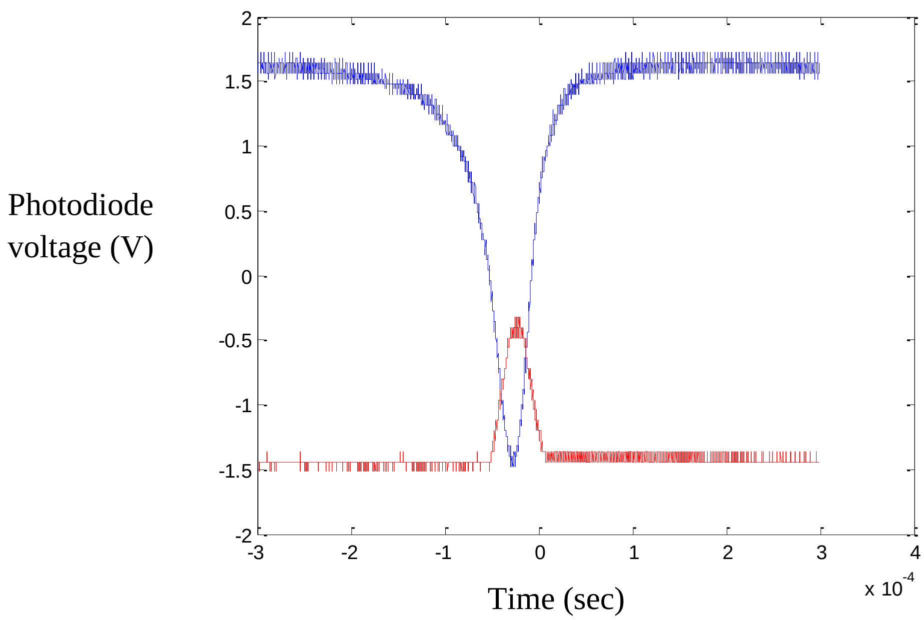


Fig 12: The red curve shows the input of the adder circuit while the blue curve is the output into the adder circuit.

The red curve is the signal from the photodiode, while the blue curve is the signal from the output of the voltage adder circuit.

PI Control

This section talks about the theory behind PID control, which is essential in locking a laser to a set frequency and to minimize the linewidth of said laser. The general theory behind PI theory will first be discussed, but the focus of this section will be on the theory behind the operation of the JILA PI controller provided to us by the sponsor.

Basic PI Theory

A measured output signal, such as an output voltage from a device, will deviate from its desired value (called the set point) over time. These deviations are caused by uncontrollable external factors such as noise or imperfections of the hardware used and cannot be eliminated. The purpose of a PID controller is to lock a signal at its set point by first taking in the measured output signal and generating an error signal (the difference between the measured output signal and the set point of the signal). It then produces a control signal which is a function of the error signal. This control signal, the output of the PID, is fed back to control the device generating the measured output signal [1].

. The general equation of a PID signal is:

$$u(t) = K\left(e(t) + \frac{1}{T_i}\int_0^t e(\tau)d\tau + T_d\,\frac{de(t)}{dt}\right)$$

where K is the proportional gain constant, e(t) is the error signal, T_i is the integration time, and T_d is the derivative time. The first term of the equation is from the proportional gain of the controller [1]. The second term is from the integral gain of the controller, and the third term is the derivative gain of the controller [1]. The proportional gain takes into account the error signal at the present time, while the integral gain takes into account the past values of the error signal, and the derivative gain takes into account the rate of change in error at the present time, which can also be interpreted as taking future values of error into account [1].

While the proportional gain is responsible for correcting the measured output signal so that it matches the set point for all time, using the proportional gain alone causes the output signal to drift to a steady state error value over a long period of time [1]. While increasing the proportional gain will decrease the value of the steady state error, it will also increase the oscillations of the signal about its steady state value. Implementing an integral gain control in parallel with proportional gain and adding the two gains will eliminate the steady state error [1]. The derivative gain simply decreases the oscillations of the measured output signal about its steady state value, and for our purposes, is not useful. Thus, our feedback control should only require a PI servo.

JILA PI Servo Description

Instead of fabricating a PCB for the PI controller, the JILA high speed loop filter PI controller was used (for an image of this controller, see Figure *n*). This PI controller is more complex in terms of its circuitry. In addition, it is different from the typical PI loop circuits in that instead of having one op-amp provide proportional gain in parallel with the second op-amp providing integral gain and having those two signals followed by a voltage summer, this PI loop has these gain stages in series.

The controller has several different gain settings: Acquire, Proportional, -6dB, -6dB+,or 9dB. When either the ‘Acquire’ or ‘Proportional’ mode is selected, the controller only provides proportional gain. The difference between the two modes is that ‘Proportional’ mode provides a gain of higher magnitude than the ‘Acquire’ mode. The -6dB mode provides a single integrator transfer function whose zero is set by the PI corner settings. The function of the PI corner will be elaborated below. This integrator function provides the integration gain desired in our PI controller. At the -6dB+ mode, the control signal generated by the JILA PI controller passes through an additional proportional gain stage before being outputted. The final mode available is the -9dB/CPU mode. This mode has an additional pole in the PI loop transfer function. Thus, when the controller is operating in the ‘-9dB/CPU’ mode, the transfer function of the PI controller looks like:

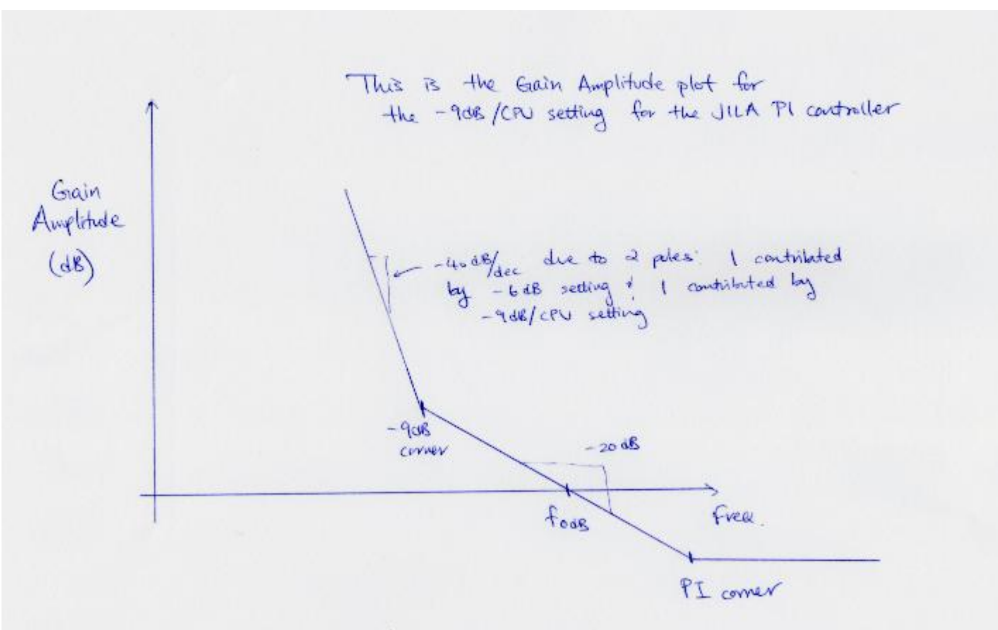


Fig 13: Transfer function of JILA PI controller in the ‘-9dB/CPU’ mode

In the -9dB/CPU mode, all of the zeros and the poles that the PI controller can provide are present. This is ultimately the mode the PI controller should operate when locking a laser to a cavity because this mode provides the tightest lock.

It can be seen from the graph above that the transfer function behaves like a low-pass filter. Note that the graph crosses the 0 dB mark at a certain frequency. This frequency is known as the phase margin. If the signal that is to be locked has a higher frequency than the phase margin of the PI controller and that signal is fed into the PI controller, the PI loop will cause that input signal to oscillate very rapidly about its desired value. This is because that the gain of the PI controller becomes negative, which means that instead of generating a control signal that corrects the error, the signal will now generate a control signal that magnifies the error. Some of the DC lock tests showed this phenomenon. The result is shown in figure n. in Section *n* of this report.

Thus, the bandwidth of the PI controller is limited by the PI value.

Locking the Laser to the Cavity

Lasers are locked in frequency to some absolute reference in order to ensure they do not drift away from their intended operating point during precise experiments. A laser will vary in frequency as its source heats up, oscillates due to mechanical vibrations, etc, and this is generally an undesirable behavior. Closed-loop feedback can be used to keep the laser's frequency close to some absolute reference frequency (or 'set point' in control theory terms); this is referred to as 'locking' a laser. There are many different methods of locking lasers to some set point, and the reference can vary from being an electronically generated frequency to another laser.

In this project, the 479 team was tasked with locking a laser to a Fabry-Perot cavity. Cavities are effectively a precisely determined length between two mirrors. The cavity's length is effectively the set point, as this determines the frequencies at which an inputted laser will resonate between the mirrors. The theory of which frequencies resonate for a Fabry-Perot cavity of given length are defined in the “Cavity Theory” section of this report. Ultimately, the important quality about the cavity is that its response, defined as the amount of transmitted light, resembles a Gaussian curve when the laser is near one of the resonant peaks, shown in the figure below.

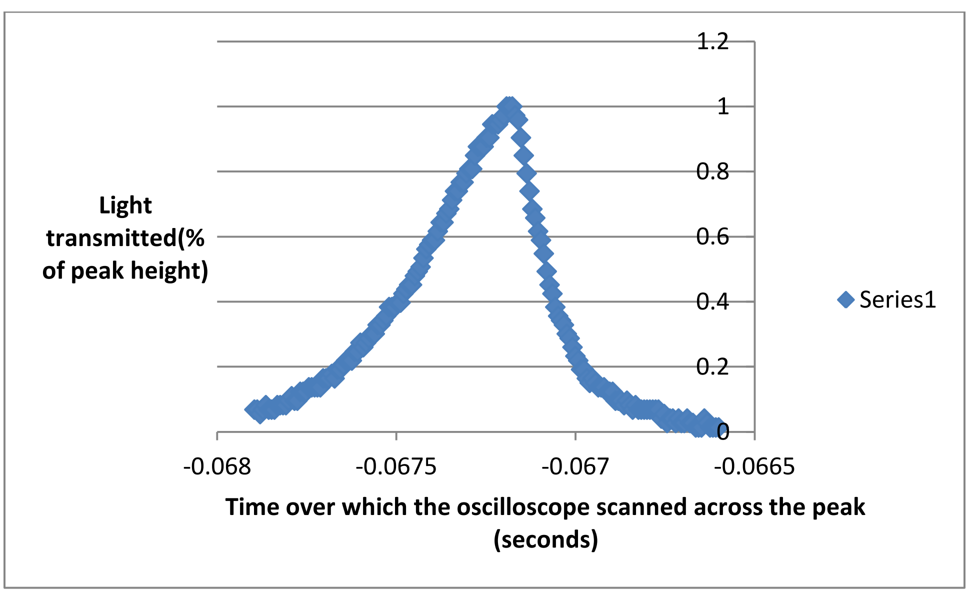


Fig 14: A example of a resonant peak.

This response allows closed-loop feedback to be performed on the laser when it is near one of these resonance peaks. In the case of the 479 project, a PI servo uses the transmitted signal through the Fabry-Perot cavity to perform closed-loop feedback by changing the way the Ti-Sapph laser.

Methods

This section of the report describes how the 479 group attempted to fulfill its objectives. The assembly of the Ti:Sapph laser is first detailed. Following that is a description of the beam path of the laser over the lab table in the sponsor's lab, including how the Ti:Sapph laser and the Rb-locked reference laser are coupled into the optical cavity. The method of locking the laser is next described. Then come descriptions of experiments to determine the cavity's drift and finesse. Lastly the report outlines a way to construct a more stable and accurate optical cavity.

Assembling the Ti:Sapph laser

The method used to assemble the Ti:Sapph laser was taken directly from "Operator's Manual: The Coherent 899-2 Titanium: Sapphire Ring Laser – Section I". Specifically, the procedure is illustrated in Chapter 6: Installation Alignment. The heading of the procedure used to get broadband lasing is <u>899-21 Titanium: Sapphire Installation Alignment Procedure – Low Power Pump</u> (from pg. 6-3 to 6-20). The heading of the procedure used in an attempt to get narrowband lasing is <u>Setting Up the 899-21 to Operate as a Scanning Single Frequency Laser</u> (from pg. 6-21 to 6-24).

Beam Path Of Ti:Sapph Laser Into Cavity and Photodiode Sensor

The Ti:Sapph laser was ultimately routed through a series of beam splitters and mirrors to reach the Fabry-Perot cavity, passing through the cavity and a focusing lens to reach the photodiode which measured the intensity of the transmission through the cavity. The older Ti:Sapph currently in use in the sponsor's lab was used in place of the newer Ti:Sapph assembled and aligned by the 479 group.

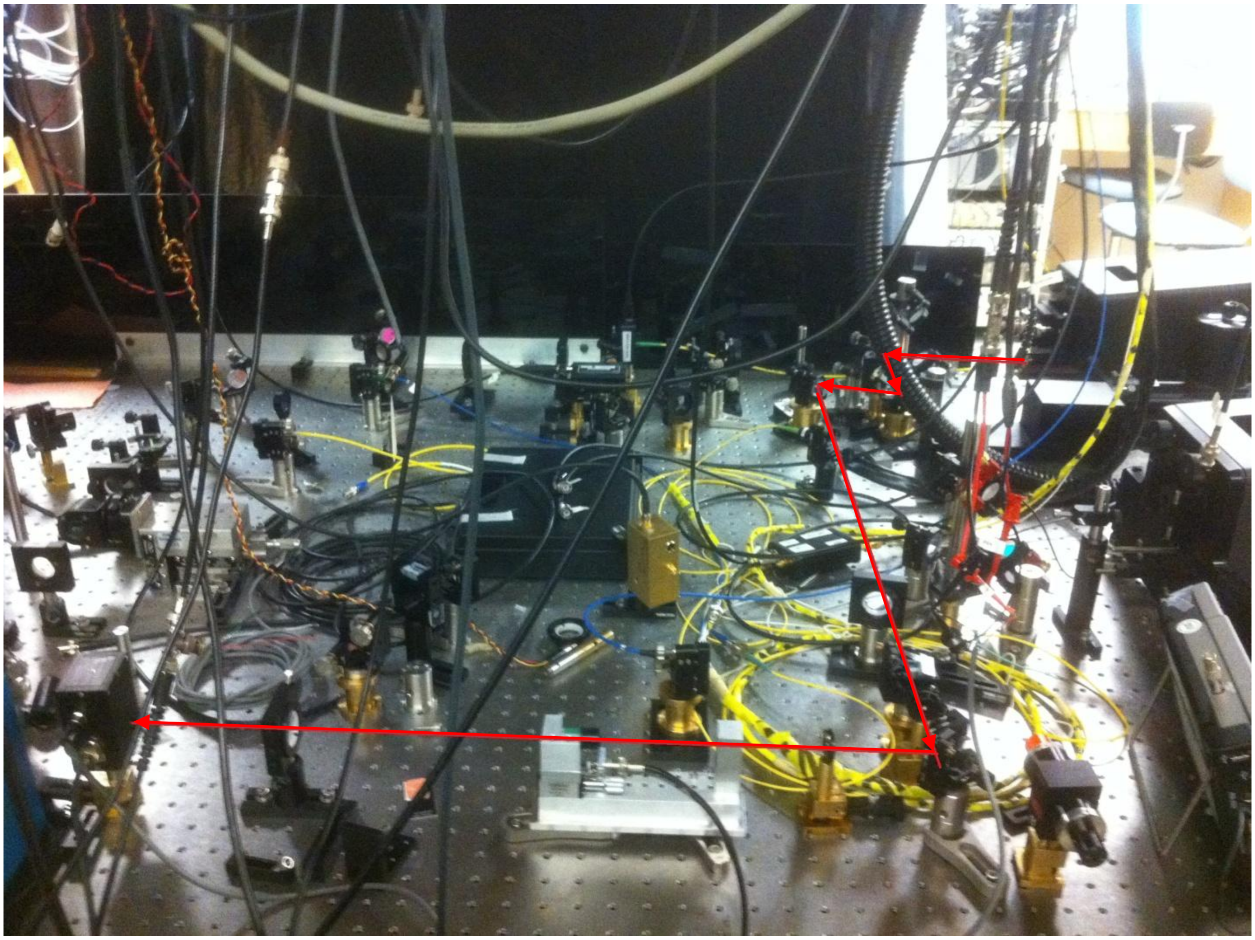


Fig 15: A picture of the beam path.

Since the older Ti:Sapph laser was in use for other experiments, a small fraction of its light had to be siphoned off using a half-wave plate and a beam splitter (shown in the figure below and in Figure n above as stage 'A'). The laser light was sent through a half-wave plate first and then into a beam splitter, so that a portion of the laser light would be reflected by the beam splitter instead of transmitted through it. The amount of light reflected by the splitter is controlled by changing the axis of the half-wave plate. In this way, the flow of light into the 479 set-up can be completely shut off if the other experiment can't be disturbed by it.

Fig 16: The beamsplitter setup that splits the light from the functioning Ti:Sapph.

The light was then aligned into the cavity using two mirrors. A figure showing the cavity is below.

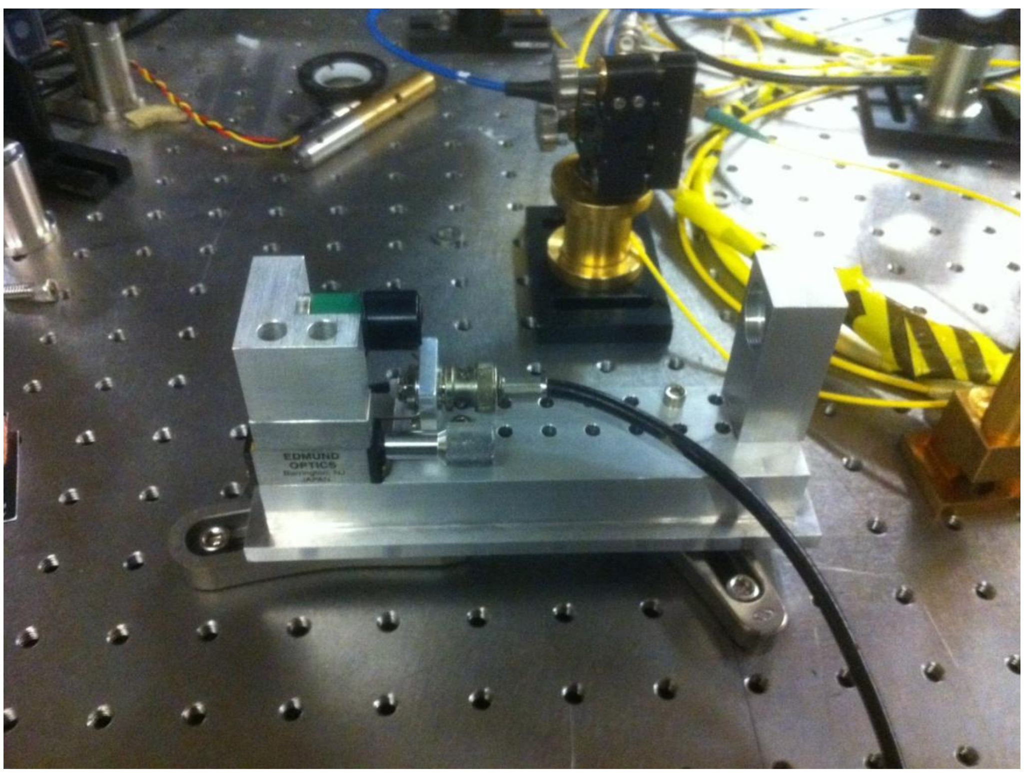


Fig 17: The external cavity used for locking.

Effectively, in order for the laser to be coupled into the cavity it is necessary for it to enter and leave the cavity normal to the surface of the mirrors, and roughly in the centre, and to then adjust the incoming laser's orientation to the cavity until resonance can be noted. The steps the 479 group took in doing so are listed below:

1. The laser was aligned by first taking measurements of the height and position of the cavity mirrors and roughly positioning the laser so that it passed through both mirrors roughly at the centre.

2. The Ti:Sapph laser was powerful enough that despite passing through two 99.15% reflective mirrors, a faint signal transmission could still be noted with an IR viewer. The 479 team placed a piece of paper in front of the mirror on the terminus side of the cavity and viewed the pattern the light formed on the paper. When the laser is closest to being properly aligned, the team noticed a dot typical to the profile of a laser beam. Non-aligned profiles generally resembled two or more dots with a series of elliptical lines of light connecting them, and the cavity was aligned by aligning the dots together.

3. The paper is now removed and the light is coupled into the photodiode, after being focused into a point by a lens to make it easier to direct the laser light into the photodiode. The photodiode output is then read by an oscilloscope while the cavity is scanned across a range of frequencies greater than the FSR of the cavity (the team generally used about 12 V triangular wave). While the cavity is moving closer to alignment, the oscilloscope shows resonance peaks of increasing height (See Figure below for an image of several resonance peaks (Ch. 1) due to a triangular voltage signal scanning the cavity via its piezo element (Ch. 2)).

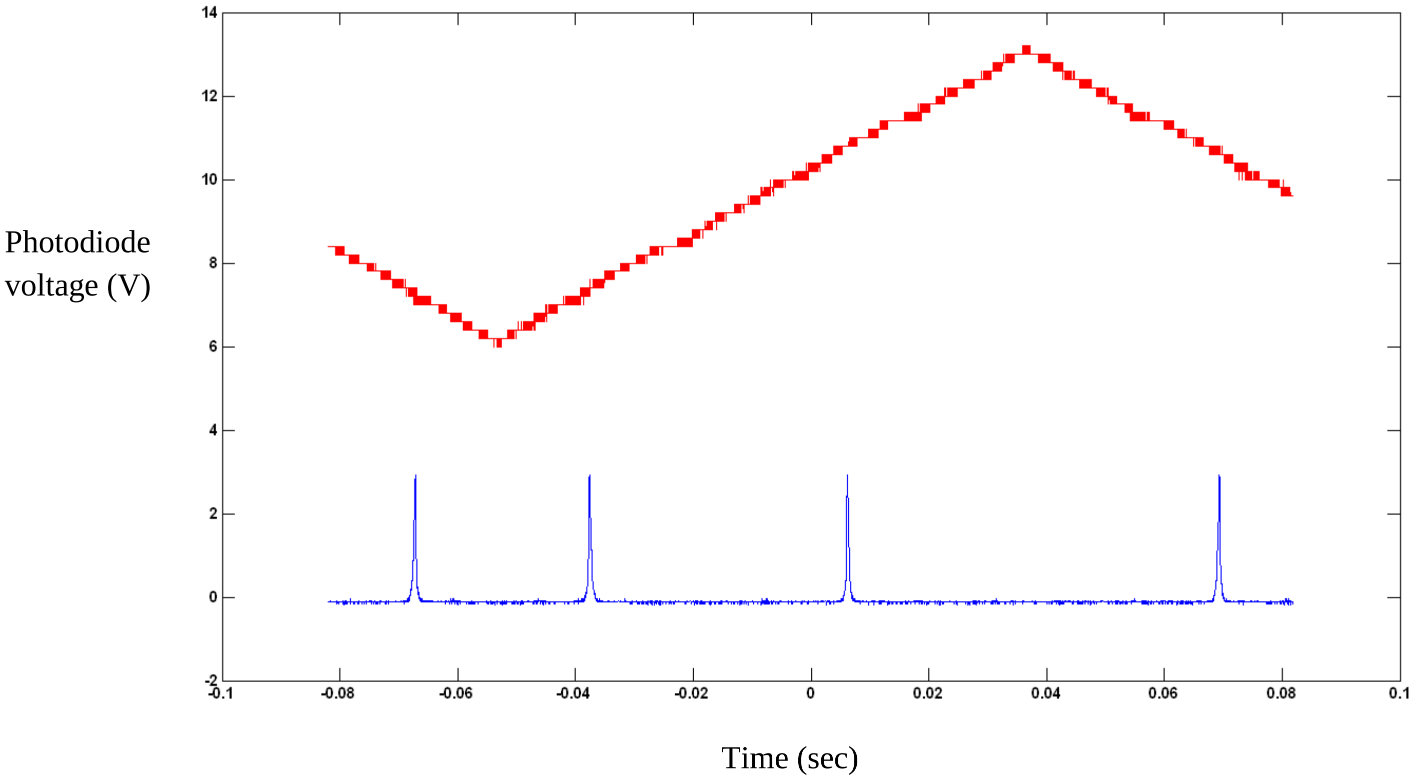


Fig 18: The red curve is the voltage input into the cavity, and the blue curve is the output of the photodiode.

<u>Coupling the Rb Laser Into the Cavity:</u>

In order to measure the drift of the cavity the rubidium-locked laser also had to be coupled into the cavity. This was performed using another beam splitter/half-wave plate combination. The half-wave plate was used to change the polarization of the Rb-locked laser so that as much as possible of the laser would be reflected by the beam splitter (the Ti:Sapph laser travelled through the beam splitter). Irises were used to mark the path of the Ti:Sapph laser in two places, and the Rb-locked laser was aligned through these irises in order to align it to the cavity.

Experimental Equipment

Shown in this section are pictures of all of the experimental apparatus that we used in order to complete our project. The captions below each picture provide a detailed description of each piece of equipment.

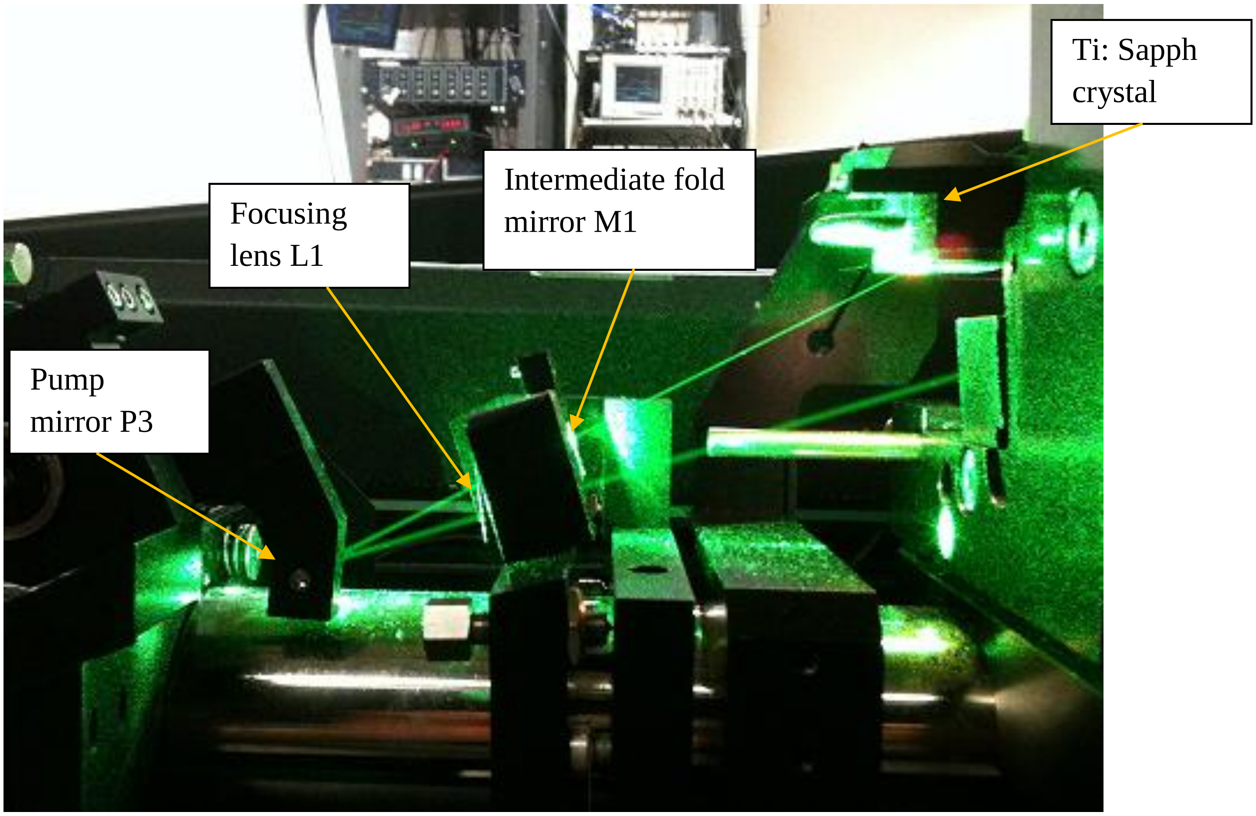


Fig 19: This figure shows a portion of the green pump laser beam path of the Ti: Sapph laser that we assembled. The laser is currently lasing at 1.8 W.

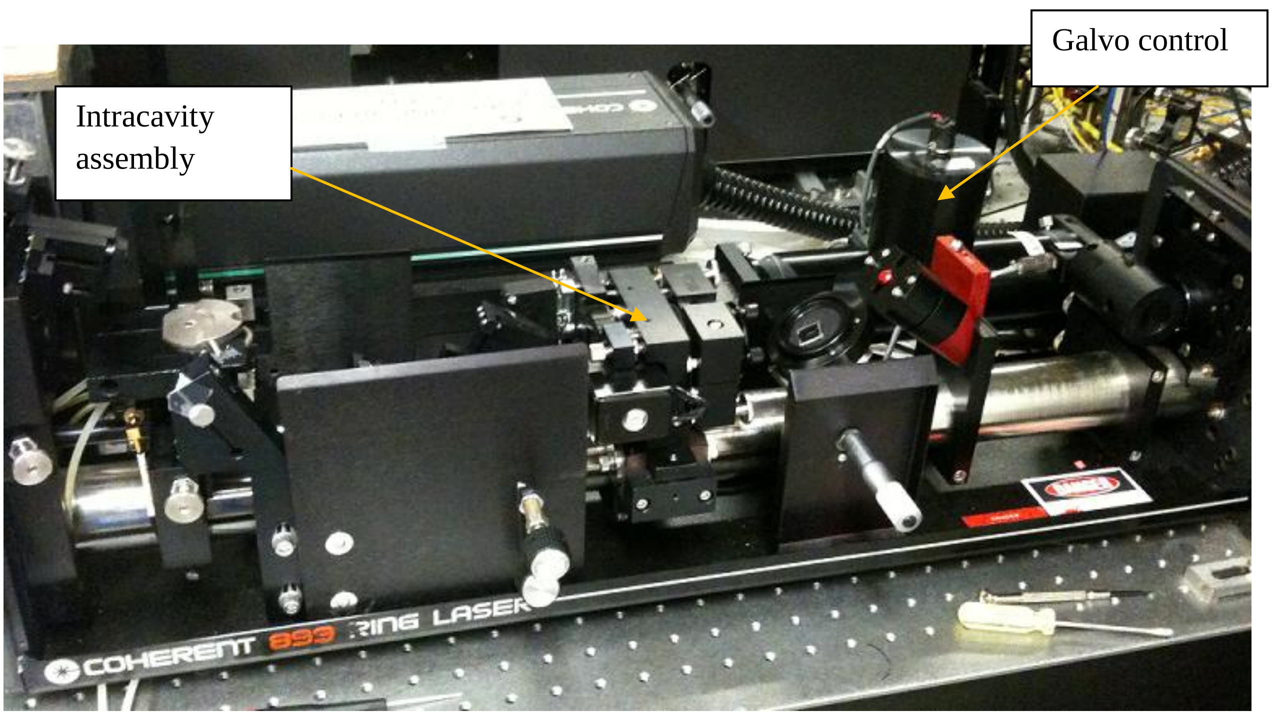


Fig 20: This figure shows the working Ti: Sapph (the one that is lasing narrowband). It can be seen that both the ICA and the galvo control is installed in this Ti: Sapph laser.

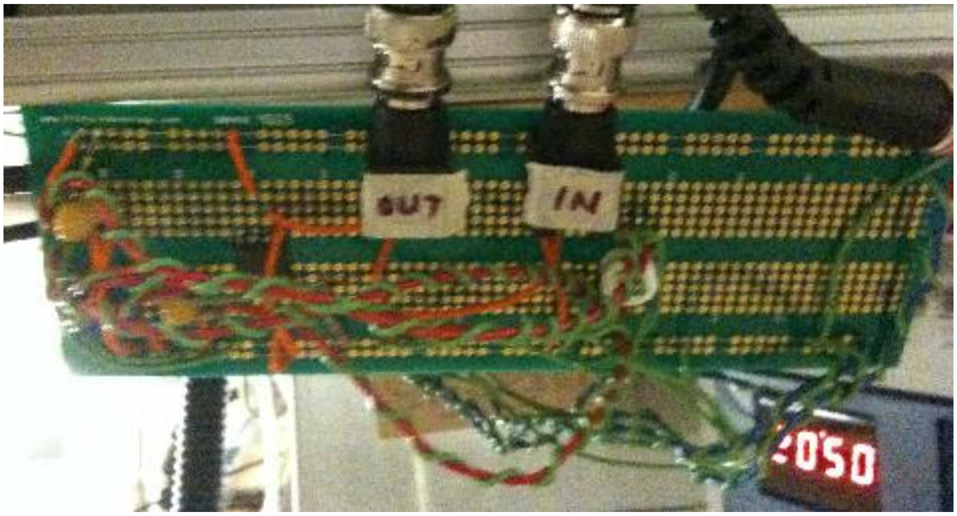


Fig 21: This figure shows the voltage adder that was synthesized by the 479 team. The BNC connection labeled "IN" is the photodiode signal input, and the BNC connection labeled "OUT" is the output of the voltage adder circuit which is fed into the JILA PI controller.

Fig 22: This figure shows a standard function generator. This function generator is used to control the piezoelectric element inside the cavity, thereby changing the length of the cavity. This function generator can also generate a sawtooth wave, which is used to sweep the cavity across different lengths in order to locate the length at which a resonant peak exists in the cavity.

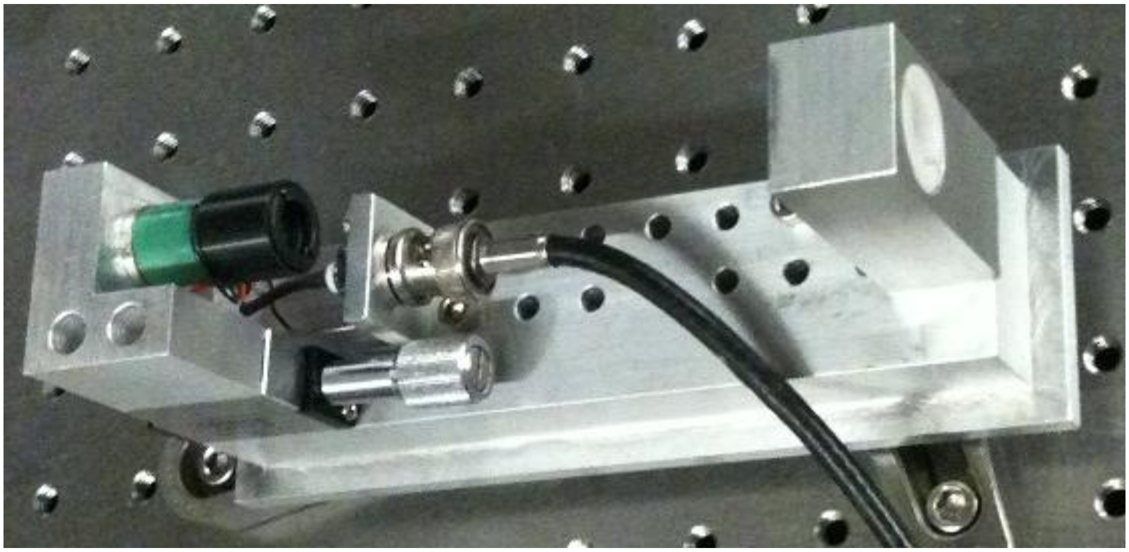


Fig 23: This figure shows the Fabry-Perot cavity that was provided to us. This is the cavity that the laser was being locked to.

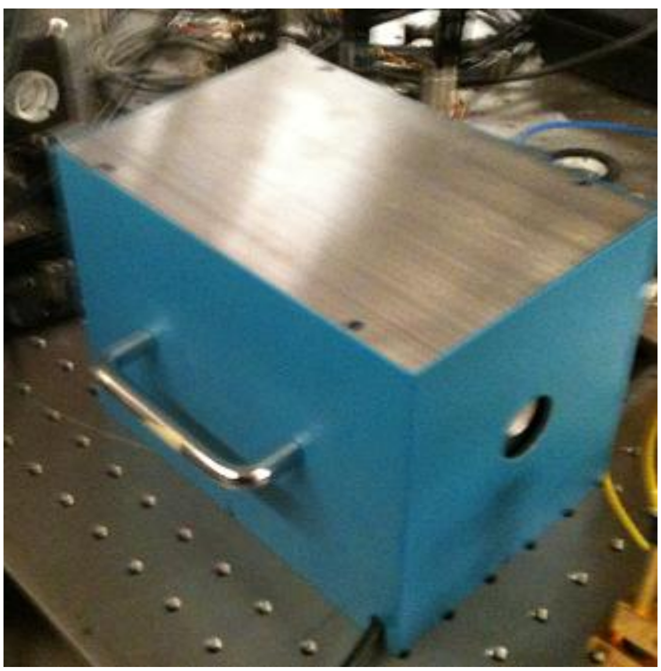


Fig 24: This figure shows the thermal enclosure that was made and used to decrease the effect of temperature fluctuations.

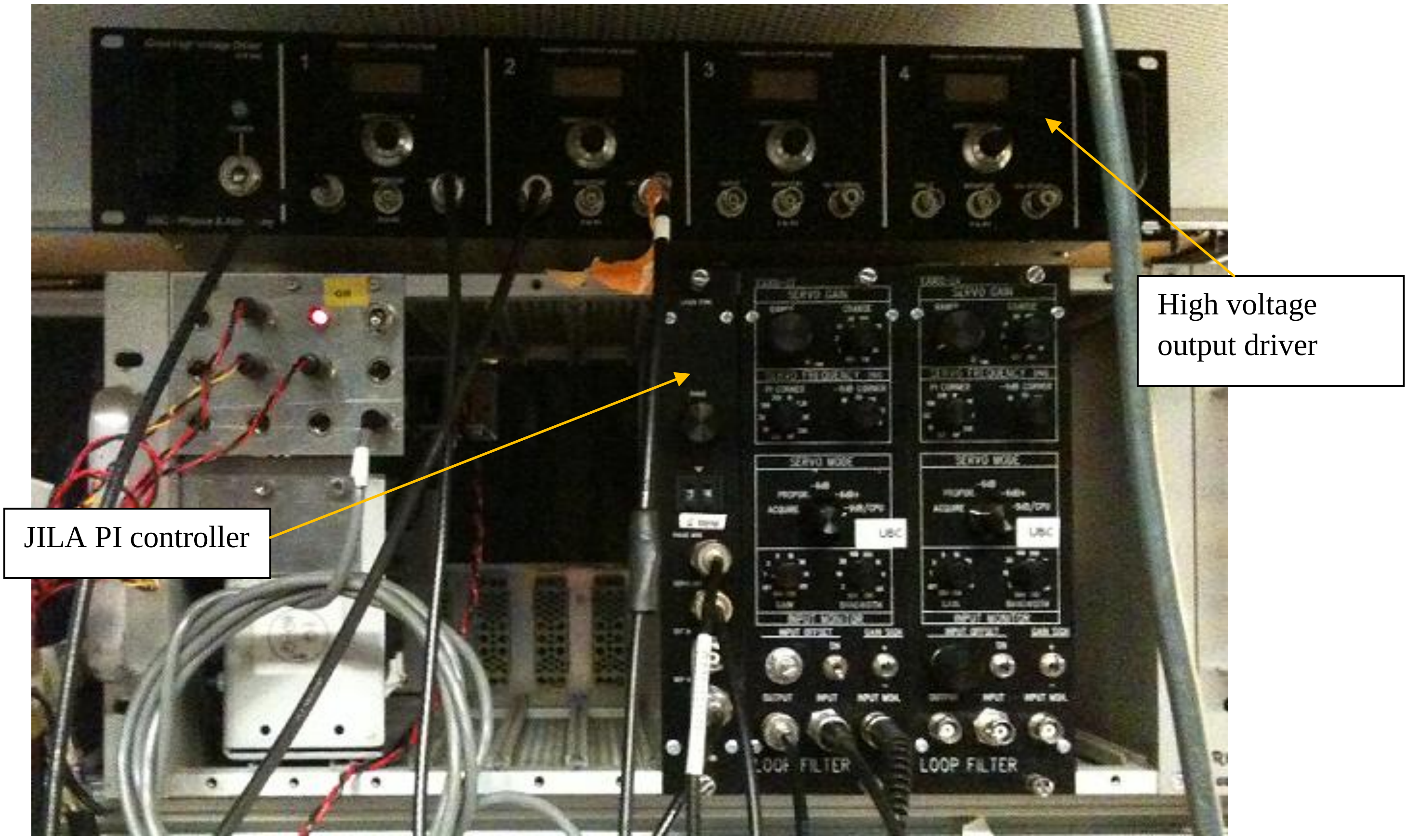


Fig 25: This figure shows the JILA PI controller that is connected to the laser and is responsible for providing the signal that controls the piezoelectric transducer in the tweeter mirror. This figure also shows the high voltage output driver.

Fig 26: This figure shows a clearer picture of the front panel of the JILA PI controller. Here the knobs are used to change the values of the various parameters. What these parameters mean are discussed in detail in the "Theory" section.

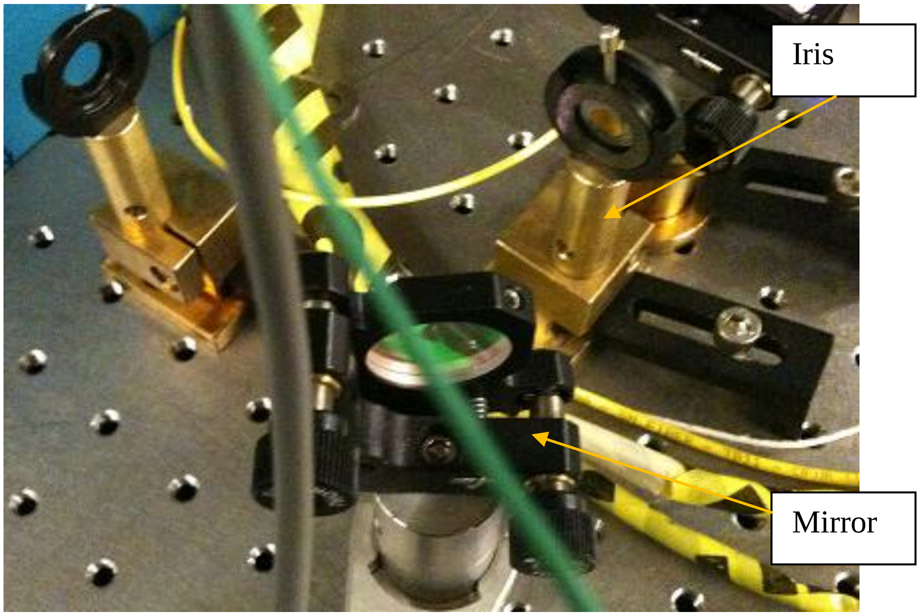


Fig 27: This figure shows two optical components that we used to control the beam path, the mirror and the iris. The mirror redirects the beam, while the iris ensures that the beam is not tilted.

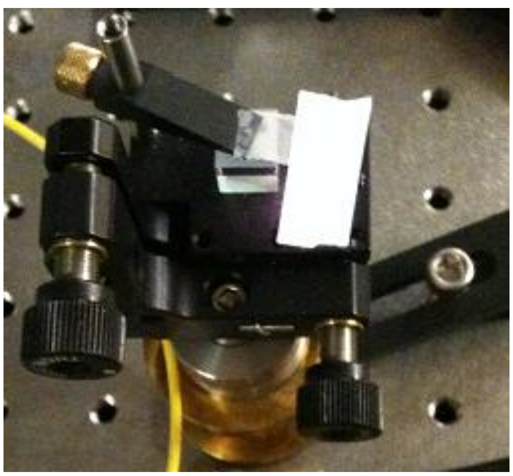


Fig 28: This figure shows the beamsplitter, a device that splits the beam into two beams that travel perpendicular to each other.

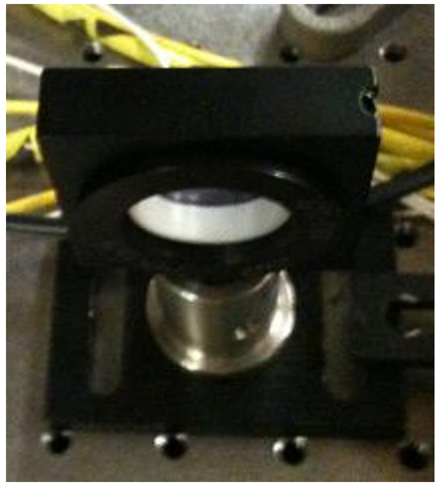


Fig 29: This figure shows the half-wave attenuator. This device controls the intensity of the beam exiting it, and thus, is used to attenuate the beam.

Fig 30: This figure shows the photodiode, a device that converts the intensity of the laser beam into a voltage value.

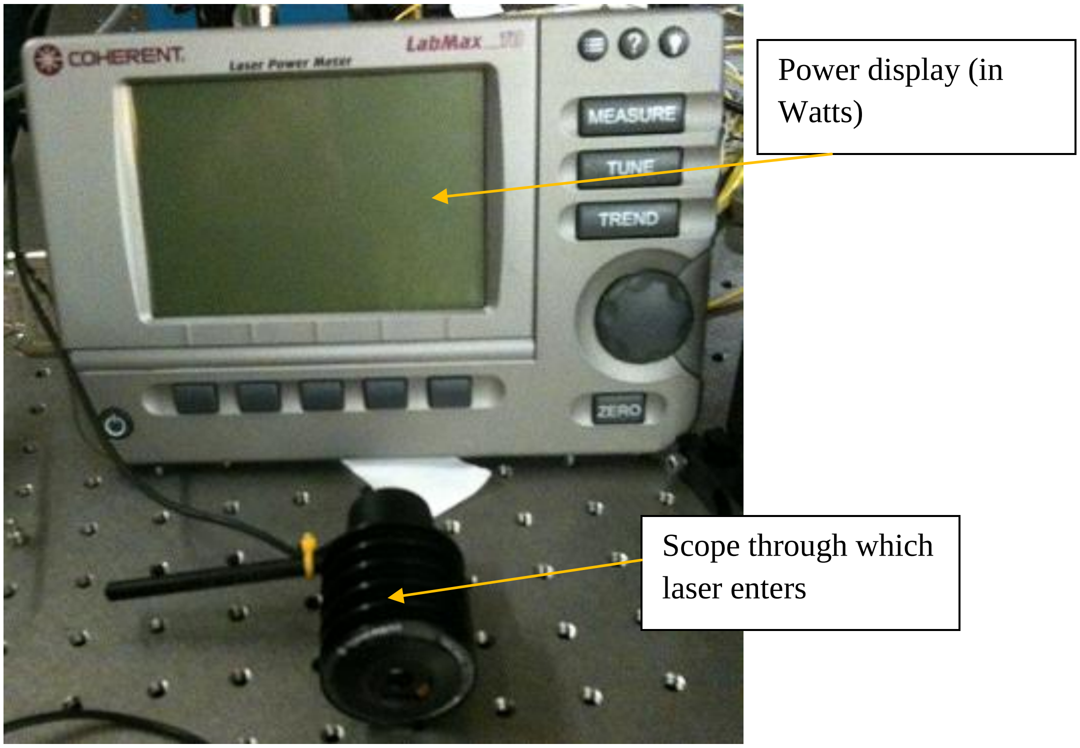
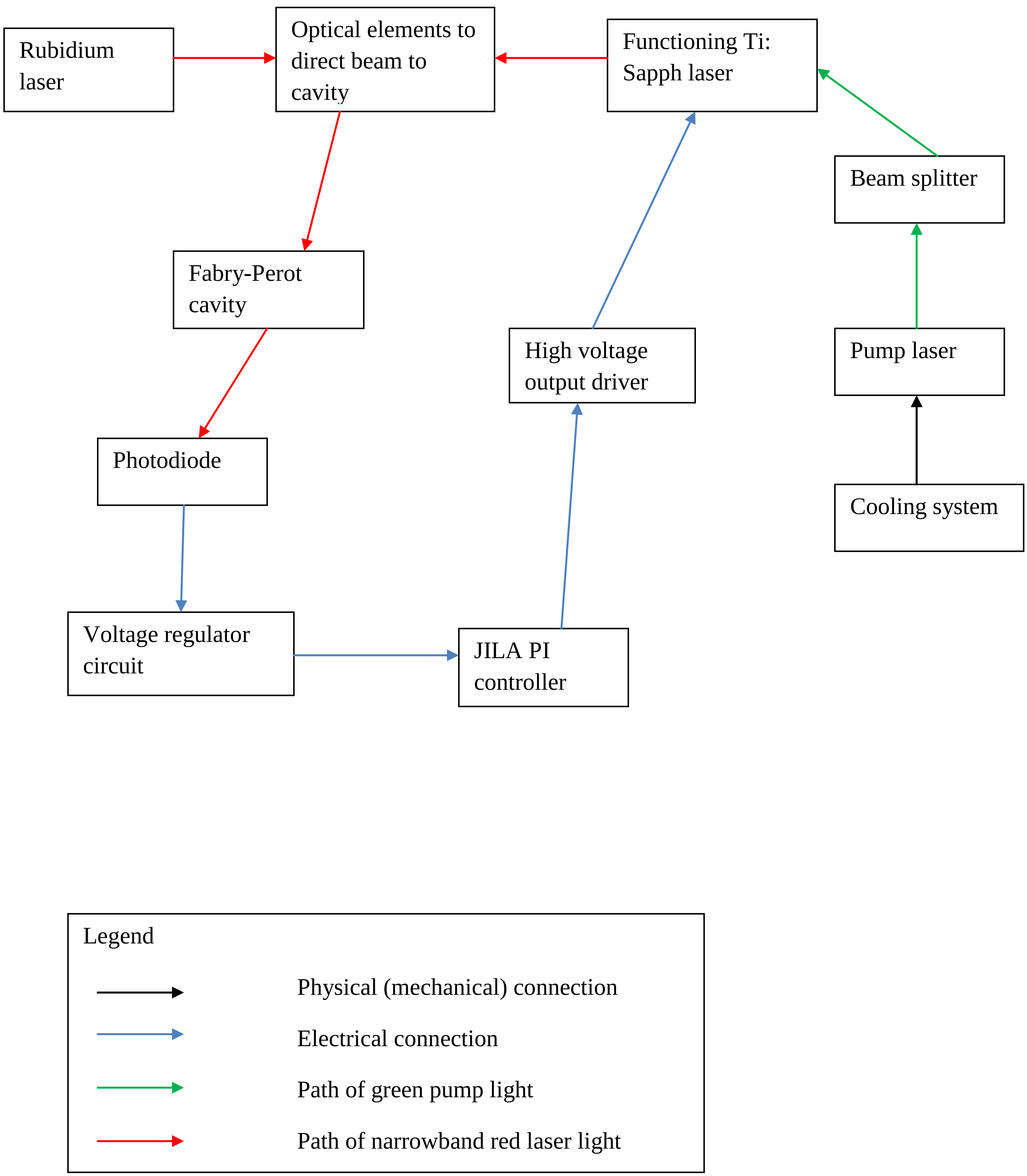


Fig 31: This is the power meter that is used to measure the output power of the broadband lasing Ti: Sapph laser that the group assembled.

Flow Diagram



Laser Locking

Since the Ti: Sapph laser that the 479 group assembled did not lase broadband, the functioning narrowband Ti: Sapph sitting next to the broadband Ti: Sapph was used instead to lock to the cavity.

The transmitted light can be monitored using a photodiode, which produces a voltage proportional to the amount of light. This voltage is then inputted into an adder circuit which offsets the voltage by some constant value, making some point approximately midway between the floor and peak of the cavity the 0-point. When this voltage is inputted to a servo, the servo will tend the laser's frequency toward this 0-point provided by the adder. The servo's output is sent to a high-voltage driver to amplify and offset the input voltage. The high-voltage driver's output is sent into a piezo element inside the laser, referred to as a 'tweeter' mirror, which alters the length of the cavity used to produce the laser. This has the effect of changing the laser's frequency and completes the circuit. Shown in the figure below is the tweeter mirror:

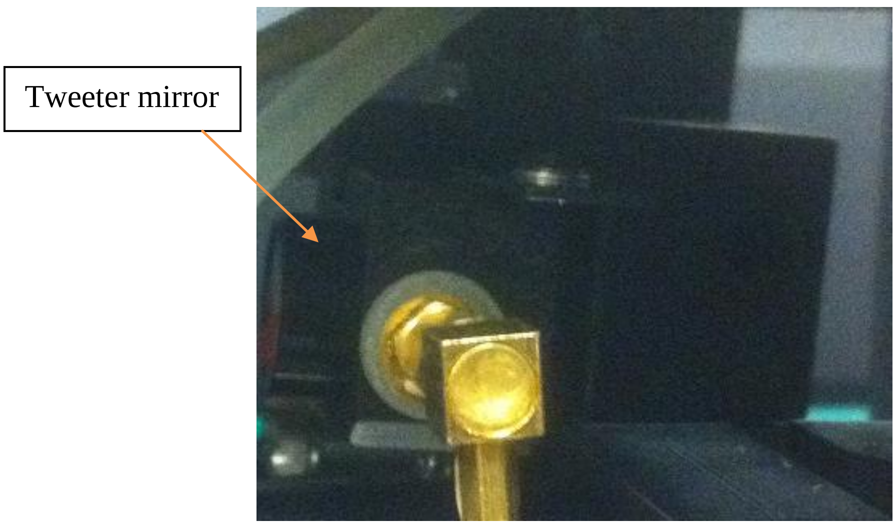


Fig 32: This figure shows the tweeter mirror.

The 479 group used two methods to try to achieve a lock. The first involved biasing the cavity with a DC voltage such that the cavity was evidently at or near one of its resonance peaks, which could be observed by looking for high-voltage noise as if the laser was repeatedly crossing back and forth over a portion of the resonance peak due to thermal noise. The group would then adjust the PI servo to counter the drift for as long as possible, maximizing the amount of time the laser was resonating. This 'DC lock' illustrates the PI servo's ability to counteract long-term cavity drift. The second was to scan the cavity over a broad enough frequency that the laser would cross onto a resonance fringe regardless of the drift and lock the laser for a short time as it did so. This 'scan lock' method proved that in concept the laser could be locked if the cavity could be made stable enough around that lock point.

DC Lock

The 479 group would try to create a DC lock by doing the following:

1. Change the cavity's DC bias until it is near a fringe. When the cavity is near a fringe, the photodiode will begin seeing rapid, high-amplitude noise as the noise in the system causes the laser to oscillate back and forth over the cavity in a chaotic fashion.
2. Now that the cavity is near a fringe, it is theoretically possible for the PI servo to lock the laser. The 479 group now tries to adjust the PI servo to counter the drift and cavity noise by changing the gain and PI frequency corners.

Scan Lock

The other method was:

1. Send a voltage into the cavity's piezo element so that the cavity scans back and forth over several resonance peaks.
2. The PI servo is adjusted to keep the laser at the set point as long as it can before the scan pulls the cavity out of the laser's range.
3. The voltage signal entering the cavity could then be decreased in amplitude, in effect 'zooming in' on the region in which the servo could keep the laser locked until the cavity was effectively being supplied a DC voltage and the photodiode was outputting an effectively constant signal.

Characterization of Cavity

Finesse, Linewidth and FSR:

The characteristics of the cavity most pertinent to locking it is the finesse, as described in Section *n*. To find an estimate of the FSR and linewidth in order to find the finesse, the team did the following:

1. The light coming into the cavity from the Ti:Sapph laser was blocked so that only the Rb-locked laser light was resonating.
2. The cavity's piezo element was driven with a 12 V triangular wave, so that the cavity's length oscillated back and forth in a linear fashion.
3. An oscilloscope trace of that measurement is shown in the Figure above.
4. Measure the FSR and linewidth (see Section *n*). Find the finesse by dividing the distance between two of the resonance peaks by the FWHM. When finding the FSR, take care to select peaks that are in the same scan; it's a meaningless quantity otherwise. Figure *n* below illustrates the problem.

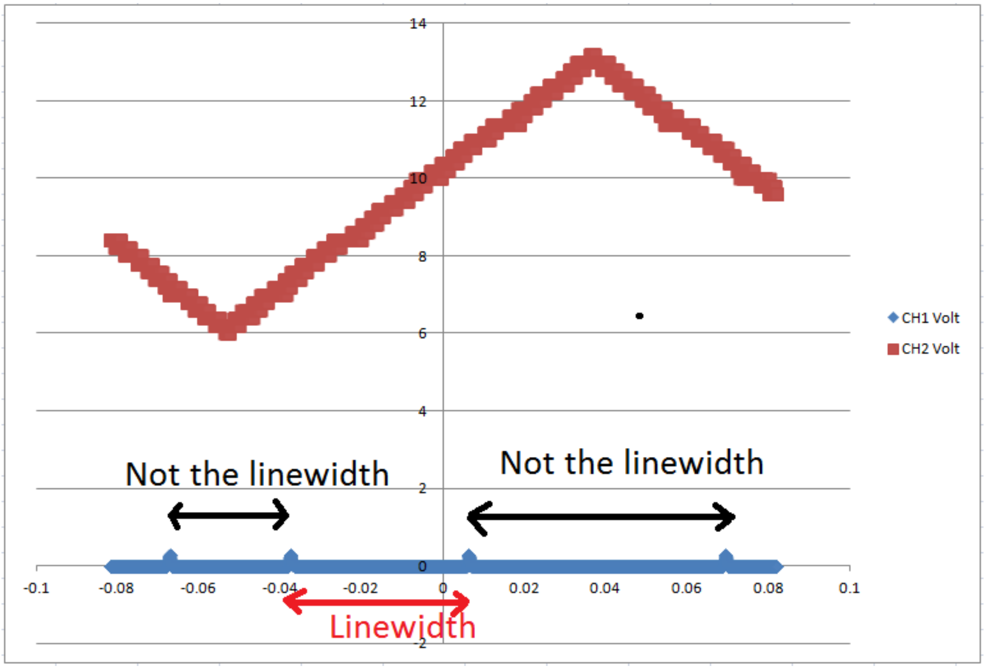


Fig. 33

Note that this method of scanning the cavity to find the finesse only provided the finesse and not the linewidth or FSR. When obtaining these quantities by scanning the cavity with some triangular voltage signal as in Figure *n*, it would be necessary to know the characteristics of the piezo element's expansion (microns/volt) as well as the exact frequency of the voltage signal. Otherwise the measurements provided by the oscilloscope have as much to do with the rate at which the cavity is being scanned as they do to the linewidth of the cavity. Since the 479 team never found adequate documentation for the cavity and do not know the piezo element's expansion rate, there is no easy way to know what that rate of expansion is. However, since the FSR was estimated by scanning the Rb-lock laser in Section *n*, the linewidth can be estimated as well.

Characterizing the Cavity Drift

It was found during locking attempts that the system appeared to drift too significantly for the laser to become locked. Since both the Rb laser and the Ti:Sapph laser were coupled into the cavity, the drift of both the Ti:Sapph and the cavity could be characterized by scanning the cavity and measuring how the resonance peaks of the Ti:Sapph and Rb laser drifted over time

<u>Alternative Methods</u>

Alternative methods were not considered because Dr. Madison, the project sponsor, was very specific on how he wanted the lock to be achieved with the apparatus provided. However, alternatives for the PI controller and the cavity used in the lock were considered.

An alternative to the JILA PI controller that was ultimately used was a PCB designed by Todd Meyrath from the University of Texas at Austin. Shown below is the figure of the PCB. This PCB is quite versatile in that only certain portions of the PCB need to be populated in order to create a PI controller. However, this alternative was ultimately not pursued because of time constraints and lack of resources. This PCB required surface mounted components, which neither the Engineering Physics project lab nor Dr. Madison's lab had on hand. Ordering those parts would have taken weeks, and so it was decided to stick with the JILA PI controller as initially planned.

An alternative to the cavity that is currently being used was designed by our group. Ultimately, this design was not used due to time constraints. The sponsor initially stated that he was going to either purchase a high-performance cavity or provide a frequency comb for us. However, when both of those options fell through in mid-November, he suggested that we design a new cavity whilst trying to lock the laser with the one provided. However, at that point, the design was complete at the end of November.

The design of the cavity and the calculated parameters are located in the "Recommendations" section of the report, while the CAD files that show the cavity are located in the "Appendices" section.

Cavity Design

A vertical mounting of cavity at a single central plane has some unique advantages over the conventional horizontal cavity. In the vertical cavity design, a cylinder with mirrors mounted within it is supported at the horizontal geometrical midplane with a simple cylindrically symmetric geometry. In the vertical mounting, the gravity-induced sag of the structure is along the laser beam path so that the cavity spatial mode position stays the same on the mirrors' surfaces with acceleration. In addition, vibration induced distortion results in near-zero net change in the distance between two mirrors. Horizontal geometrical midplane is defined herein as a plane perpendicular to the cavity axis, which is vertical in this design[8].

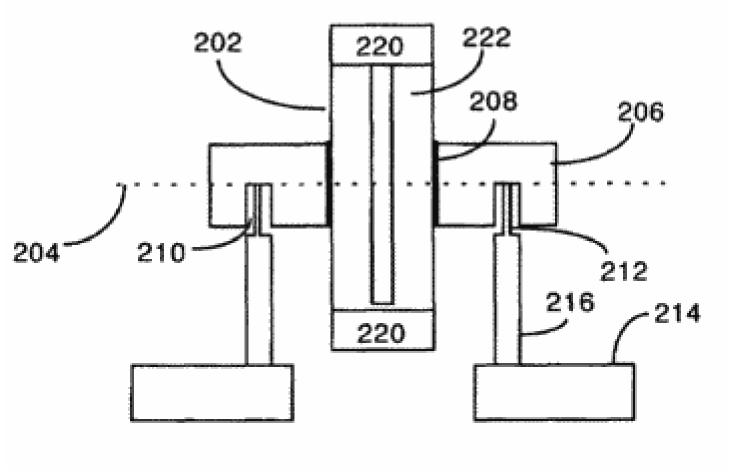


Fig .34 Courtesy Image of “Mounting System for Optical Frequency Reference Cavities”

To realize a maximum degree of symmetry, the portion above the geometrical midplane should be equivalent to the portion below it so that masses are equivalent for two portions. The cylinder is suspended at this plane by a disk using RTV Silicone Bond to hold in place. The disk shall also be made of low thermal expansion material which is heat-treated and annealed. A Solidworks model is generated based on this vertical design idea, as shown in Appendix A. In this implementation, the cavity cylinder is suspended at its horizontal geometric plane from outside. The cylinder is threaded from inside so as to fit mirrors in. The distance from both mirrors to the horizontal geometrical plane should be equal to each other. The cavity cylinder needs to be made short and light here in order to improve stability in the central mounting mechanism. Low densities should also be a factor of considerations when selecting cavity materials. The disk, which surrounds the spacer cylinder and supports it, has a central axial bore and four other partial bores at its lower flat surface for support points. Besides, to balance the weight above and below the disk, four additional holes are counter bored into the top surface of the disk. The counter bores should be made to avoid collisions with the bottom bores.[7]

The design for an embodiment is demonstrated in the solidworks model. There can also be other embodiment in an effort to realize the maximum symmetry.

In an alternative embodiment design, the cylindrical cavity spacer can be made extra thick so that holes can be drilled longitudinally from the end-faces. These holes stop at a depth near the midplane, so that the supporting rods from below will provide the support again in the midplane, effectively preserving the upper/lower symmetry. Dummy holes are also desired for weight balance purposes.[7]

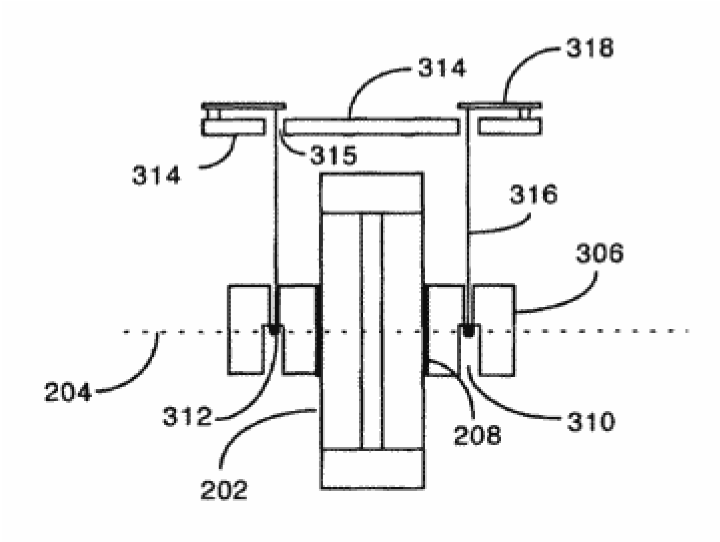


Fig .35 Courtesy Image of "Mounting System for Optical Frequency Reference Cavities"

The cavity can also be hanged at its symmetry plane from above using a wire instead of being supported by rods from below, as illustrated above. The weight-bearing points will be located essentially in the midplane of the cavity vertical length. Additional isolation elements are also desired, such as leaf springs, will serve as a low pass filter for mechanical vibrations.[7]

Once the disk has been properly located, it is held in place using RTV Silicone Bond, which has a very low Young's Modulus so that the spacer cylinder is gently and uniformly supported. The mounting base and the support arms should preferably be made of low thermal expansion materials as well.

A schematic of the vertical cavity mounting is shown below in side-view.

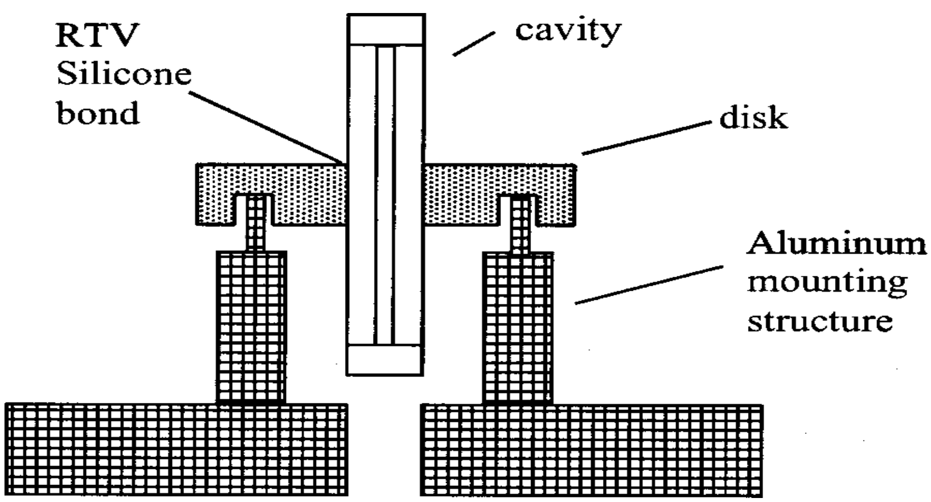


Fig. 36 Courtesy Image of "Simple and compact 1Hz Laser system via an improved mounting configuration of a reference cavity"

As mentioned before, two aluminum bars of the existing cavity are mounted onto a horizontal beam independently. Different oscillations of two aluminum bars lead to the unstable cavity length change. We tried to place a horizontal tube between two aluminum bars and mechanically clamp two bars to hold the cavity length stable. Meanwhile, we also placed an insulated enclosure around the cavity to provide passive temperature isolation from the environment.[6]

Results

Assembled titanium: sapphire laser

The titanium: sapphire laser that was assembled by the group successfully lased broadband with a peak power of 1.8 W. However, the power of the laser fluctuates greatly between uses. The power of the output laser was often between 1.3 – 1.6 W. It never dropped lower than 1 W. The resonant peaks generated by the cavity from the broadband light were not recorded because the resonant peaks were not distinctly visible due to the large bandwidth of the laser light.

Instead, shown below is a picture of the titanium: sapphire we assembled when it is turned on and lasing broadband.

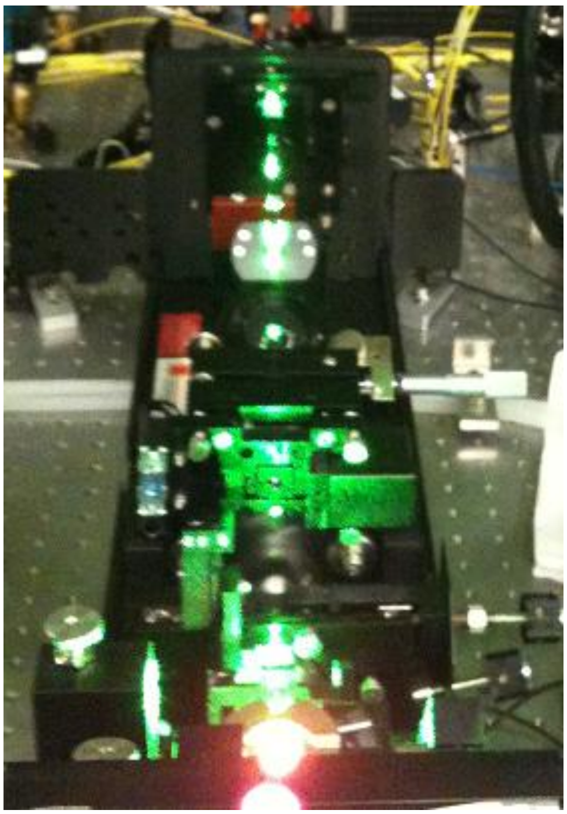


Fig 37: This figure shows the broadband titanium: sapphire laser that was assembled by the 479 group.

The laser does not lase narrowband. The reasons for this are further elaborated upon in the "Discussion of Results" section.

Cavity Characterization

The cavity's finesse was found via the method in (section num. here).

Cavity linewidth in s: The figure above (*Figure Reference here)* shows the cavity's resonance response (Ch. 1) while it is being scanned across frequency (driving voltage for the cavity scan is on Ch. 2). It is zoomed in on one of the resonance peaks, in the Figure below:

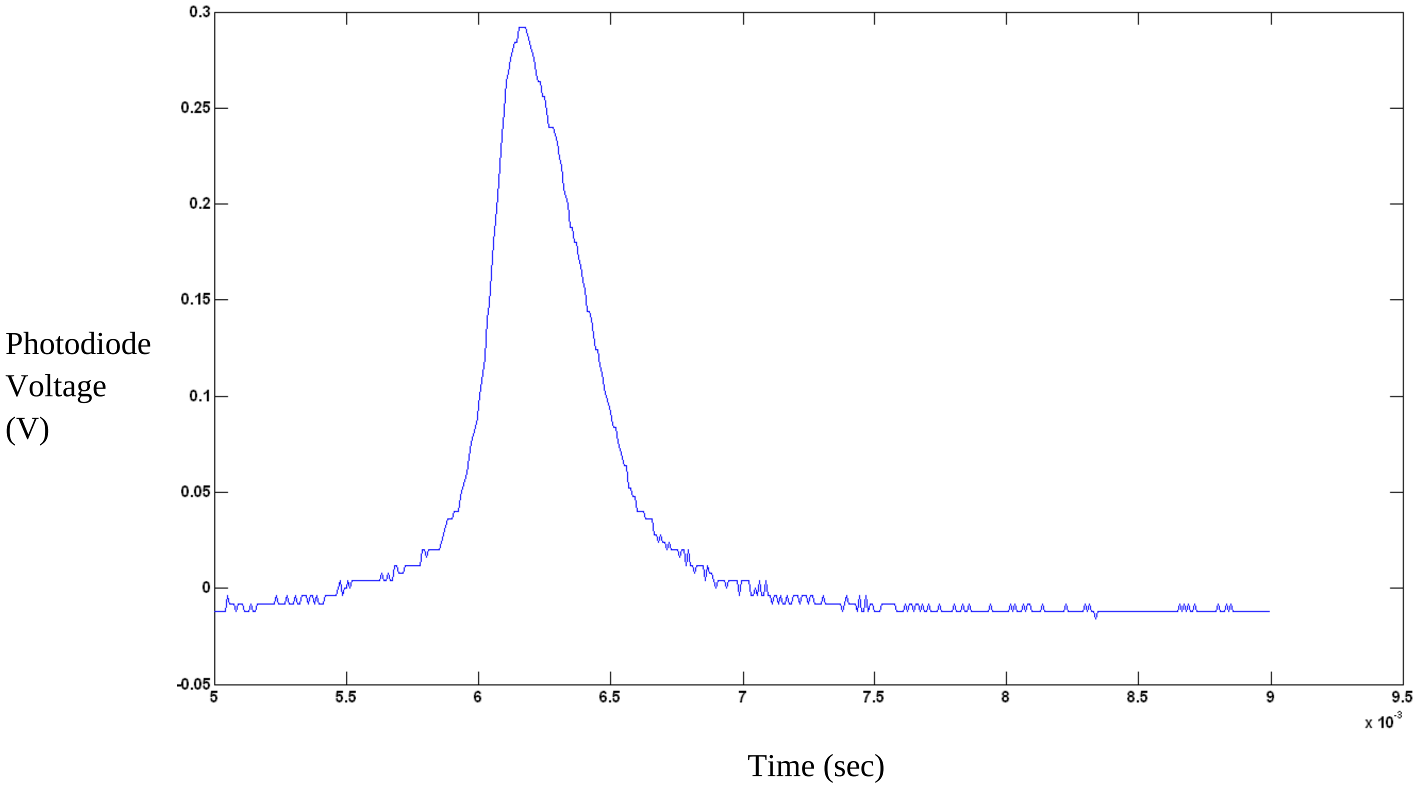


Fig. 38

Cavity FSR: The figure below shows the cavity's response over a larger range, large enough to see the FSR of the cavity. The FSR is the distance in frequency between each resonance peak, so it can be found by measuring the distance between two resonance peaks on the same scan. The FSR is depicted in the Figure below:

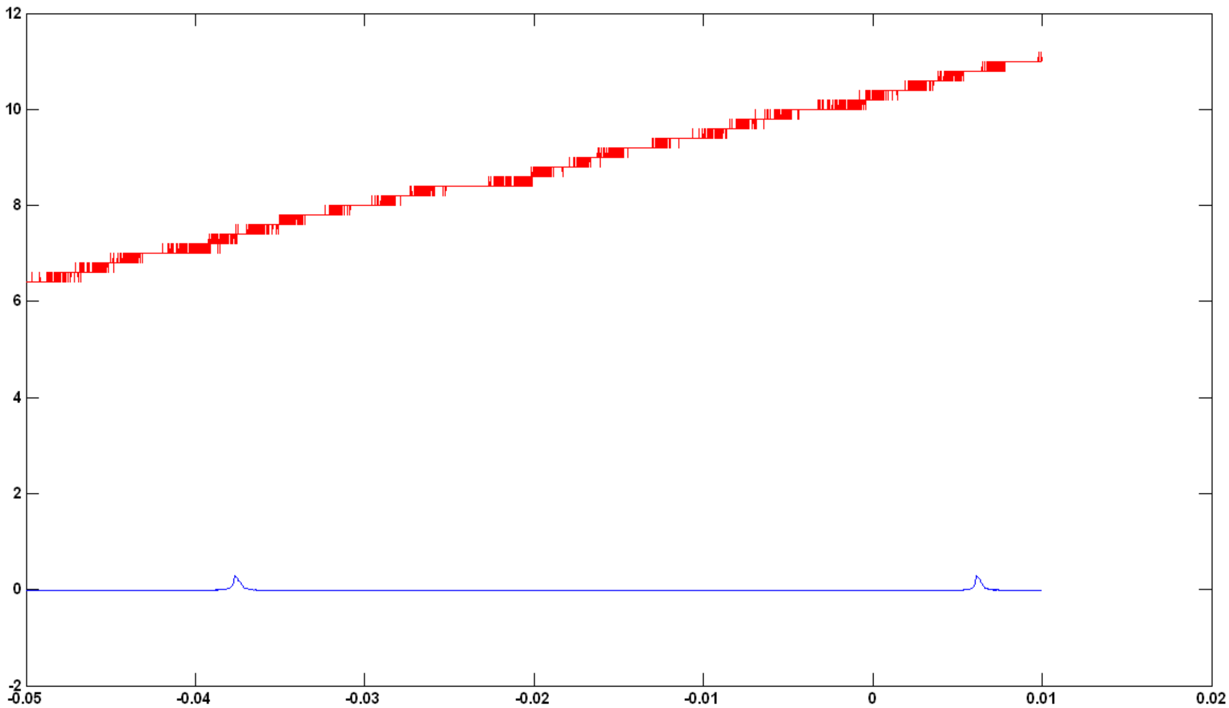


Fig. 39

The finesse was found to be equal to 120.

Note that the 479 team does not have sufficient information about the cavity it was using to compute the linewidth or FSR absolutely. If it were to absolutely derive those quantities using the data above, this would require knowing the rate of expansion (microns/volt) of the piezo element which is driving the cavity. There was no documentation for the cavity used by the 479 group, so there is no straightforward way to derive the piezo element's characteristics.

The 479 team was able to use a different method to estimate the absolute FSR and linewidth quantities, by scanning the Rb-locked laser instead of the cavity. The graduate students familiar with the Rb-locked laser were able to provide an estimate of its scan range: ~ 3 GHz. In this measurement, the finesse was found to be the same value as in the other measurement. The FSR was estimated to be about 1.5 GHz, which would make the linewidth about 75 MHz. Note that this values are probably only correct to about an order of magnitude: Nobody using the Rb-locked laser was able to provide documentation as to its scan range, and were at best able to estimate it to one significant figure. The results of this experiment are only included to provide a rough estimate of the cavity's linewidth and FSR.

Cavity Drift Characterization

The cavity drift was also measured. The team recorded several waveforms of the driving triangular wave and the Rb-locked/Ti:Sapph lasers' peaks over the course of 12 or so minutes, so that the drift over time of the Ti:Sapph laser and cavity can be viewed. A plot of the resonance voltage of the Rb-locked laser, as a function of time, is below.

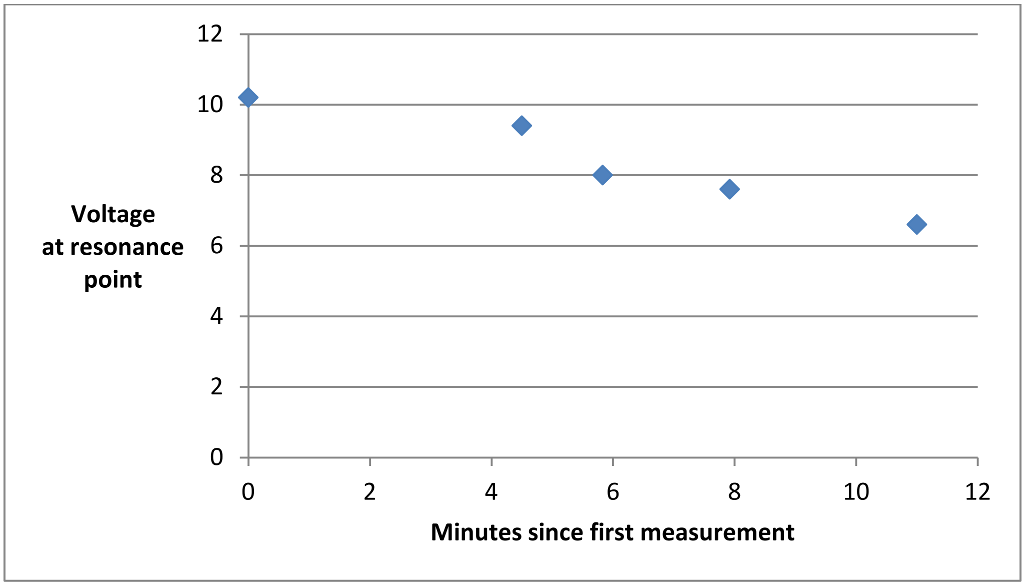


Fig. 40

This suggests the cavity is systematically drifting in one direction relative to the Rb-locked laser's position, since it can be assumed that the Rb-locked laser is relatively stationary.

The 479 group's ability to lock to a cavity depends on that cavity's stability, which is discussed in Section *n*. The 479 group determined that the cavity drifted in one direction, effectively forever as the behavior could be noted even after the cavity had been aligned for hours (See Section *n*). It is hypothesized (see Section *n*) that this is due to the spring inside the set screw used to coarsely adjust the cavity distance. Since the set screw does not have a latch or locking mechanism to hold it in place, it is plausible that the set screw is being slowly pushed by the spring in one direction, forever. This would explain the never-ending drift observed by the 479 students when using the cavity. This stuff in red should be moved once we merge the document. The cavity's drift made it impossible to ever fully lock the cavity. If the cavity was locked for even a matter of minutes, the drift would require the servo to have a range of voltage outputs a few orders of magnitude larger than the gain required to keep the laser steady. It would have at the very least required a slow integral gain from a PI servo in parallel to the proportional gain, which (see Section *n*) was not something the given PI servo could be easily adjusted to do easily.

Regardless of the group's inability to create a full cavity lock, the PI servo was able to keep the laser locked on a frequency for a small amount of time while the cavity was being scanned. This is later referred to as a 'scan lock'. One issue was that the cavity length would drift and eventually the cavity would no longer scan across any resonant peaks, forcing the team to manually readjust the voltage input to the cavity every 2-3 minutes at most. This always happened eventually, regardless of the amplitude of the voltage signal driving the cavity. This meant that the team was unable to effectively 'zoom in' on the location of the lock and ultimately led to the failure of reaching a full cavity lock with this method. The Figure below is a graph of one of the scan locks the team achieved.

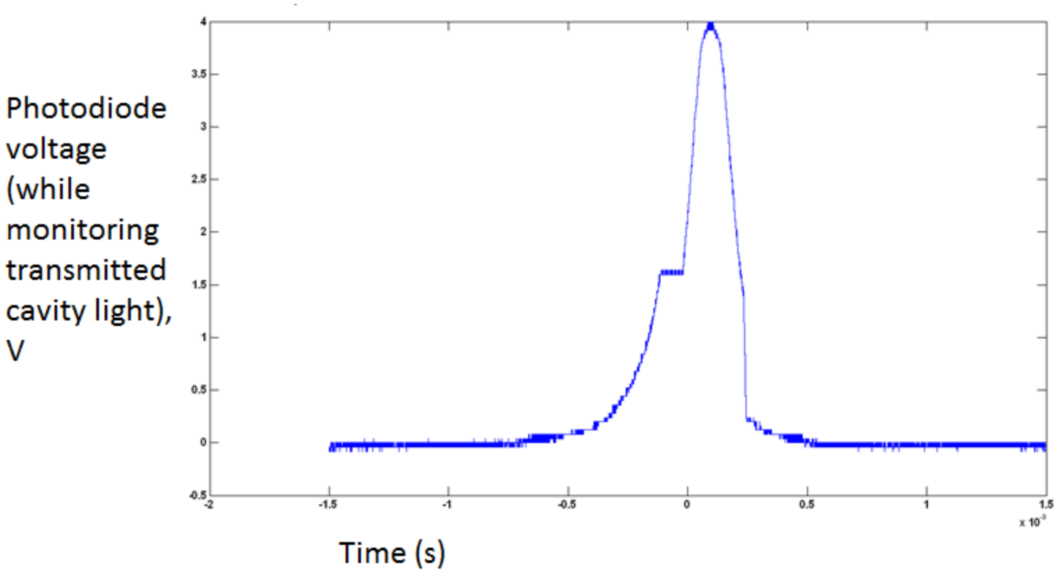


Fig. 41

The Figure below shows the same data, but zoomed in to the cavity lock location:

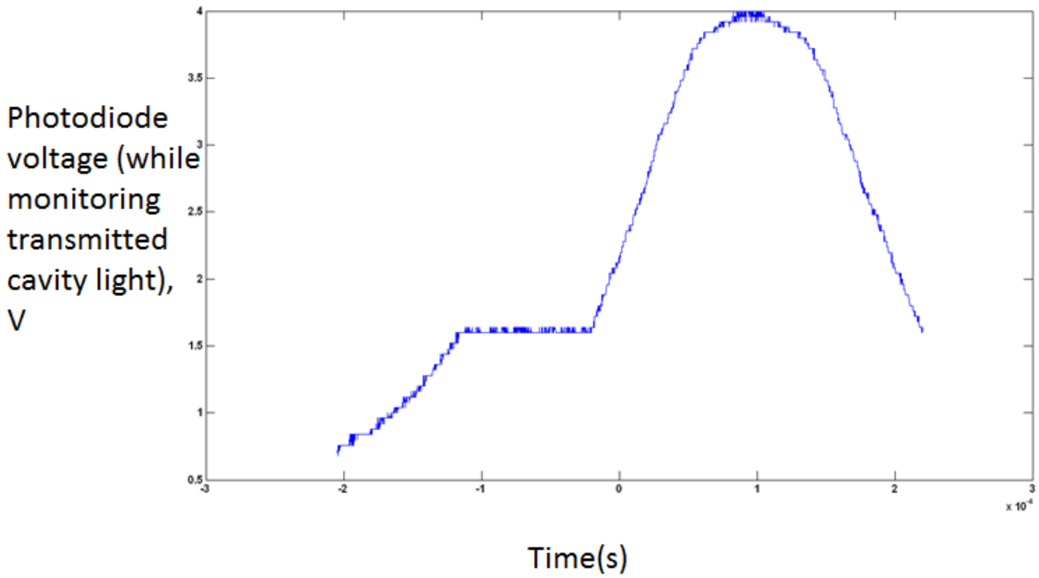


Fig. 42

Stabilized Cavity Design

Although a SolidWorks design of a new and improved cavity was completed, it was not approved by the sponsor. Therefore it was never built or characterized. The 479 team cannot offer any information as to the effectiveness of a prototype of this cavity.

After the cavity failed to be approved, the attention was turned to improving the stability of the current cavity. Before the implementation, a Fabry-Perot cavity in the optical lab was used for evaluating the effects of cavity length on the resonance peak drifting. When a tentative length of 30cm is set up for the cavity, the drifting range of resonance peaks is calculated to be 20nm(See Appendix ??), which is considered to be within the tolerance limit. The 479 group has two conclusions regarding improving the stability of the Fabry-Perot cavity assigned to them by the sponsor:

- The cavity drifts significantly, possibly because the spring-loaded adjustable mirror cannot be secured in place. As a result it is very plausible that the spring is slowly pushing the mirror out of alignment.

- It was noted while working with the cavity that air currents passing between the mirrors could introduce noise. The team tested this qualitatively by measuring laser resonance while blowing air through the cavity, and comparing the jitter of the resonance signal to when not doing so. In order to remove this potential noise source, the team built an aluminum box to fit on top of the cavity.

DC Lock Results

Cavity signal at constant voltage without PI controller

This measurements provides a benchmark for how the laser responds to locking attempts by a PI servo. It is a plot of how the cavity responds when the laser light from the functioning narrowband Ti: Sapph laser enters the cavity. The cavity has been set to one of the laser's resonance points by supplying the cavity a constant voltage bias. In other words, the voltage going into the piezoelectric transducer (PZT) that finely controls the length of the cavity is constant and is set at the value such that the laser resonates inside the cavity.

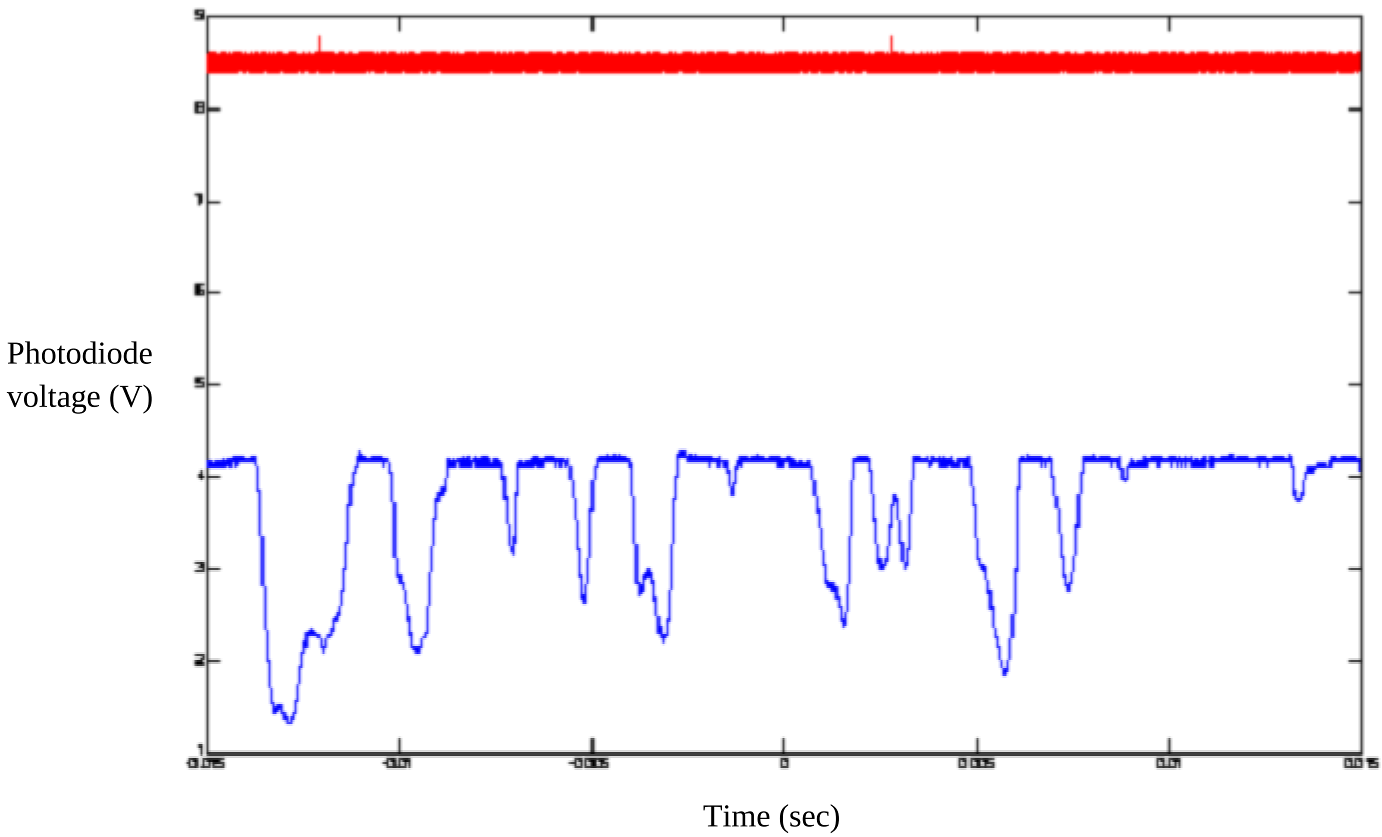


Figure 43: This figure shows the output of the cavity when a constant voltage is fed into the PZT of the cavity. The red line is the voltage going into the PZT of the cavity, while the blue line is the output of the photodiode.

<u>Cavity signal with laser locking setup and PI controller</u>

This is the result that was achieved when an error signal, the output of the voltage adder circuit (which is the output signal of the cavity with an adjusted zero point), is fed into the input of the JILA PI controller. The output of the JILA PI controller is connected to the PZT of the tweeter mirror in the Ti: Sapph, which provides a fast adjust for the frequency of the laser from the Ti: Sapph. In this setup, the PI controller is attempting to lock the laser at a certain frequency.

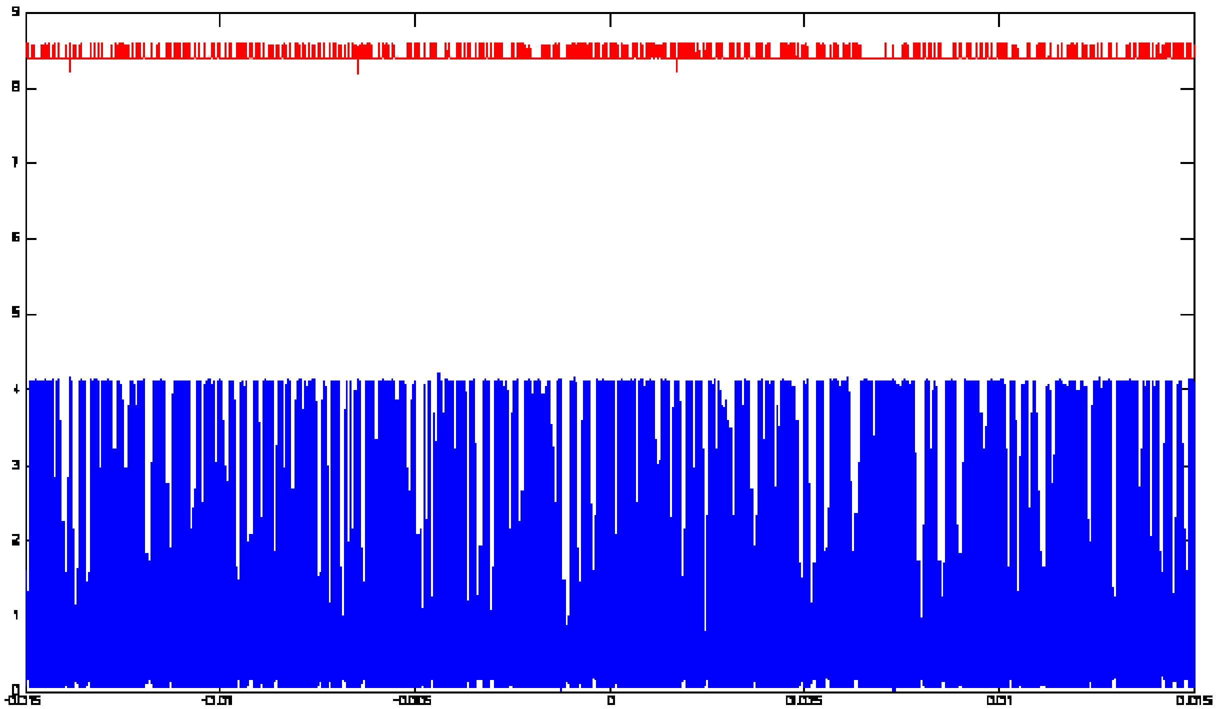


Figure 44: This figure shows the output of the cavity with the locking setup and the PI controller turned on. The red line is the voltage going into the PZT of the cavity, while the blue line is the output of the photodiode.

In order to see exactly what the oscillations look like, the next figure shows the photodiode output signal on the oscilloscope but with the time scale decreased. In addition, the intensity of the laser going into the cavity is also decreased. By decreasing the intensity of the laser, the overall gain of the PI controller is also decreased, which generally decreases oscillations.

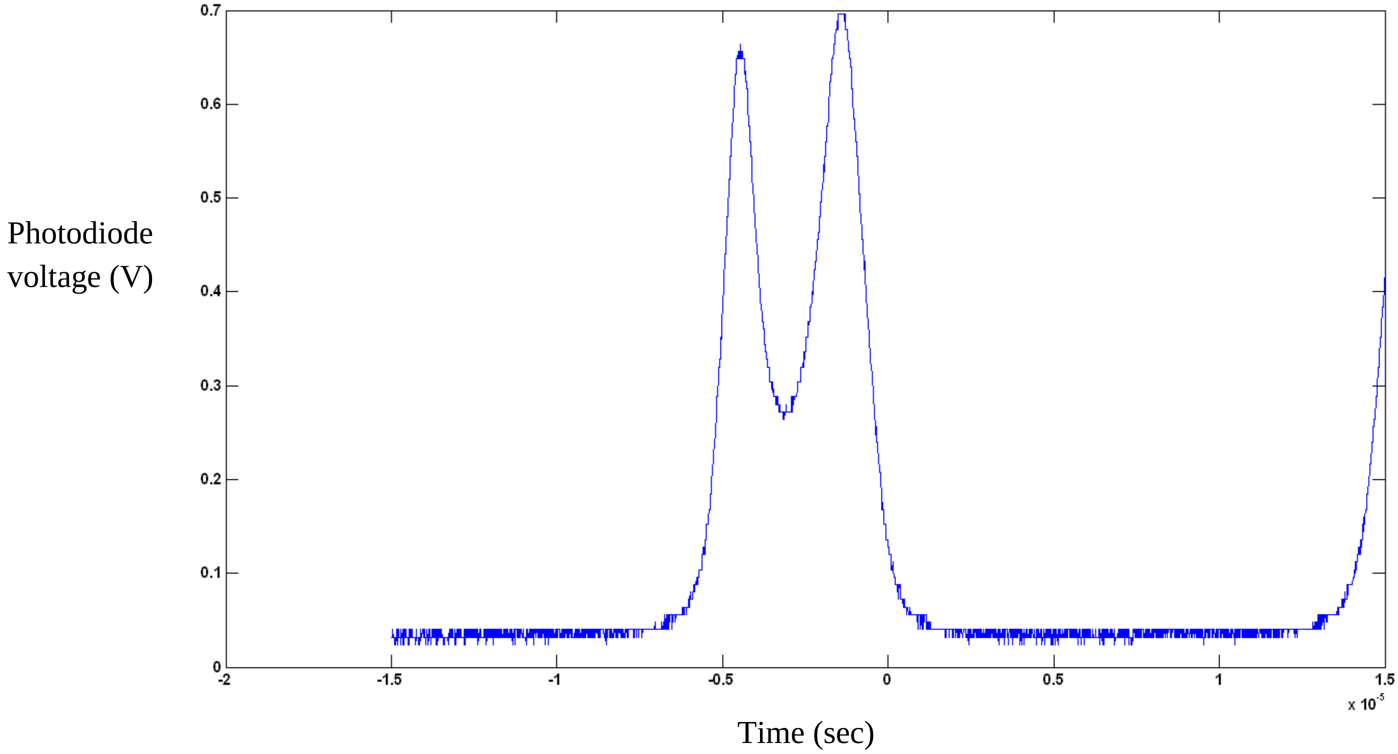


Figure 45: This figure shows the output of the cavity with the locking setup and the PI controller turned on. Here the time scale is in tens of microseconds (from the 10^{-5} shown on the axis).

The signals shown above are achieved with the following parameters on the JILA PI controller:

Servo Gain	
Range	Halfway between maximum and minimum
Coarse	30
Servo Frequency (Hz)	
PI corner	1 K
-9 dB Corner	330
Servo Mode	
Setting	-6 dB
Gain	10
Bandwidth	30 KHz
High voltage driver output	64 V

Table 2.

Without the PI controller, the laser in the cavity is considered at or close to resonance while the signal from the photodiode looks like figure n. With the PI controller, the laser in the cavity is considered to be at or close to resonance while the signal from the photodiode looks like figure n.

For both cases, the laser in the cavity is considered to be at resonance when there is a nonzero voltage from the photodiode. This is due to the fact that only at or close to resonance does the laser beam exit from the cavity and into the photodiode. Ideally, the voltage from the photodiode should be flat if the laser remains perfectly at resonance with the cavity. Voltage values that are less than the maximum value means that the laser is close to but not exactly at resonance, which means that either the wavelength of the laser is fluctuating or the length of the cavity is fluctuating.

The table below shows the duration of time that the output voltage of the photodiode is like fig 43 without the PI controller and like fig 44 with the PI controller connected to the tweeter mirror of the titanium: sapphire laser.

Trial	Without PI controller (mins:sec)	With PI controller (mins:sec)
1	0:23.7	1:28.0
2	0:26.5	1:45.0
3	0:12.6	1:08.0
4	0:33.6	1:14.0
5	0:21.6	1:43.0
Average	0:23.6	1:27.6

Table 3.

Discussions of Results

Assembled titanium: sapphire laser

From the "Results" section it was said that even though the maximum power is at 1.8 W, the power output of the titanium: sapphire laser fluctuates between 1.3 – 1.6 W. Such a wide variation of output power occurs due to the random displacements of the optical components within the laser. The wavelength of the laser light is in the order of hundred of nanometers, which means that all of the optical components must be aligned on the order of micrometers in order for the laser to output a beam with maximum power.

Two major factors contribute to the mechanical variations of the optical components:

1. The first is thermal variations. The temperature of the room changes over time, thus the temperature of the clamps holding the optics in place will change. As a result, the positions of the optics will change as well, causing the optics to be misaligned in the micrometer-scale.

2. The second is mechanical vibrations, which also causes the laser to misalign. The effects of mechanical vibrations are evident when the table is tapped while the power meter is measuring the output power of the laser. The power first changes rapidly and then slows

down until it reaches a steady state value. This value, however, is different from the value before tapping the table.

The 479 group was not successful in getting the laser to lase narrowband. This is due to two components of the laser not functioning properly: the intracavity assembly (ICA) and the control box that controls the ICA.

The ICA was not functioning properly in that when the ICA was placed in the Ti: Sapph and is properly centered so that the laser was going into the ICA through the center of the thin etalon, the output power of the laser decreased greatly into the mW range, which means that the beam is clipping inside the ICA. Because we were not allowed to take apart the ICA to find the source of error, we only offered a solution in the “Recommendations” section as a possible remedy.

Secondly, the control box controlling the ICA (shown in fig n in the “Theory” section) was also not functioning properly. The thin etalon offset knob should have changed the position of the reflection from the ICA. However, when the box was tested by connecting it to the ICA on the functioning Ti: Sapph in the lab, the reflection from the thin etalon offset did not change. The voltage values coming out of the box from the 15-pin serial outputs located at the back of the box were then measured while tuning the thin etalon offset knob. All nonzero voltages coming out of the box remained constant while the knob was being tuned. Thus, the group concluded that the problem lies in the internal circuitry of the control box. A solution to this problem is stated in the “Recommendations” section of the report.

For this portion of the project, there are no further experiments which would give further insight into the process of lasing. It has been determined that the laser is successfully lasing broadband, and until the steps listed in the “Recommendations” section are taken and the two problems stated above are fixed, no further results can be taken and no more advancements can be made towards successfully getting the Ti: Sapph to lase narrowband.

Cavity Characterization Results Discussion

The experimentally derived finesse of the cavity was a little over 25% the expected finesse of the cavity. Poorer mirror quality, high-frequency mechanical vibration of the cavity, and possibly the lack of a locking mechanism on the cavity's coarse adjustment system (see below) contributed to the cavity finesse being lower than expected.

The biggest problem the team experienced in locking with this cavity seems to stem from a design flaw in the cavity. One interesting characteristic of the cavity drift was that it only went in one direction, very slowly, for the entire time when the cavity was in use. The team observed this because the resonance peaks would always drift towards the peak voltage of the triangular wave driving the cavity's piezo before ultimately disappearing once they reached the top. The triangular wave's offset or amplitude would need to be increased to bring the peak back into view. Since the cavity was tested over several hours, it is very unlikely that the temperature of the room increased for that long. One very plausible cause for the slow drift is the lack of a lock on the coarse adjustment knob of the cavity. The adjustment knob rotates a spring-loaded set screw, and since it isn't locked the spring could slowly turn the set screw as it slowly expands.

The drift can be roughly estimated in mV, but unfortunately since the team lacks any documentation for this cavity it is very difficult to interpret this in terms of distances or frequency shifts. Assuming the average drift rate in the data above is a good metric for the average overall drift of the cavity, the voltage resonance point is changing at a rate of around .4 V/minute based on Figure *n*. Without knowing at exactly what ratio the piezo changes its length as a function of input voltage, this data is useless. It is possible to make an order-of-magnitude estimate, however:

1. The FSR of the cavity is estimated to be 1.5 GHz.
2. The team knows the minimum Vpp of the triangular wave signal required to provoke two peaks is 3.2 V.
3. This provides a vague rate at which the cavity changes frequency as a function of voltage: 500 MHz / Volt.
4. So, the cavity must be drifting in frequency at a rate of about 200 MHz/min.
5. It would take about half a minute for the cavity to drift right over the linewidth of a resonance peak.

This seems to coincide with the 479 group's estimates during locking attempts using a DC bias on the cavity (see *Cavity DC Lock Section*).

Scan Lock

The scan lock proves that this system is able to keep the laser locked for some amount of time, but the low range of the scan lock implies the cavity will need to be much more stable in order for the lock to work with these settings. Note the time scale and the fraction of the curve over which the cavity is locked on these settings: it is locked for at most 20-25% of the total time the cavity is scanning across the resonant peak. Using the estimate of the linewidth obtained from the Rb-locked laser, this means the entire system must never drift further from its set point than approximately 19 MHz. The stability of the cavity required for the lock, then, can be approximately obtained by subtracting the maximum amount of drift expected from the Ti-Sapph laser:

19 MHz - linewidth of Ti-Sapph = maximum drift of cavity

Note that the calculation above doesn't specify the linewidth of the cavity. It specifies to what degree the cavity itself can vary and vibrate during tests. If it does so fast enough, then regardless of how steady the laser is the system will be unable to maintain the lock.

The 479 group does not have enough data about the characteristics of the cavity or the Rb-locked laser to have truly quantitative data or provide an error analysis for the scan lock. The estimate of the Rb-locked laser's scanning range was given as 'about 3 GHz' by the graduate students using the laser and the 479 team is unaware of documentation which would accurately describe the scanning range of the Rb-locked laser. The cavity itself does not seem to have any documentation, which is a major disadvantage especially considering the present need for understanding the movements of the low-voltage piezo element inside it.

DC Lock

Cavity output signal at constant voltage without PI controller

From figure n in the “Results” section, it is evident from the voltage oscillations that the laser is not maintained perfectly at resonance. The value of the voltage output when the laser is at resonance should be at 4 V. However, it can be seen that the voltage values drop below 4 V at different times, meaning that the laser is falling out of resonance. Mechanical variations can contribute to this deviation from resonance.

Mechanical variations can cause the length of the cavity to change over time. If the length of the cavity changes, the laser must have a different wavelength in order for it to remain at resonance. This factor is quite significant in our setup. It is impossible to use only mechanical means to physically lock the positions of the mirrors in the cavity. In many laser lock setups, such as the one performed by Hoogeveen, a paper provided by Dr. Madison, an error signal generated by a PI controller needs to be used in order to control the frequency of the laser to respond to the change in cavity length.

Even though mechanical variations cannot be fully eliminated, they can be minimized by proper choice of materials for the cavity, the design of the cavity, and a proper thermal enclosure. However, the cavity used for this measurement was not mechanically designed to be very stable. The coarse adjust lock for the length of the cavity is only provided by a set screw, while the mirrors are held in place by threading rings. In addition, the only thermal enclosure this cavity has is a steel box that we placed over it.

The result from measuring the cavity output without PI lock is still useful, however, in that it provides a picture of how stable the mechanical setup of the cavity is. It can from the figure that the signal is oscillating a significant amount. It can also be seen from the time measurements that the system remained close to resonance for a short amount of time (approximately 23 seconds). This means that not only is the length of the cavity oscillating about its set length, but that set length is maintained for approximately 23 seconds before it drifts out of range of the length needed for resonance.

Cavity output signal at constant voltage with PI controller

From fig n and fig n in the “Results” section, it can be seen that the PI controller is attempting to control the frequency of the laser coming from the Ti:Sapph. Firstly, the figure shows a difference in the frequency of oscillations as compared to without the lock, which signified that the PI controller is doing something. Because of the effect of offsetting the zero-point of the cavity output to be at FWHM (full width half max) with the voltage adder circuit, the voltage signal should be locked at the halfway between the minimum and maximum voltage, which in this case is approximately 2V. Thus, the PI controller seems to be trying to lock the signal to 2 V but is overshooting between 0V and 4V, which are the minimum and maximum values.

One of the reasons why the PI controller is causing the signal to oscillate so rapidly is because the cavity length is drifting in a constant direction. Thus, it is analogous to trying to hit a moving target. The input error signal of the PI controller is constantly increasing because the length of the cavity is drifting farther and farther away from the required length needed for resonance, which means that the PI controller output voltage is also increasing in order to change the frequency of the laser to match the length. However, with such high gain, the PI controller is overshooting the zero-lock point.

The second cause for the PI controller causing the oscillations is the rapid vibrations of the cavity length. This is evident from fig n in the “Results” section. It can be seen that the curve is behaving as if the signal is being locked by a PI controller in that the signal is oscillating about halfway between the minimum and maximum voltage. However, the frequency of one complete cycle of oscillations is observed to be 5 µsec as seen from the figure, which would mean that the frequency of the signal is about 0.2 MHz. Since the oscillations of the signal from the photodiode output is a result of the cavity length changing, it is implied that the length of the cavity is oscillating about its confocal length at a frequency in the order of MHz. Furthermore, this means that in order to even attempt to achieve a lock, the PI controller would need to respond in the order of MHz. However, the bandwidth of the JILA PI controller is only on the order of kHz.

At this point, no alternative tests can yield further results. The cavity is far too unstable for the 479 group to extract any more data by applying a constant bias voltage to the cavity.

Conclusions

The following results have been delivered by the 479 team:

1. The 899-21 Ti:Sapph laser is capable of lasing in broadband. Problems were discovered with the control box provided for it.
2. The cavity provided by the sponsor for locking has been discovered to drift at a rate of approximately 200 MHz per minute, making it untenable as a reference until its design can be debugged and repaired.
3. Despite various setbacks, the team was able to partially lock the laser in two different ways. The team locked the laser for about 25% or so of the cavity's linewidth while scanning the cavity, and also adjusted the servo settings to counter the cavity drift for as long as possible. The settings and calibration methods for these locks are recorded in this report for use when the cavity is replaced with a more reliable component.

The most important results are the near-completion of the Ti:Sapph laser and the obtainment of partial laser locks, since these will provide the most benefit for the sponsor in their dilithium experiments. It is obvious after this project that the long-term stability of an optical cavity is a very important quantity when locking it to a laser. This property should probably be assessed before a cavity is used in a locking project, as a criterion for using it.

Project Deliverables

Deliverables

1. A functioning narrowband 899-21 Titanium-Sapphire Laser. By the end of the project, the 479 group had completed a broadband-lasing 899-21 Ti-Sapph laser. The team was unable to align the ICA module, the component responsible for causing narrowband lasing, and as a result was unable to complete this milestone.
2. Cavity-locked 899-21 laser using the tweeter mirror inside the 899-21 laser. The 479 group has determined that the cavity they were provided is too poor to use for locking due to its slow continuous drift and instability. The 479 group was not provided with resources to purchase a better cavity or build their cavity design.
3. Optional deliverable: Cavity-locked 899-21 laser using the tweeter mirror inside the 899-21 laser and an acousto-optic modulator. The acousto-optic modulator would have required a cavity orders of magnitude more stable than the cavity required by Deliverable 2, and requires the laser to be locked using the tweeter. The cavity was too unstable to achieve Deliverable 2.

Financial Summary

#	**Description**	**Quantity**	**Vendor(s)**	**Cost**	**Purchased by:**	**To be funded by:**
1	LM399	2	n/a	Approx. $10 each	Jon Nakane	Engineering Physics project lab
2	INA128		n/a	Within Engineering Physics budget	Jon Nakane	Engineering Physics project lab
3	Tubing to connecting cooling system to Ti: Sapph		n/a	Approx. $200	Kirk Madison	Optics Lab

Table 4.

Ongoing commitments by team members

There are currently no ongoing commitments planned for any of the team members. The sponsor has been out of town since we achieved our results and has not responded since. Thus, it is unknown whether Dr. Madison wishes for the project to continue forward once he purchases a more stable cavity or if the frequency comb supposedly supplied by James Booth from BCIT is ready.

Recommendations

- The cavity must be replaced with a more stable cavity, or a frequency comb laser to avoid the problem of cavity instability and drift altogether. At the very least the cavity must be modified so that the coarse adjustment knob is able to lock. If the cavity was altered in that way so that it did not drift, it might be possible to use a PID controller to overcome the problems of cavity instability.
- The newer Ti:Sapph laser lacks a functioning ICA. The older Ti:Sapph's ICA should be swapped into the new Ti:Sapph to confirm that the new Ti:Sapph's ICA definitely is the problem. If the ICA is faulty, the team suggests that the sponsor either purchases a new one from a secondhand Coherent distributor like Laser Innovations or finds out whether Coherent, Laser Innovations or the UBC electronics shop is able or willing to effect repairs.
- Low thermal expansion glass is recommended to be used for the cavity spacer material and ideally, a vacuum environment is recommended for to limit the thermal motion of molecules. A vertical mounting configuration of cavity is worth more investigation as it possesses advantages
- A mirror of high reflectivity(99.998%) is to be used in conjunction with a flat mirror (non-confocal configuration)
- The cavity with 1 m length would be most suitable for locking.

Appendices

Voltage Adder Circuit Design Template

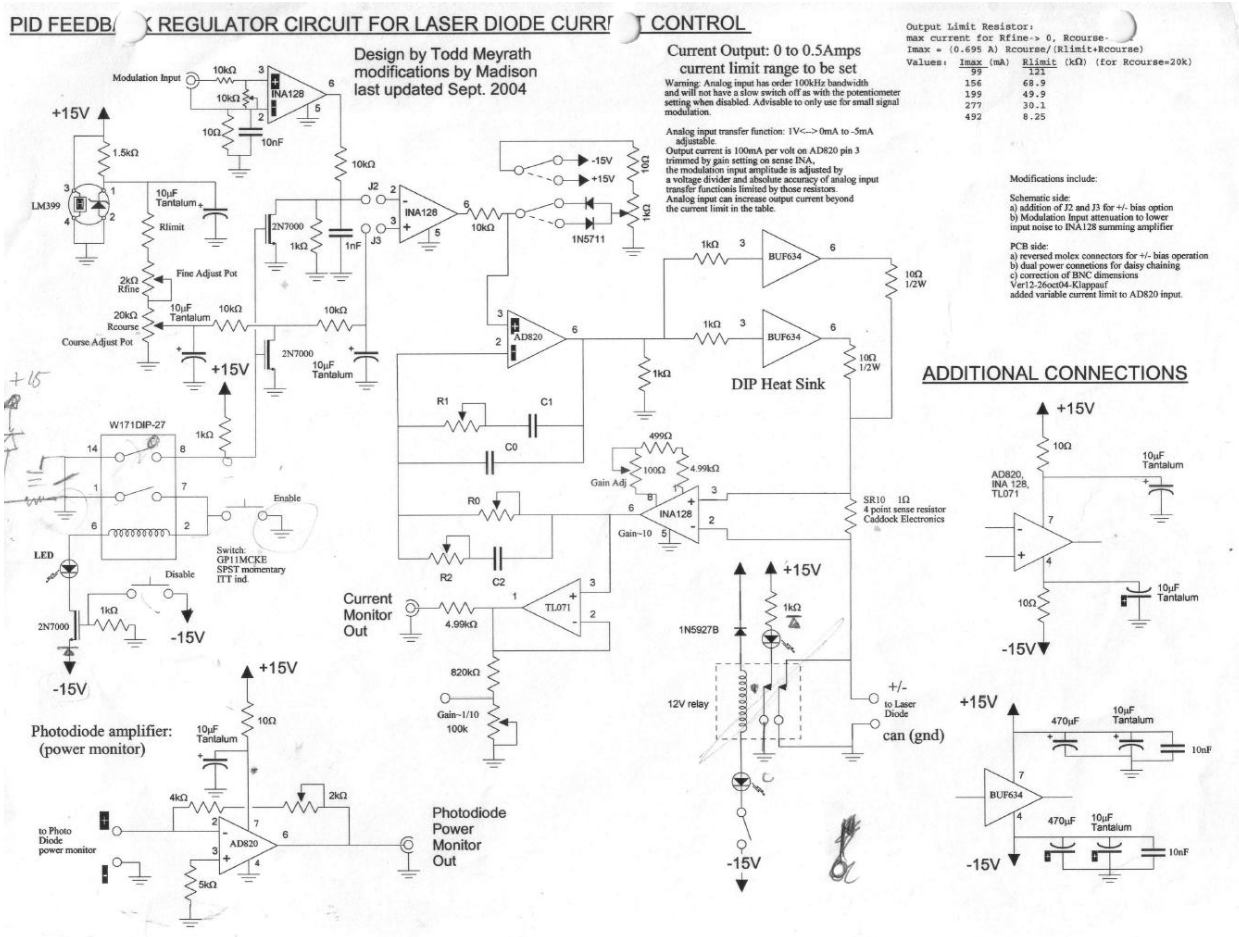


Fig 46: This is the circuit diagram that Janelle Dongen provided as a template for the voltage adder circuit

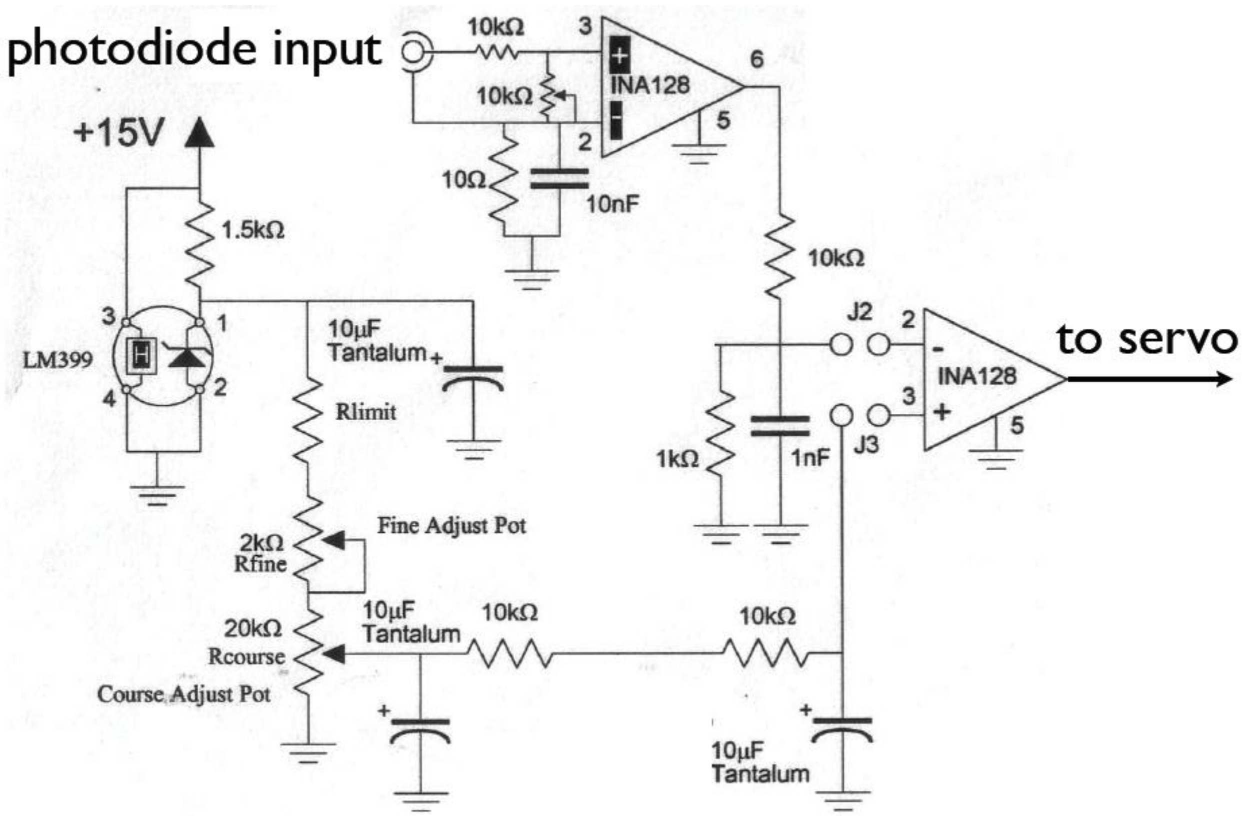


Fig 47: This figure shows the portion of the circuit from the one provided by Janelle. This is the portion of the circuit that provides the voltage addition needed.

Cavity Drift Characterization

Below are plots of the cavity being scanned while light from both the Ti:Sapph and Rb lasers are coupled into it. The taller peaks are from the Ti:Sapph laser.

This data was used to derive the drift of the cavity in Section *n*. The Ti:Sapph data was not used, but the voltages at which the Rb laser resonated were plotted as a function of time.

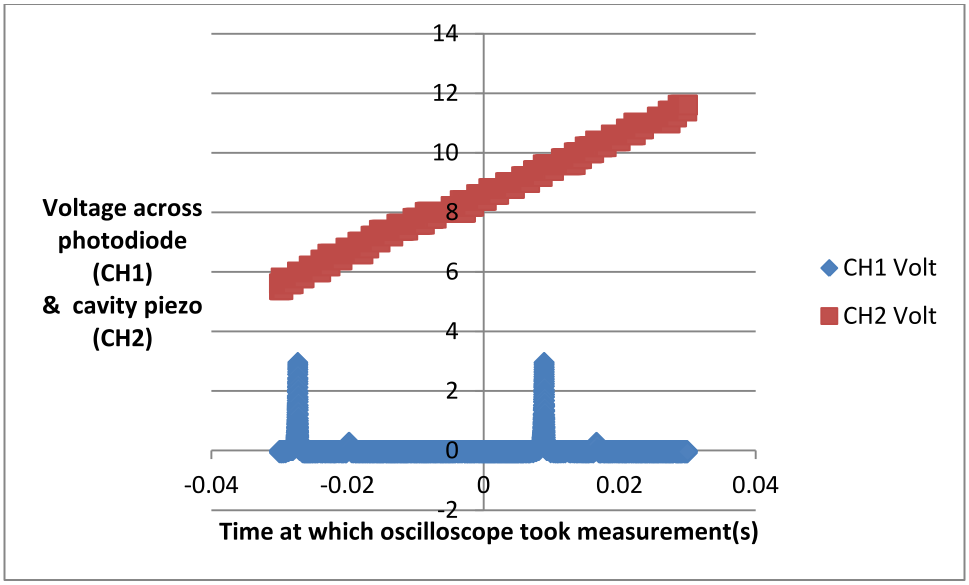


Fig. 48

The above measurements were taken at T=0 mins 0s.

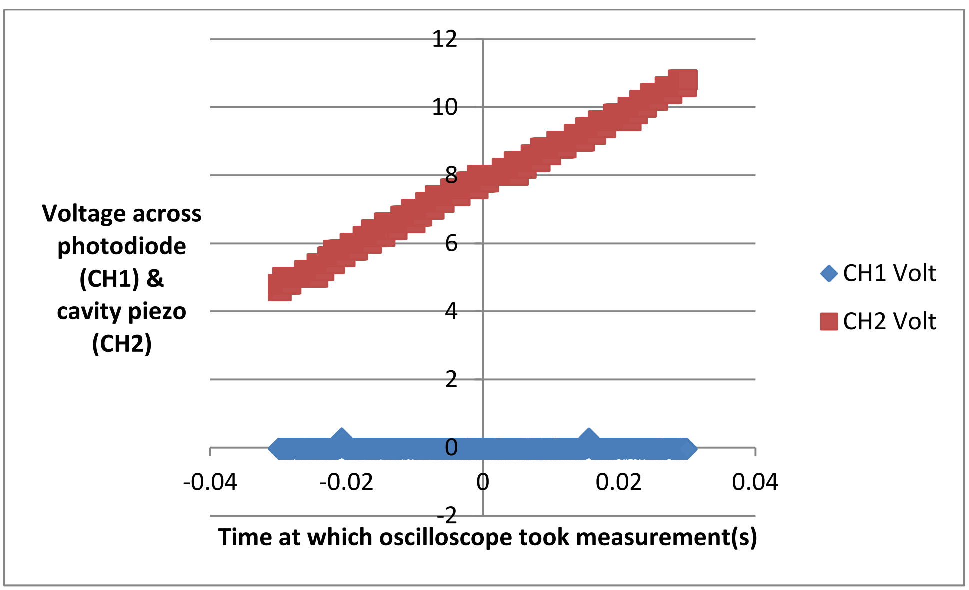


Fig. 49

The above measurements were taken at T= 4min 30s.

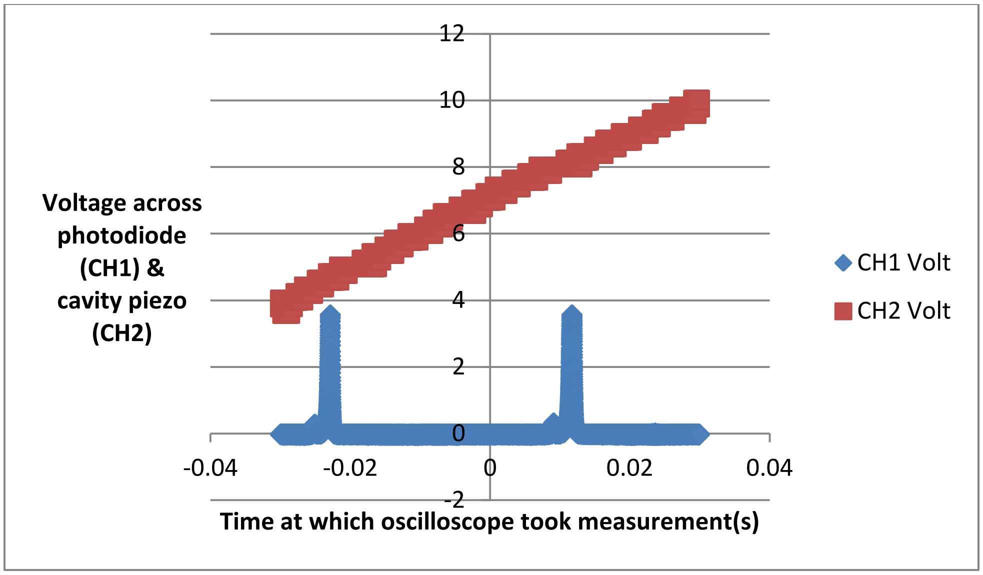


Fig. 50

The above measurements were taken at T=5min 50s

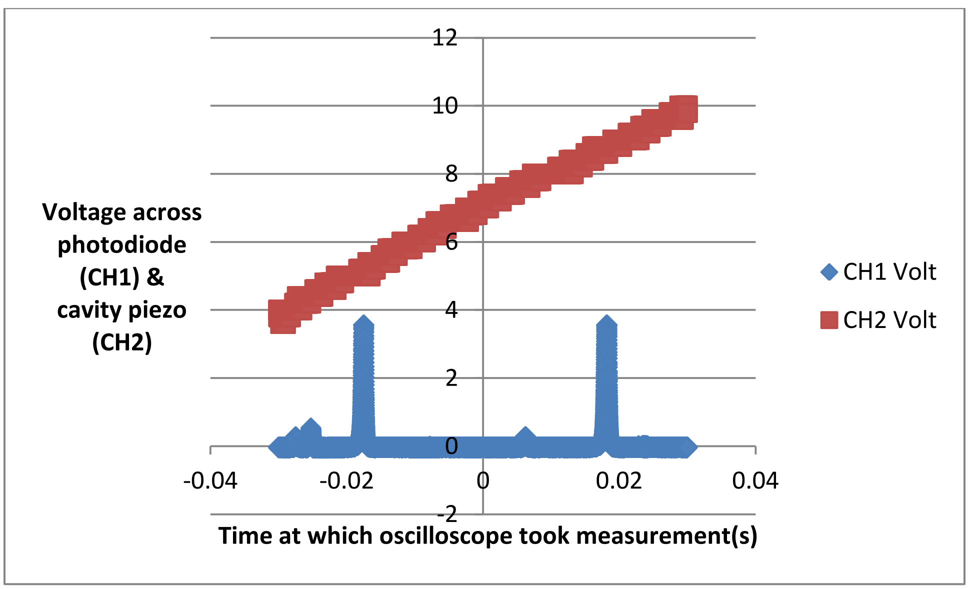


Fig. 51

The above measurements were taken at T=7min 50s

Cover of Ti:Sapph Operating Manual

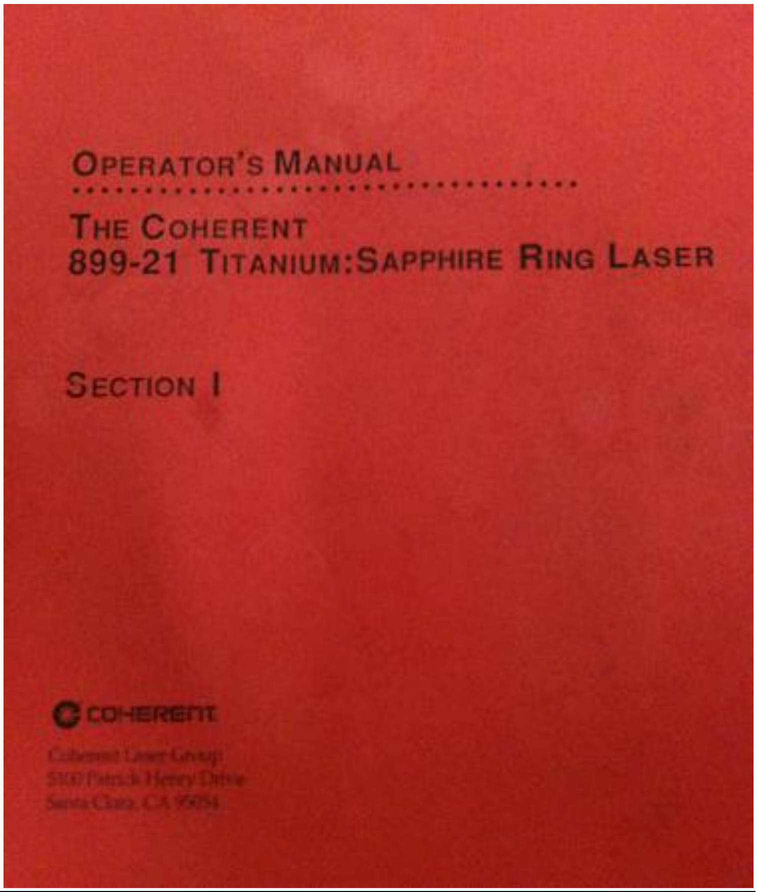


Fig 52: This figure shows the cover of the Manual that was used to align the optics in the Ti: Sapph. Many sections of the report refer to this manual. This manual can be found in Dr. Madison's office.

SolidWorks Model Of New Cavity Design

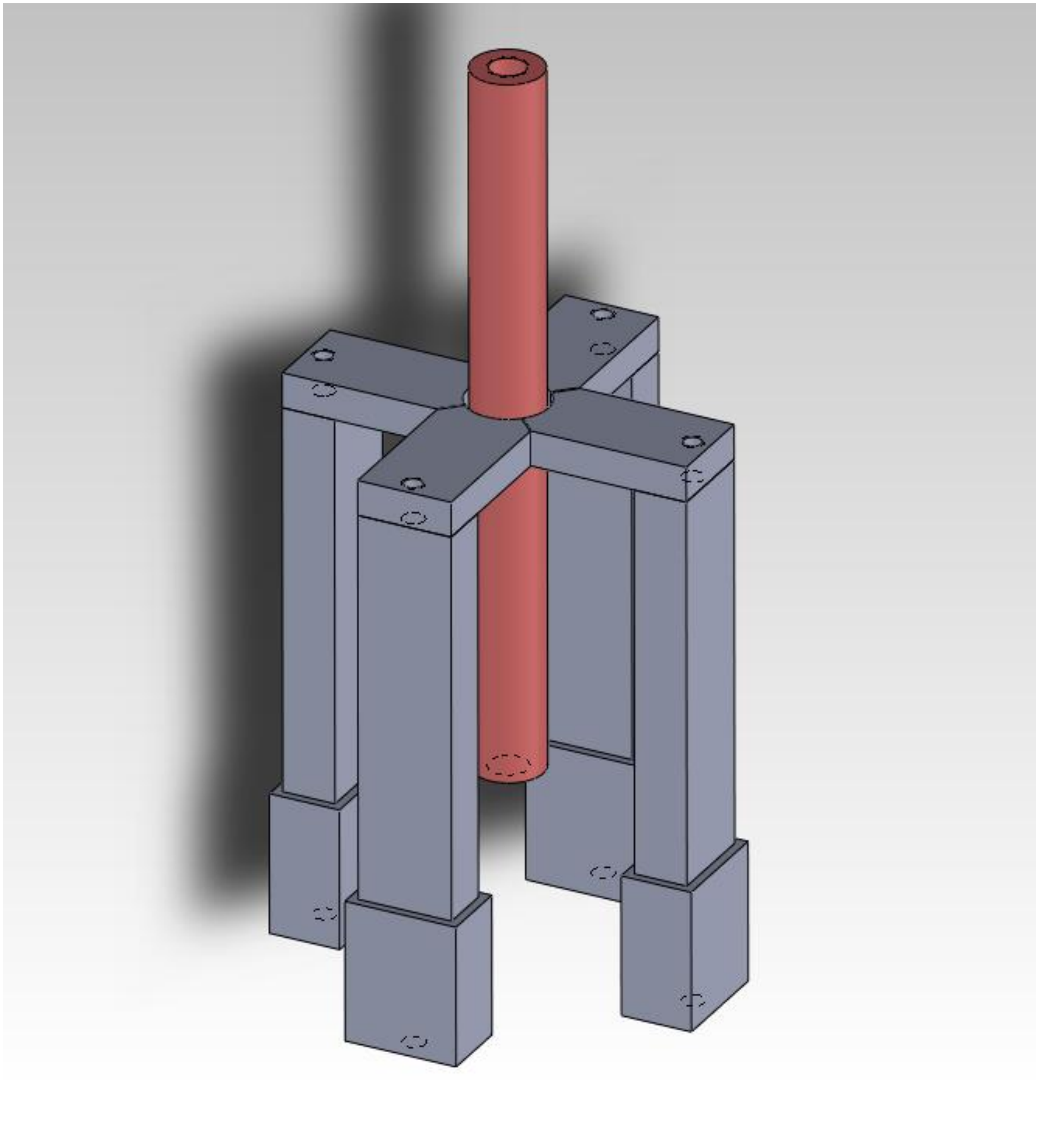


Fig. 53 Vertical Mounting of Cavity

Cavity Length Calculation

The laser beam source in the optical lab provides a wavelength λ of 632nm with frequency ν_L = c/ λ = 4.74e14Hz. The positions of mirrors are adjusted to set the distance between two mirrors to be 30cm. In order to take into account the factor of drifting of resonance peaks, a factor of δL is included

$$\nu_{FSR} = C/2(L+\delta L)$$

where c is the speed of light,

L is the cavity length,

δL is the cavity length change

As part of the definitions of paramters here, $\nu_{FSR}{}^{o}$ is defined to be the precise FSR, which is the spectral range between two adjacent resonance peaks. Then

$$\nu_{FSR}{}^{o} = C/2L = 3\times10^{8}\text{m/s} / (2\times0.3\text{m}) = 500\text{MHz}$$

Subsequently,

$$n = \nu_L / \nu_{FSR} = 10^{6}$$

Using Taylor expansion,

$$\nu_{FSR} = \nu_{FSR}{}^{o} (1+ \delta L/L)^{-1} = \nu_{FSR}{}^{o} (1-\delta L/L)$$

From equation 1 into equation 2,

$$\nu_L = 10^{6} \times \nu_{FSR}{}^{o} (1-\delta L/L)$$

Let ν_L' be the frequency of the offset resonance peak,

$$\nu_L' = \nu_L (1-\delta L/L)$$

Thus, offset frequency would be

$$\delta\nu_C = \nu_L' - \nu_L = - \nu_L(\delta L/L)$$

$$\delta\nu_C = -4.74\times10^{14} (\delta L/L)$$

A tolerance of 33MHz for $\delta\nu_C$ is tentatively used here and with L = 0.3m, it can be derived that a cavity length change of approximately 20nm would lead to 200MHz drifting of resonance peaks. [4]

References

1. Astrom, K. J. (2002). PID control. In 2002 (Ed.), Control system design (pp. 216-251)

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