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STABILIZING DIODE LASERS TO HIGH-FINESSE CAVITIES

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ABSTRACT

STABILIZING DIODE LASERS TO HIGH-FINESSE CAVITIES

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This thesis introduces an important and powerful laser locking technique: The Pound-Drever-Hall method. This thesis is not only meant to be conceptual, but it also includes a mathematical derivation of the error signal used to stabilize the laser and details about how to design the cavity and PID circuits used to lock the laser and control temperature fluctuations. The reader will learn how to design and build a real setup, suitable for research application, from this thesis. Another aim of this thesis is to provide an operational manual of this for researchers in Prof. Brian Odom's lab.

Acknowledgements

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I would also like to thank Yen-Wei Lin and Chris Seck who gave me the most help in this research project. I learned from them not only the knowledge in this field, but also the ways to analyze a problem and solve a problem, which is greatly helpful to me. I would also like to thank the people in this lab such as Mark Kokish, Patrick Stollenwerk, Joseph Cordero-Mercado, Panpan Huang, Zeke Tung, Vincent Carrat and James Dragan who offered me lots fo help in every aspect.

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Finally, I must express my gratitude to my parents for providing me with support and continuous encouragement throughout my years of study and through the process of this project. What has been done here is as much their accomplishment as my own. Thank you.

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CHAPTER 1

Introduction

Since the first laser was built in 1960s, it began to play a significant role in our daily life and scientific research. As the development of laser technique in the past few decades, more stable and shorter pulse lasers were built and implemented in conducting AMO experiments such as laser cooling, precise measuring physical quantities and precison spectroscopy. However, when people conducted those experiments they found that the stability of currently commerical lasers are inadequate, and they need some external devices to make a more stable laser source. To achieve this, people have discoverd several ways, but one of the most popular and powerful technique is the "Pound-Drever-Hall"(PDH) method. This method was first invented in 1983[1, 2], and was orignally used for the mircrowave experiments done by R.V. Pound and it was conceived by Ron Drever. Finally, it was largely developed by Jan Hall at JILA in practical implementation[3]. The idea behind the Pound-Drever-Hall method is quite simple: Use a Fabry-Perot cavity to measure an existing laser's frequency, and compare this measurment with expected frequency to get an error signal and feed this signal back to the laser to suppress the frequency fluctuations. With the help of this method, people can get better 100 Hz stability. Modern implementations with careful vibration isolation have achieved several Hz stability[4].

The motivation of the project in this paper is to build a laser locking system for the experiments in Odom's Lab, such as Doppler laser cooling of different spcies of molecules or ions. Currently, there is no robust laser locking system in this lab. We currently are using a wavemeter to lock our lasers, the response is quite slow and the stability is poor. If we want to use one wavemeter to lock different lasers, the result becomes even worse. Therefore, we need to build this locking laser system (PDH method) to greatly improve the stability of several existing lasers simultaneously with a fast response. We successfully built this system and demonstrated one of the cavities can lock a diode laser with wavelength 657 nm. However, due to the bad location of this cavity and time considerations, the frequency fluctuations measurment of the locked laser is not included in this paper.

Since most reference papers only focus on the theory of PDH method, few of them contain steps of building one, the aim of this thesis is to present people wuth the whole process of building a PDH locking laser system and include almost all the details that was considered in this project. Additionally, this paper will also provide information for the people in Odom's lab who wants to lock a different diode laser in the future.

The layout of the thesis is as follows: In chapter 2, the general theory of Pound-Drever-Hall method and the overall setup will be presented which will give reader a overview of this locking laser system. In chapter 3, I will introduce the cavity design in practice and how to choose mirrors for the cavity. Chapter 4 will discuss how to control the temperature of this laser locking system and show the temperature performance under temperature controlling. Chapter 5 introduces how to couple light into the cavity and how to examine the performance of the Mode-Matching. In Chapter 6, I will introduce the final steps of locking laser such as modulating the laser, generating the error signal and servo loop design. Finally, I will include the future plan and improvements of this project in last Chapter 7.

CHAPTER 2

Principles of Pound-Drever-Hall Method

2.1. Conceptual Overview

Before going to the details about the construction of this system, I want to introduce the Pound-Drever-Hall (PDH) method first. The basic idea of locking the laser is to dynamically adjust one laser with unstable frequency to match the known and stable frequency of a specific cavity mode. Therefore, the difference between the cavity's resonant frequency and laser's frequency, δf, should be continually measured. However, there is currently no electronics that can directly measure frequency, so one good way to measure frequency is to send laser beam into a Fabry-Perot (F-P) cavity and measure how much light get transmitted. Remember that only if the light's frequency is an integer number of times the cavity's free spectral range, $\Delta\nu_{fsr}\equiv c/2L$, can pass through a Fabry-Perot cavity, where L is the length of the cavity and c is the speed of light. When the laser frequency is far from the cavity resonance, all light will be reflected, but when the laser frequency is near resonance, the reflection coefficient, F, dependent on δf will decrease. Therefore, some methods before PDH simply measured the reflected intensity of the light $|F|^2$ and fed this signal back to the laser and hold the intensity, but this method has a big problem that one cannot distinguish between fluctuations in the laser's frequency, which changes the intensity reflected from the cavity, and fluctuations in the intensity of the laser itself. One better way to solve this is to hold the reflected intensity to zero, which will decouple intensity and frequency fluctuations. However, another problem arises from the fact that the reflected intensity of the light is symmetric around resonance, so if the laser frequency drifts out of resonance one cannot tell just by looking at the reflected intensity whether the frequency is below or above the resonanc.

The PDH method successfully solve this problem: although the reflection coefficient F is symmetric around the central frequency, the derivate of F with respect to δf is antisymmetric as shown in the Fig 2.1, which is the key point of the PDH method. To achieve the derivate of F, we can modulate the frequency slightly and see how the reflected beam responses. From Fig 2.1, we know above resonance the derivative of the reflected intensity with respect to laser frequency is positive which means the intensity will respond in phase with frequency variations. Below resonance, the reflected intensity will respond in opposite phase with frequency variations and on resonance will not change significantly. Thus, we can determine which side of the cavity resonance the laser frequency is on with the help of varying frequency slightly. Then we could get an error signal, and feed this error signal through a servo loop into the laser and lock it. That's the basic overview of Pound-Drever-Hall method.

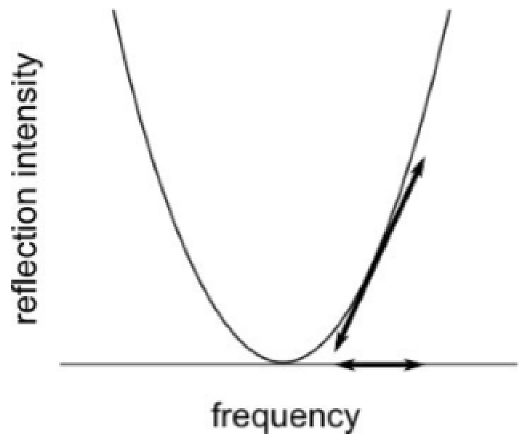


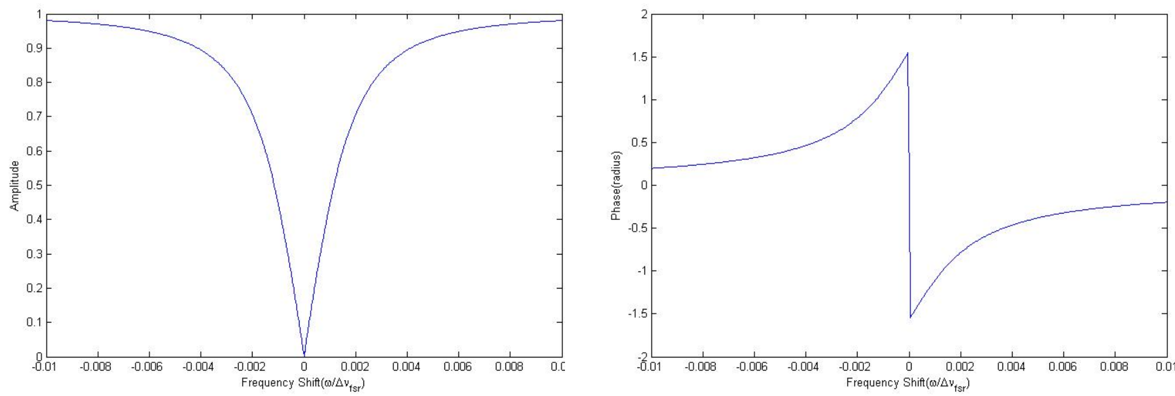
Figure 2.1. The reflected light instenity from F-P cavity as a function of laser frequency, near resonance.

2.2. Mathematical Treatment

This section will explore a mathematical treatment of PDH method, which helps one understand the PDH locking technique well in detail. Let's start with the proportities of the Fabry-Perot cavity. Assuming that the incident and reflected beam have an approximately constant frequency, then we can write the magnitude of the incident beam as

$$E_{inc} = E_0 e^{i\omega t}. \tag{2.1}$$

The beam reflected from F-P cavity consists of two parts: the promptly reflected beam, which directly bounces off the first mirror and never enters the cavity; and a leakage beam, which is the small part of the standing wave inside the cavity that leaks back through the first mirror. These two beams have the same frequency, and near resonance their intensities are almost the same. However, their phases are different: the prompt



(a) Amplitude vs Frequency Shift (b) Phase vs Frequency Shift

Figure 2.2. Plots of the amplitude and phase of the reflection coefficient $F(\omega)$, assuming r equals 0.999.

reflection has a phase shift of π; the leakage beam consists of mulitple phase components, the first round-trip component having a phase shift of -$2L\omega/c$ from its travel along the cavity of length L, where $\omega = 2\pi f_L$ is the angular laser frequency, so the second round-trip component should have a phase shift of -$4L\omega/c$. Then we can express the reflected beam as

$$E_{ref} = E_0(re^{i(\omega t+\pi)} + trte^{i(\omega t-2\omega L/c)} + tr^3te^{(\omega t-4L\omega/c)} + ...), \tag{2.2}$$

where r is reflectivity and $t = \sqrt{1-r^2}$ is transmitivity of the cavity mirror. Thus, we can obtain the reflection coefficient and simplify it to

$$F(\omega) = \frac{E_{ref}}{E_{inc}} = \frac{r(e^{i\omega/\Delta\nu_{fsr}} - 1)}{1 - r^2 e^{i\omega/\Delta\nu_{fsr}}} \tag{2.3}$$

After we plot the figures of amplitude and phase of $F(\omega)$, we can see from Fig 2.2 that the amplitude of F is symmetric around reasonance, but its phase is antisymmetric and its sign different depending on whether the laser's frequency is above or below the cavity's reasonance, which we can use this to make an error signal.

To get the phase of the reflected coefficient, we need to modulate the laser. We can modulate either the frequency or the phase of the laser, but in pratice it is much easier to modulate the phase. To understand the phase modulationg, we should look at the mathematical describation first. An electro-optic modulator(EOM) is usually used for this. We can consider EOM as a variable waveplate, because it is a crystal that can rapidly change its index of refraction in response to electrical signal, which induces a small phase change in light passing through it. Therefore a laser beam passing through an EOM modulated at frequency $\Omega/2\pi$ will have an electric field of

$$E_{inc} = E_0 e^{i(\omega t + \beta \sin \Omega t)} \tag{2.4}$$

$$\approx E_0 (J_0(\beta) + 2iJ_1(\beta) \sin \Omega t) e^{i\omega t} \tag{2.5}$$

$$= E_0 (J_0(\beta) e^{i\omega t} + J_1(\beta) e^{i(\omega+\Omega)t} - J_1(\beta) e^{i(\omega-\Omega)t}), \tag{2.6}$$

where J is Bessel Function, β is known as the modulaton depth and Ω is the phase modulation frequency. This form shows the beam incidents on the cavity consists of three different parts: a carrier with angular frequency ω and two sidebands with frequencies $\omega \pm \Omega$, respectively. Once this phase-modulated beam reaches the cavity and reflects, each frequency component will be transformed by $F(\omega)$, leading to a reflected electric field of

$$E_{ref} = E_0 (F(\omega) J_0(\beta) e^{i\omega t} + F(\omega + \Omega) J_1(\beta) e^{i(\omega+\Omega)t} - F(\omega - \Omega) J_1(\beta) e^{i(\omega-\Omega)t}). \tag{2.7}$$

We cannot measure the reflected electric field directly, however, the intensity (power) of the electric field can be detected by the photodetector. The reflected electric field intensity can be expressed as

$$P_{ref} = |E_{ref}|^2 \tag{2.8}$$

$$= P_c|F(\omega)|^2 + P_s(|F(\omega+\Omega)|^2 + |F(\omega-\Omega)|^2) \tag{2.9}$$

$$+ 2\sqrt{P_c P_s}\Re[F(\omega)F^*(\omega+\Omega) - F^*(\omega)F(\omega-\Omega)]\cos\Omega t \tag{2.10}$$

$$+ 2\sqrt{P_c P_s}\Im[F(\omega)F^*(\omega+\Omega) - F^*(\omega)F(\omega-\Omega)]\sin\Omega t \tag{2.11}$$

$$+ (O[2\Omega]), \tag{2.12}$$

where P_c and P_s are the power of the carrier and sideband components, respectively. If $P_0 = |E_0|^2$ is the total power of the incident beam, then the power of the carrier will be $P_c = J_0^2(\beta)P_0$ and the power of each first-order sideband is $P_s = J_1^2(\beta)P_0$. If the modulation depth is small ($\beta < 1$), the almost all the power will be in the carrier and first-order sidebands,

$$P_c + 2P_s \approx P_0. \tag{2.13}$$

Now we take a look at the reflected power in expression Eq. 2.8, we can see clearly that the reflected power contains several frequency components: a DC power from the carrier, two components oscillating at the modulation frequency from the sidebands, and high-order components from the interactions between the sidebands. We are only interested in the two oscillating terms because they contain the phase of the reflected carrier. One of the oscillating term is sine and the other is cosine term, usually only one of them will be important, the other will vanish. Which one vanishes and which one survives depends on the modulation frequency. Normally, at low modulation frequencies the cosine term survives. At high modulation frequencies, only the sine term is important. In either case, we will measure $F(\omega)F^*(\omega+\Omega) - F^*(\omega)F(\omega-\Omega)$ and determine the laser frequency from that.

Then we need to know how to measure the error signal. In practice, we should use a high-frequency photodetector to measure the reflected power given in Eq. 2.8. The output of the photodetector includes all terms, but we are only interested in the $\sin(\Omega t)$ and $\cos(\Omega t)$. Therefore, we use a mixer and a low-pass filter to demodulate the error signal. Remember that a mixer multiplies its two inputs, so the product of two sine waves are

$$\sin(\Omega t)\sin(\Omega^{'} t) = \frac{1}{2}\{\cos[(\Omega - \Omega^{'})t] - \cos[(\Omega + \Omega^{'})t]\}, \tag{2.14}$$

where Ω is the modulation freqeuency and $\Omega^{'}$ is the demodulation signal into the other input. From Eq. 2.14, we know the output will contain signals at both the sum $(\Omega + \Omega^{'})$ and difference $(\Omega - \Omega^{'})$ frequencies. If $\Omega^{'}$ is equal to Ω, which is the case we usually use, the $\cos[(\Omega - \Omega^{'})t]$ term will be a DC signal, which we can isolate with a low-pass filter. On the other hand, if we mix a sine and a cosine signal, rather than two sines, we get

$$\sin(\Omega t)\cos(\Omega^{'} t) = \frac{1}{2}\{\sin[(\Omega - \Omega^{'})t] - \sin[(\Omega + \Omega^{'})t]\}. \tag{2.15}$$

In this case, if $\Omega = \Omega^{'}$ our dc signal vanishes. Therefore, if we want to measure the error signal when the modulation frequency is low we must match the phases of the two signals going into the mixer. We can simply introduce a 90 degree phase shift to turn a sine to a cosine. However, in reality even when the modulation frequency is high you still need a phase shifter, because there are always unequal delays in the two signal that need to be compensated, and when you try to set up a Pound-Drever-Hall signal you usually need to sweep the laser frequency and empirically adjust the phase in one signal path until you get an error signal that looks like Fig 2.3 and 2.4 below.

After we understand how to generate the error signal and measure it, we should know what the real PDH signal looks like under both low and high modulation frequency. Firstly, we start looking at the reflected power when we slowly dither the laser frequency. For our phase modulated beam, the instantaneous frequency is

$$\omega(t) = \frac{d}{dt}(\omega t + \beta \sin \Omega t) = \omega + \Omega\beta \cos \Omega t. \tag{2.16}$$

The reflected power is just $P_{ref} = P_0|F(\omega)|^2$, thus we can expect it to vary over time as

$$P_{ref}(\omega + \Omega\beta \cos \Omega t) \approx P_{ref}(\omega) + \frac{dP_{ref}}{d\omega}\Omega\beta \cos \Omega t \tag{2.17}$$

$$= P_{ref}(\omega) + P_0 \frac{d|F(\omega)|^2}{d\omega}\Omega\beta \cos \Omega t. \tag{2.18}$$

Here we suppose we dither the frequency of the laser adiabatically, slowly enough that the standing wave inside the cavity was always in equilibrium with the incident light. Therefore, we can express $F(\omega)F^*(\omega + \Omega) - F^*(\omega)F(\omega - \Omega)$ with small Ω as

$$F(\omega)F^*(\omega + \Omega) - F^*(\omega)F(\omega - \Omega) \approx 2\Re\{F(\omega)\frac{d}{d\omega}F^*(\omega)\}\Omega \tag{2.19}$$

$$= \frac{d|F(\omega)|^2}{d\omega}, \tag{2.20}$$

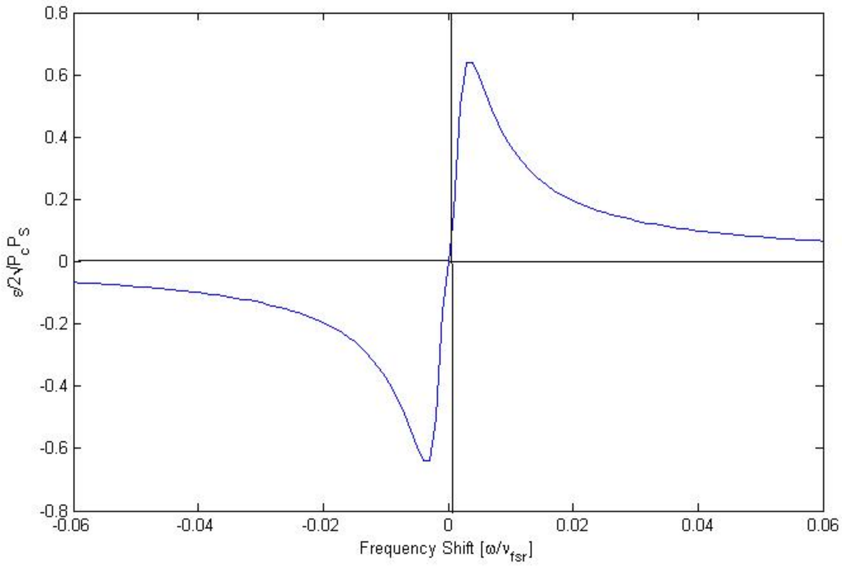


Figure 2.3. Pound-Drever-Hall error signal when the modulation frequency is low, the modulation frequency is about 10^{-3} of the free spectral range, r is 0.999.

which is purely real. Thus, for Eq. 2.8 only the cosine term will survive. Then the reflected power will become

$$P_{ref} \approx (constant\ term) + 2\sqrt{P_c P_s}\frac{d|F(\omega)|^2}{d\omega}\Omega \cos \Omega t + (O[2\Omega]). \tag{2.21}$$

Next, we can use a mixer to filter out everything but the cosine term, so the Pound-Drever-Hall error signal is then

$$\epsilon = 2\sqrt{P_c P_s}\frac{d|F(\omega)|^2}{d\omega}\Omega. \tag{2.22}$$

Fig. 2.3 shows the plot of this error signal.

Now, if the modulation frequency is high enough, we can assume the sidebands are totally reflected, $F(\omega \pm \Omega) \approx -1$. Then the expression

$$F(\omega)F^*(\omega+\Omega) - F^*(\omega)F(\omega-\Omega) \approx -i2\Im[F(\omega)], \tag{2.23}$$

is purely imaginary. Therefore, the cosine term in Eq. 2.8 vanishes, and the error signal becomes

$$\epsilon = -2\sqrt{P_c P_s}\Im[F(\omega)F^*(\omega+\Omega) - F^*(\omega)F(\omega-\Omega)]. \tag{2.24}$$

Fig. 2.4 shows this plot. In practice, we usually use high frequency to modulate laser frequency, so that the process of mixing and filtering to the DC signal we expecct does not yield a significant phase shift. Therefore, we normally can see this kind of error signal in Fig. 2.4 Besides, from this figure we can see this error signal has a large slope near resonance, which is helpful for the servo loop to lock laser.

If the laser frequency is close to the cavity resonance, then we can approximate $F(\omega)$ as

$$\Im[F(\omega)] \approx 1/\pi \frac{\delta\omega}{\delta\nu}, \tag{2.25}$$

where $\delta\omega$ is the offset from resonance, and $\delta\nu$ is the cavity linewidth. Therefore, the error signal can be approximated as

$$\epsilon = \frac{4}{\pi}\sqrt{P_c P_s}\frac{\delta\omega}{\delta\nu} = D\delta f \tag{2.26}$$

$$D = \frac{8\sqrt{P_c P_s}}{\delta\nu}, \tag{2.27}$$

where δf is the frequency offset from the resonance. From the equation above, we notice that the error signal is linear with offset frequency near resonance, an ideal condition for

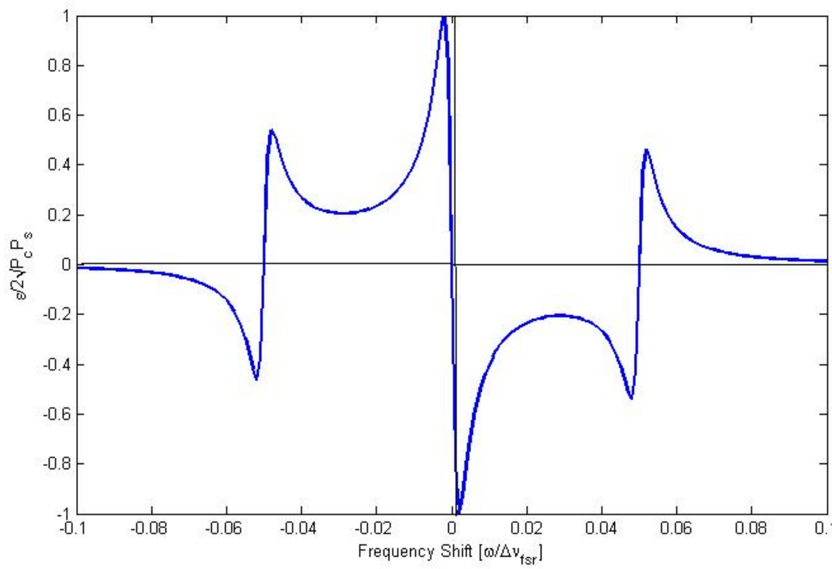


Figure 2.4. Pound-Drever-Hall error signal when the modulation frequency is high, the modulation frequency is about 4% of a free spectral range, r is 0.999.

a servo loop to operate. This region corresponds to the highly sloped central area about zero in Fig. 2.4.

2.3. Experimental setup

After the principle and mathematical treatment, this section is going to introduce the experimental setup and shows how to achieve Pound-Drever-Hall in practice. Fig. 2.5 shows the basic setup that used in this project. First, the laser used in this experiment is diode laser with the center wavelength at roughly about 650nm. Here, we directly modulate the laser by local oscillator, which is a DDS board, without using EOM, because the aim of this project is to test the stability of the cavity not runig experiments. In reality, we should use EOM after the laser output to modulate the laser frequency instead of using a DDS board, because if we directly modulate the laser it will also cause some influence to the expriment. After modulation, we send the laser through an optical isolator which is used to keep the reflected beam from getting back into the laser and destabilizing it. Then we use a series of optical set up like waveplate and PBS to make the light's polarization correct for coupling into the fiber. The telescope in this figure is used to shrink the laser beam coming from the fiber to match the beam size that the cavity's feature requires, also called mode-matching. To do this, we need to calculate the beam size of the first mirror in the cavity requires and the beam coming from the fiber, then determine the focal length of the telescope. I will talk about this in detail in a later chapter. The second PBS after the telescope is used to pick up the laser beam reflected from the cavity and send it into a photodetector, whose output is compared with the radio frequency (RF) also generated by a DDS board via a mixer. The output of the mixer will be the Pound-Drever-Hall error signal that we derive above. After the output of the mixer we can use a low-pass filter to isolate the low frequency signal (DC signal), and feed it into the tuning port on the laser through a servo loop. After adjusting the gain and phase of the servo loop, we can lock the laser to the fundamental cavity mode TEM_{00}.

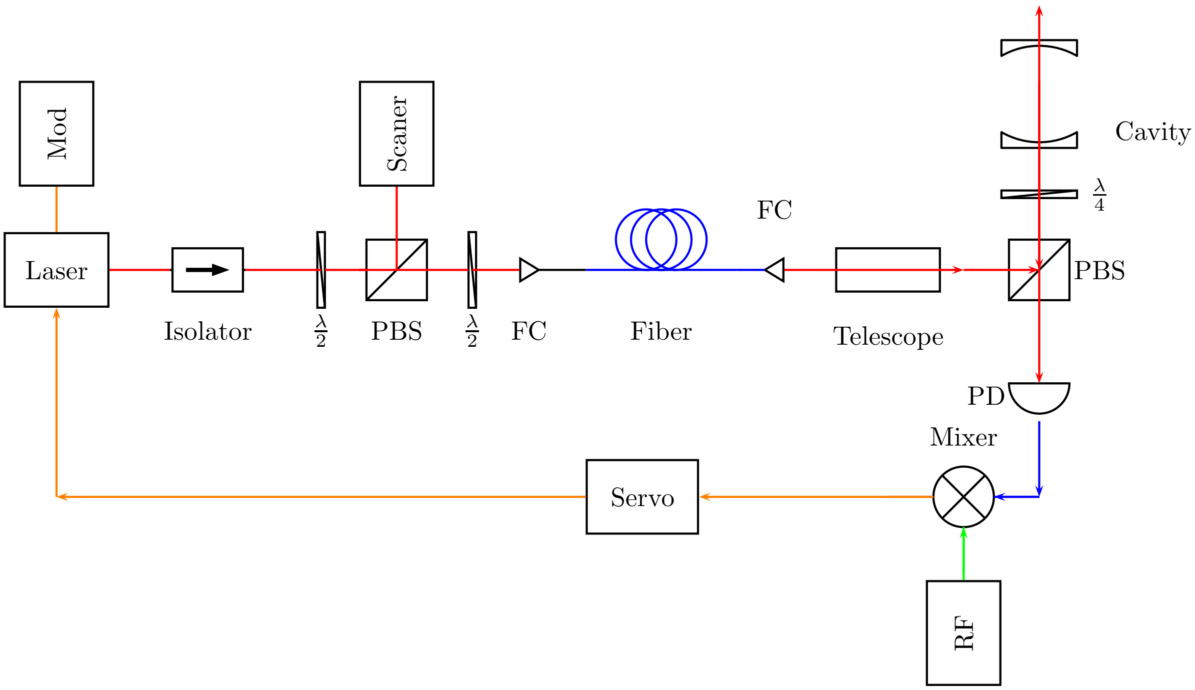


Figure 2.5. This figure shows the layout of the experiment setup. The red line represents laser beam, other color lines are signal paths. The signal going to the laser controls its frequency.

CHAPTER 3

Cavity Design

3.1. Zerodur Glass Cavity

The most important part in the whole experimental setup shown in Fig. 2.5 is the cavity, because the quality of one cavity can greatly determine how stable you will lock a laser. Therefore, we should be very careful and serious when we build a cavity, and this chapter will introduce aspects we need to think about during the process of building a cavity. As we know one F-P cavity consists of two mirrors seperated by a certain distance, and the Pound-Drever-Hall method requires a fixed length between two mirrors. However, even a fixed length cavity can be influenced by temperature. Thus, in order to get as much stable the cavity length as we can, we choose a kind of special material to build the cavity with, which is Zerodur Glass. This kind of material has a extremely low thermal expansion, $\Delta L/L = 2.15 \times 10^{-3}/K$, at room temperature.

Then we need to design a shape for this cavity considering the aim of this project is try to lock several different lasers in the lab simultaneously, thus we decided to make the cavity into a block shape with different tube channels. The dimension of this cavity shown in Fig. 3.1. It is a square block and contains 6 cavities, and each cavity has same length 9cm, so free spectral range $\Delta\nu_{fsr} \approx 1.67$ GHz. The reason we choose this length is that we will put it into a vacuum chamber which has a 6 inch six-cross chamber, so the size of the chamber limits the length of this cavity.

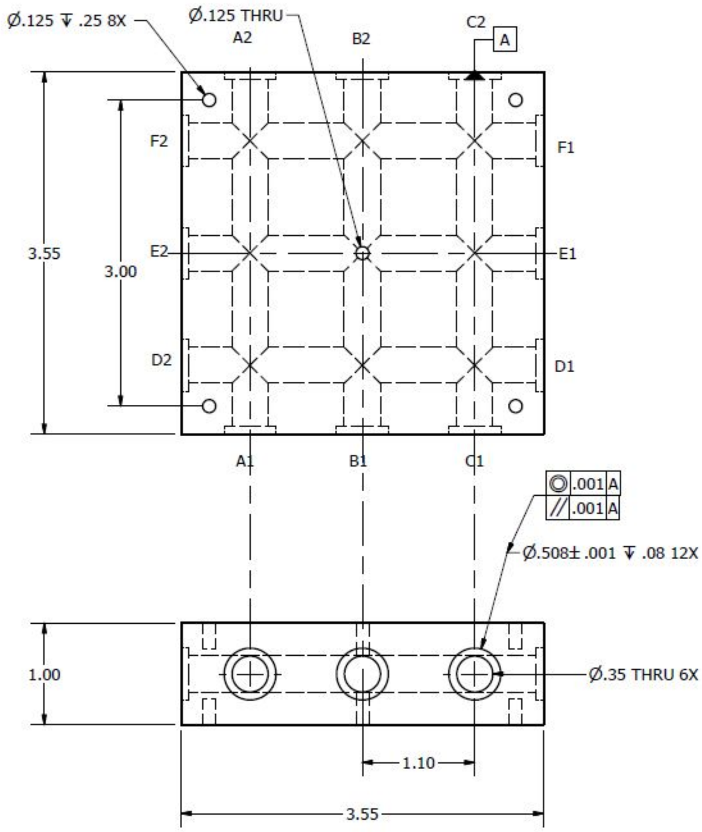


Figure 3.1. Cavity Design. The annotations in this figure are given in the unit of inch.

After we set the length of the cavity, we need to choose proper mirrors for each cavity to make it suitable for our application. There are several things need to consider when we choose mirrors.

Firstly, we need to build a stable cavity, which can form a standing wave. To achieve this, you need to choose proper mirrors' curvature to meet the following equation

$$0 < (1 - \frac{L}{R_1})(1 - \frac{L}{R_2}) < 1, \tag{3.1}$$

where L is the seperate lenght of the two mirrors, R_1 and R_2 are the curvature radius of two mirrors respectively.

Usually, there are several different geometries of stable cavities such as plane-pareller concentric (spherical), confocal and hemispherical. Fig. 3.2 shows the radiation pattern inside each cavity. Actually, the larger area the radiation pattern is, the better the cavity is. Although the plane-parallel cavity has the largest area, we usually don't use it because the light will leak out after several round trips. Therefore, people usually use confocal and near confocal geometry configuration. In order to couple a laser into cavity easily, people also use hemispherical cavities.

Secondly, we also need to be careful with the TEM modes distribution in a cavity, when we try to lock one laser we need to lock it to one of TEM modes in the cavity, Fig. 3.3 shows TEM modes distribution in the different kinds of cavity. Usually, we don't want the modes in cavity are too dense or too sparse, we want them distributed evenly in the cavity, which we can calculate from the following equation

$$\nu_{nmq} = \frac{c}{2L}[q + \frac{1}{\pi}(m + 2n + 1)\cos^{-1}(\sqrt{g_1 g_2})]. \tag{3.2}$$

This equation gives us the frequency difference between different modes. Here n and m are the mode number we need to consider, we usually keep q unchanged and ignore it, and $g_1 = 1 - \frac{L}{R_1}$ and $g_2 = 1 - \frac{L}{R_2}$.

Another thing we need to consider when we choose mirrors is the Q factor of one cavity which also refers to Finesse of one cavity. Finesse of one cavity is given by

$$\mathcal{F} = \frac{\Delta\nu_{fsr}}{\delta\lambda} = \frac{\pi}{2\sin^{-1}(1/\sqrt{F})}, \tag{3.3}$$

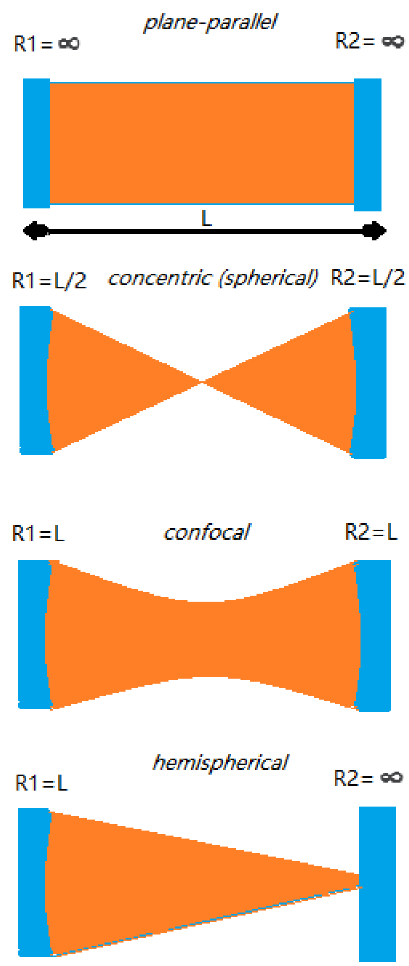


Figure 3.2. Four kinds of optical cavities, with mirrors of various curvature, showing the radiation pattern inside each cavity

where $F = \frac{4r}{(1-r)^2}$ is the coefficient of finesse, r is the reflectivity of the mirrors, and $\delta\lambda$ is full-width half-maximum of one transmission band. From this equation, we can notice that higher Finesse cavities make locking laser more accurate, but it is limited by the laser source. If the laser you want to lock has a wider linewidth than $\delta\lambda$, then the transmission

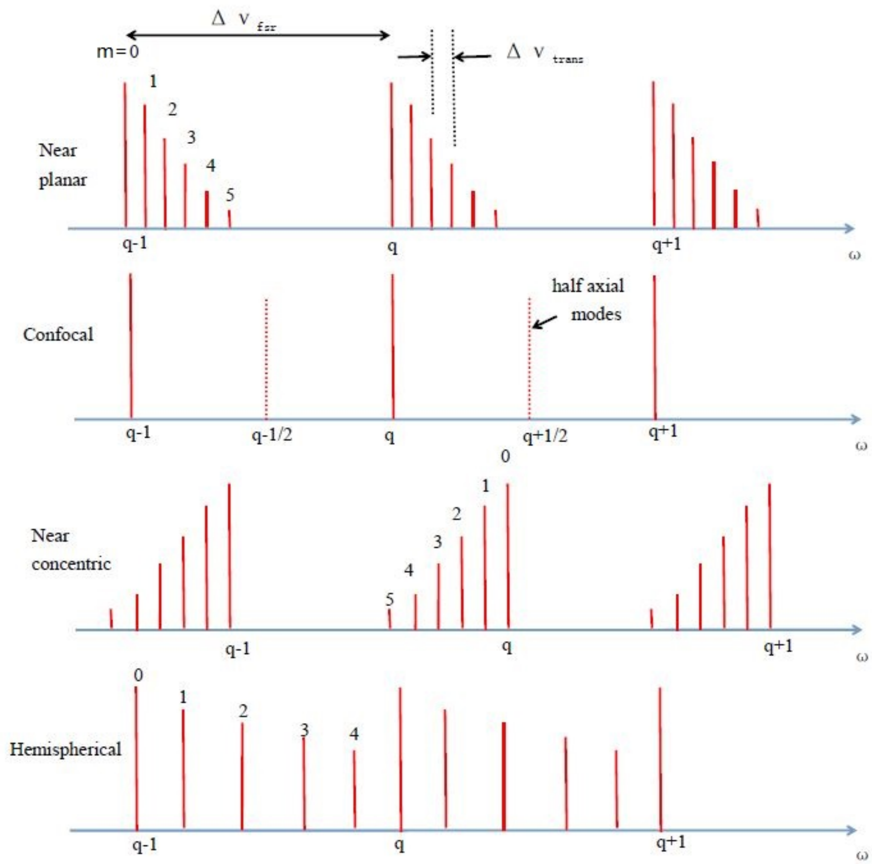


Figure 3.3. The TEM modes distributed in each different cavity within 1 FSR, where q and number $m = 0, 1, 2...$ are the first and second order of the TEM mode number seperately.

energy will decrease a lot, which will be very diffcult to obtain an error signal. Thus, we should choose a proper cavity Finesse. We also notice that Finesse is determined by the reflectivity of the mirrors. When r is larger than 0.5 we can get approxmate the Finesse $\mathcal{F} = \frac{\pi r^{1/2}}{(1-r)}$ showed in Fig. 3.4. If the two mirrors are not equal, the finesse becomes

$$\mathcal{F} \approx \frac{\pi (r_1 r_2)^{1/4}}{1 - (r_1 r_2)^{1/2}}. \tag{3.4}$$

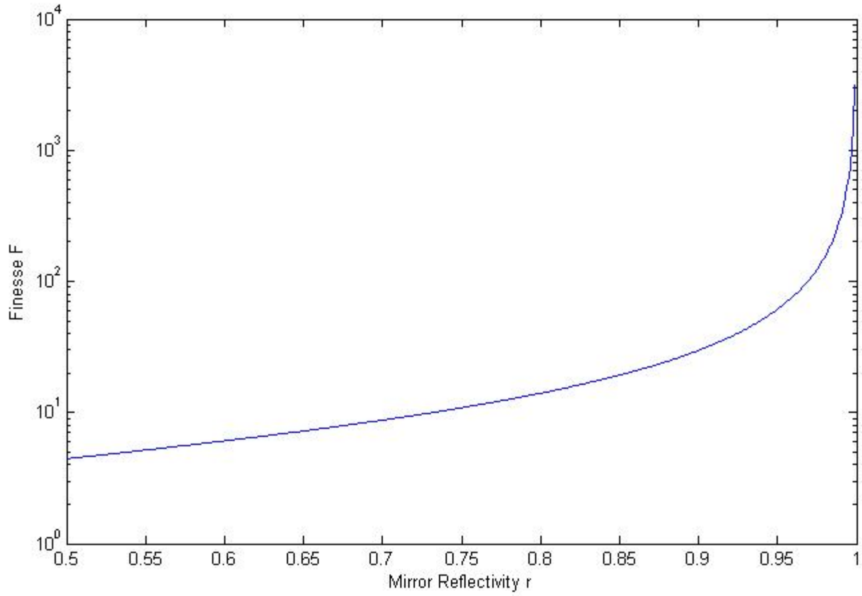


Figure 3.4. Finesse as a function of reflectivity. Very high finesse factors require highly reflective mirrors.

Based on experience, we usually choose one cavity finesse to be greater than 1000.

3.2. The Choice of Cavity Mirrors

After we take these above factors above into account, we chose the set of mirrors listed in the table below. The number A1, A2 ... in this table correspond to the number in the Fig. 3.1, which is convenient for people to tell which cavity is which.

Table 3.1. A summary of cavity mirror parameters

	A1	A2	B1	B2	C1	C2
Wavelength range(nm)	430-490		610-660		610-660	
Radius(mm)	500	500	Flat	500	Flat	500
Reflectivity	99.9%	99.9%	99.9%	99.98%	99.9%	99.9%
Finesse	3140		5234		3140	
Beam size(mm)	0.150	0.150	0.199	0.220	0.199	0.220
	D1	D2	E1	E2	F1	F2
Wavelength range(nm)	750-850		950-1150		430-490	
Radius(mm)	Flat	500	Flat	250	500	500
Reflectivity	99.98%	99.99%	99.98%	99.98%	99.9%	99.9%
Finesse	20942		15706		3140	
Beam size(mm)	0.221	0.244	0.205	0.256	0.150	0.150

Notice that the beam size in the above table means the laser spot size on each mirror w_1 and w_2, calculated by

$$w_1 = \sqrt{\frac{\lambda L}{\pi}}[\frac{R_1^2(R_2 - L)}{L(R_1 - L)(R_1 + R_2 - L)}]^{1/4} \tag{3.5}$$

$$w_2 = \sqrt{\frac{\lambda L}{\pi}}[\frac{R_2^2(R_1 - L)}{L(R_2 - L)(R_1 + R_2 - L)}]^{1/4} \tag{3.6}$$

In this project, we used the B1, B2 cavity because the laser we want to lock is 657nm.

3.3. Support System for the Cavity

As discussed above, we need to put the cavity into a vacuum chamber, because we want it work under vacuum environment to reduce the effect of temperature, vibration

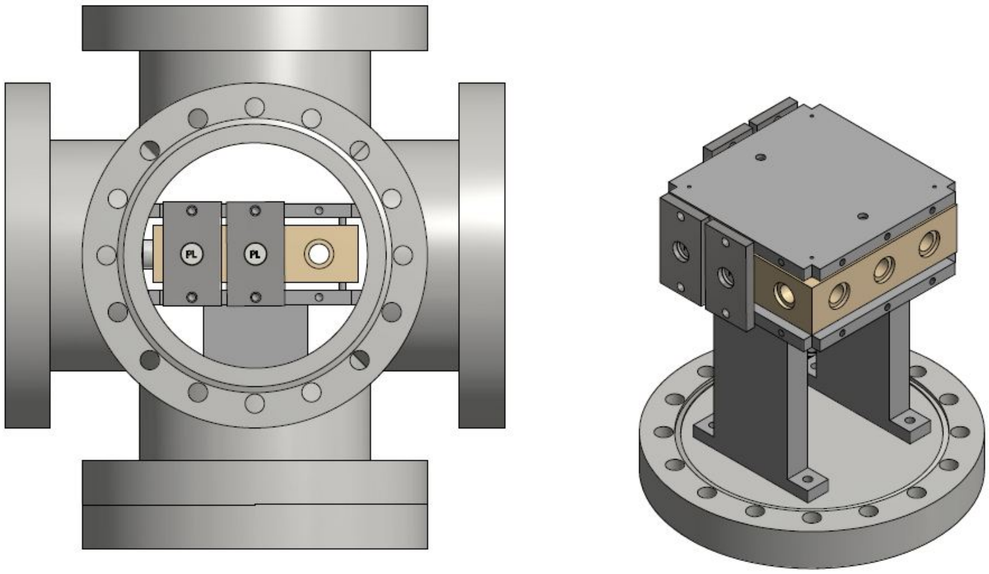


Figure 3.5. This is the support system for the cavity,

and air reflection. To achieve this, we have to build a support system to hold the cavity in the chamber showed in Fig. 3.5. Next we need to attach the mirrors to the cavity, but we cannot use glue, becuase glue has a large thermal expansion which will cause changes to the length of the cavity as temperature changes. Therefore, we made a special mirror holder to push the mirrors to the cavity. The design of this support system and the mirror holder are presented in the Appendix A.

CHAPTER 4

Temperature Control

In the last chapter, we mentioned that PDH method requires a fixed length cavity to lock a laser. In order to get a better locking result, we need to keep the length of the cavity as stable as possible. One significant thing that will change the length is temperature, even if we use very low thermal expansion Zerodur Glass, the temperature drift will still cause a big influence on the locking result. For example, one degree Kelvin shift in room temperature would result in a laser frequency drift of roughly 357 kHz. Therefore, if we want to keep the frequency fluctuations within 100 kHz, then the temperature can drift by no more than 200 mk. To achieve this, we need temperature controllers (PID circuit) to help us.

4.1. Electronic Circuits Design

4.1.1. Thermal Design

First, we need to design the heaters that will be used to heat the whole system. As the Fig. 3.5 shows, our system is a large six-cross chamber, which is not a regular shape and difficult to cover. Therefore, in order to make the distribution of blackbody radiation even, for different parts of the chamber we use different design of heaters. The arm of the chamber which is a cyclindrical shape, so we use heating wires (Alloy 875, 24 AWG solid) to wind them around each arm. There are six arms of this chamber, so we make six sets of these heating wires and control them separately, showed in the Fig. 4.1. Besides,

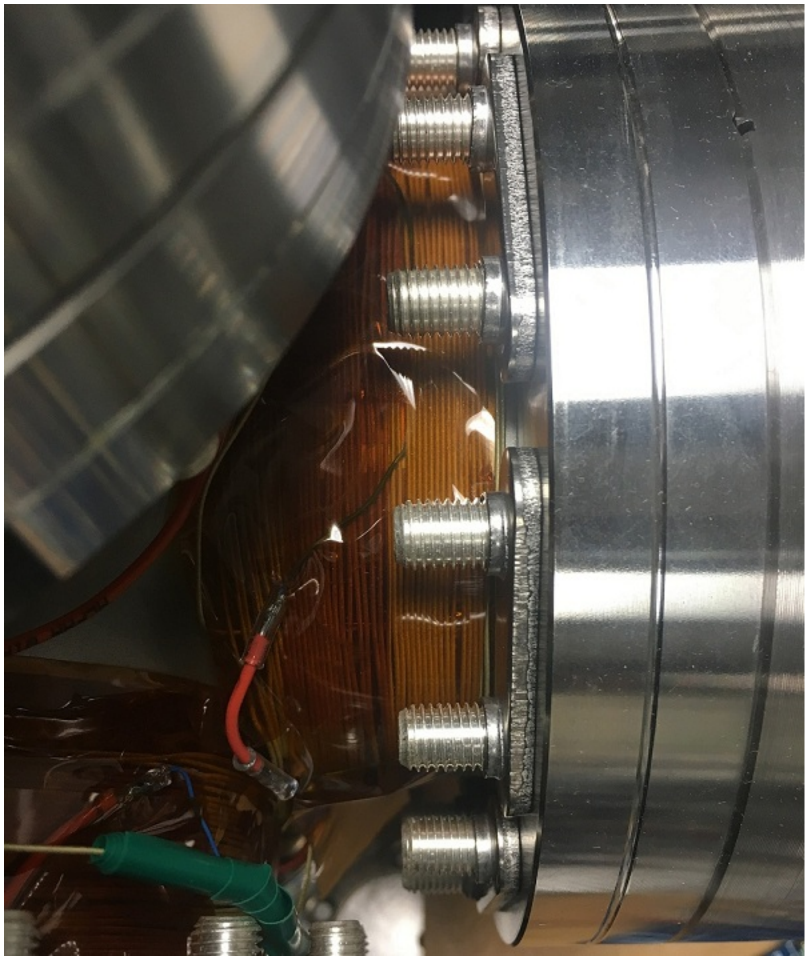


Figure 4.1. Photo of the heater around the arm of the vacuum chamber. The yellow wire under the tape is the heater. The blue one is the thermistor connected to the red wire. In each arm we use four thermistors to measure temperature.

the faces of the chamber will dissipate a lot of heat, so we also built six heating sheets to cover them. Fig. 4.2 shows the design of the heating sheet. Thus, the 12 different heaters needed to be controlled, which is a lot work. We also test those heaters and make sure the resistance of them are roughly the same, here we choose 120 Ω. Those heaters can reach the temperature of nearly 30 °C under a working voltage 25 V.

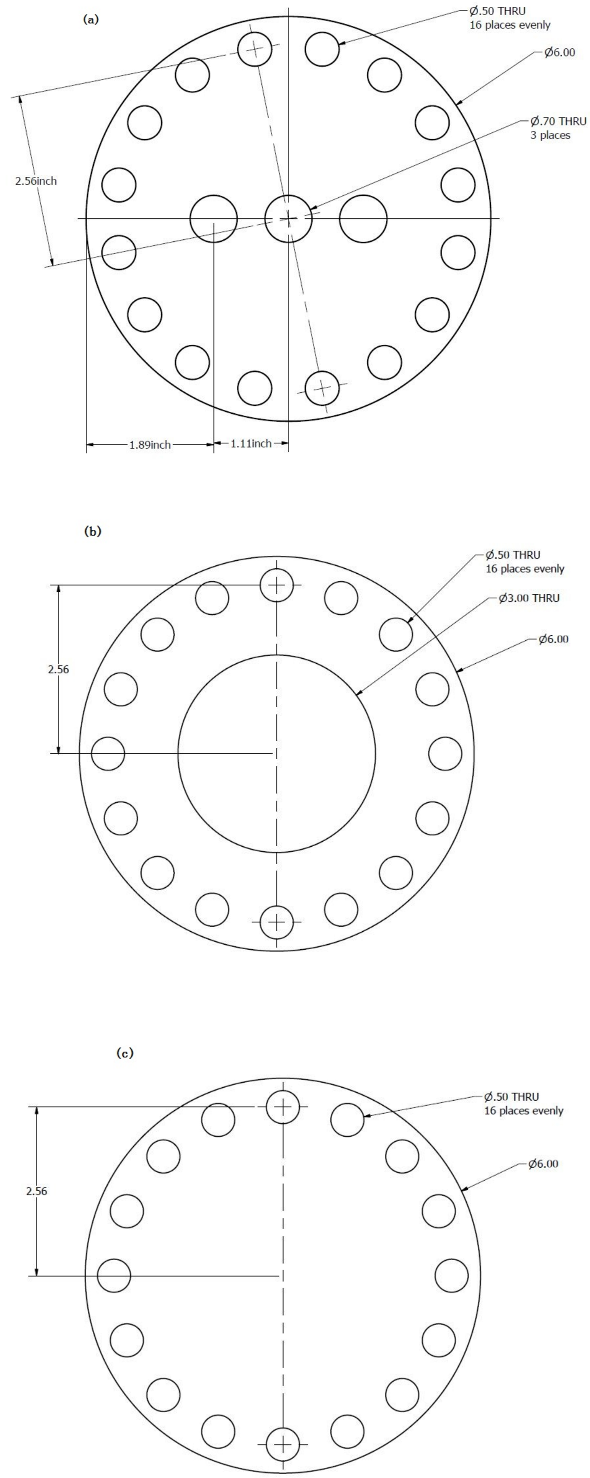


Figure 4.2. Design of the heater for the vacuum chamber's faces. (a) is the heater for the viewport, the three holes in the middle are used for guiding laser into the cavity. (b) is the heater for the top face (reducer), the middle holes are used for installing ion pump. (c) is the heater for the bottom.

4.1.2. Current Driver

Next, we need to control the current in those heaters to keep the temperature stable by using current driver. Fig. 4.3 shows the design of the current driver [5]. In this schematic, J1 is a connector that let the error signal goes in. J2 should be connected to the heater. The amplifer IC1, transistor Q1 and T1 work together as a linear power amplifier stage. The resistor R2 and R3 provide biasing for the transistor Q1 and T1 which form a Darlington Pair, feeding the heater. The diode D1 ensures that the heater receives power only when it is positive. The capacitor C1 and C2 are used to reduce the noise in the signal.

4.1.3. PID Circuit

Next we need to know how to generate error signal, and this section will introduce the circuit that was used to provide the error signal. Fig. 4.5 shows the schematic of the circuit to generate the error signal. The resistors R1, R2 and R3 are of the Wheatstone bridge desgin to measure the temperature of the heater, and this design will help us reduce the noise. J1 is connected to the thermistor(NTC 10 KΩ) covered by the heater. This kind of thermistor has a resistance of 10 KΩ at 25 °C. There is a model that you can use to calculate temperature from the resistance you read, which is the β model.

$$R = R(25\,^{\circ}\mathrm{C})\exp(\beta(\frac{1}{T} - \frac{1}{298.15})), \tag{4.1}$$

where R is the resistacn and R(25 °C) is 10 KΩ. T is the Kelvin Temperature, β is given in the data provided in the datasheet of this thermistor. Here, β is 3988 K.

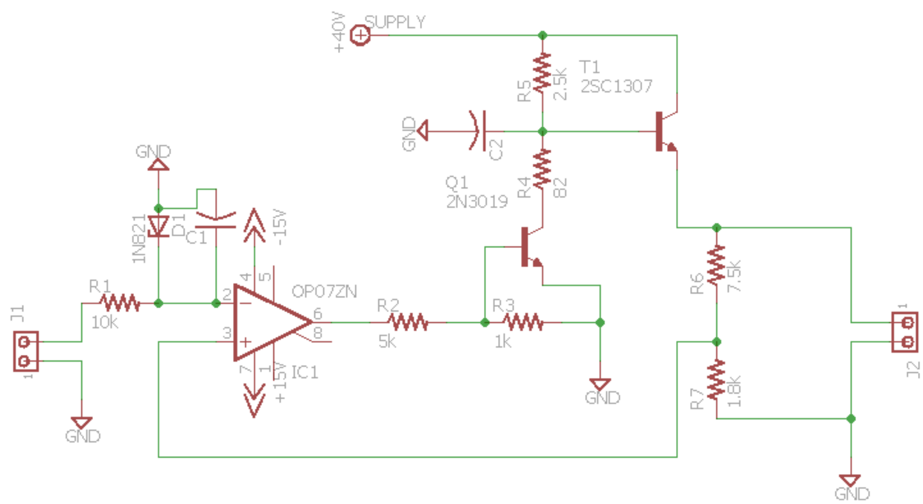


Figure 4.3. Schematic of the current driver to control the heaters. The operational amplifier IC1 is OP07. The transistor Q1 and T1 are 2N3019 and 2N6043 seperately. D1 is a diode.

The regulator REF01 is used to provide a stable voltage source of 10 V to generate the signal. The amplifier IC2 is used to amplify the signal coming from INA128, and IC4 is used to invert the signal to make sure the polarity is correct. Therefore, when the temperature of the cavity is too high, the resistance of that thermistor will decrease, which make the signal output from INA128 positive. After the inverter IC4, the signal will be inverted to a negative number. Then, we use this negative number to tell when the heater should stop heating to let the cavity cool down. On the other hand, if the temperature is too low, then the output from IC4 will be a large positive number and the heater should start to work. Besides this circuit, we also need another circuit called proportional–integral–derivative controller (PID) to fine adjust the error signal and drive the temperature to the setpoint. Usually a PID circuit is a set of operational amplifiers to do calculations to make the final error signal reach a setpoint as quickly as possible and keep it there. However, we use a microcontroller instead, because it is much more convenient to use. All we need to do is to write a code and make it have the ability to do the proportional and integre and derivative.The code is attached in Appendix C. When we use one microcontroller and want to adjust the P and I parameters, we only need to make some changes to the codes. We don't need to solder out and replace capacitors and resistors of the normal PID circuit board, which will save us lots of time. However, one disadvantage of the microcontroller is slow response, we cannot make the feedback very fast, because it is digital. Therefore, if we want to use it for fast applications like tuning lasers, it will not work, however here the response speed is enough to control the temperature. Considering the geometry and thermal properties of the vacuum chamber and optical cavity, blackbody radiation is expected to cause a thermal time constant of about 1 hour, so we can use a microcontroller instead. The one we used here is Arduino Mega 2560, which has 15 pins, of which we only use 12 of those 15 pins. There two things one needs to notice. Firstly, the maximum input voltage is 5 V, which means the output signal from the instrumental amplifier should not exceed 5V, otherwise it will kill the microcontroller. To avoid this, you can adjust your gain coeffecient of the amplifier. Secondly, the microcontroller cannot read the negative voltage, but the output from instrumental amplifier can be negative. Therefore, you should shift the error signal to positive by using an adder or subtractor which is just a set of op amplifiers. Fig. 4.4

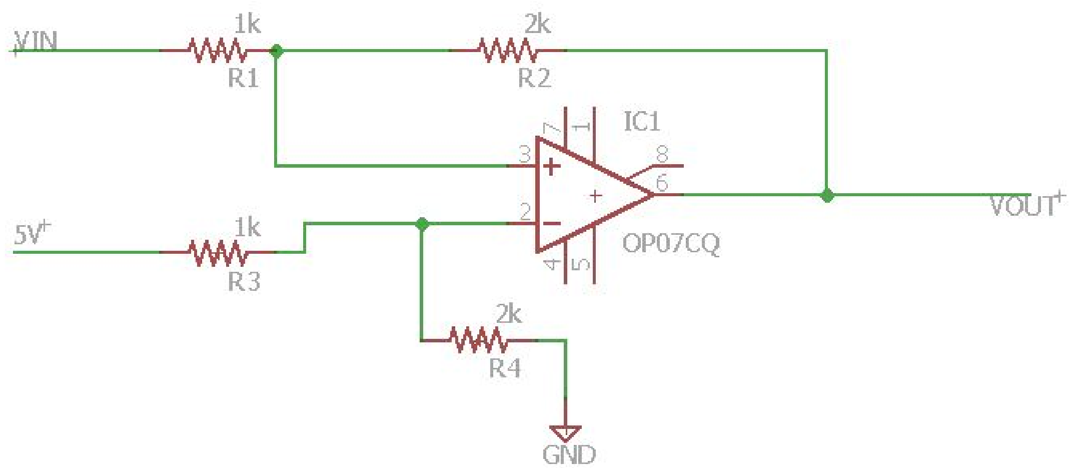


Figure 4.4. Schematic of an adder. IC1 is op amplifier OP07. One input is the error signal, the other input is 5V.

shows an example of an subtractor used to shift the error signal in this paper. The final output will equal to

$$V_{out} = \frac{1}{2}(5V - V_{in}). \tag{4.2}$$

Next thing we need to do is to connect these circuits in order: Thermistor→Instrucmental Amplifier →Adder →PID(Microcontroller) →Heater.

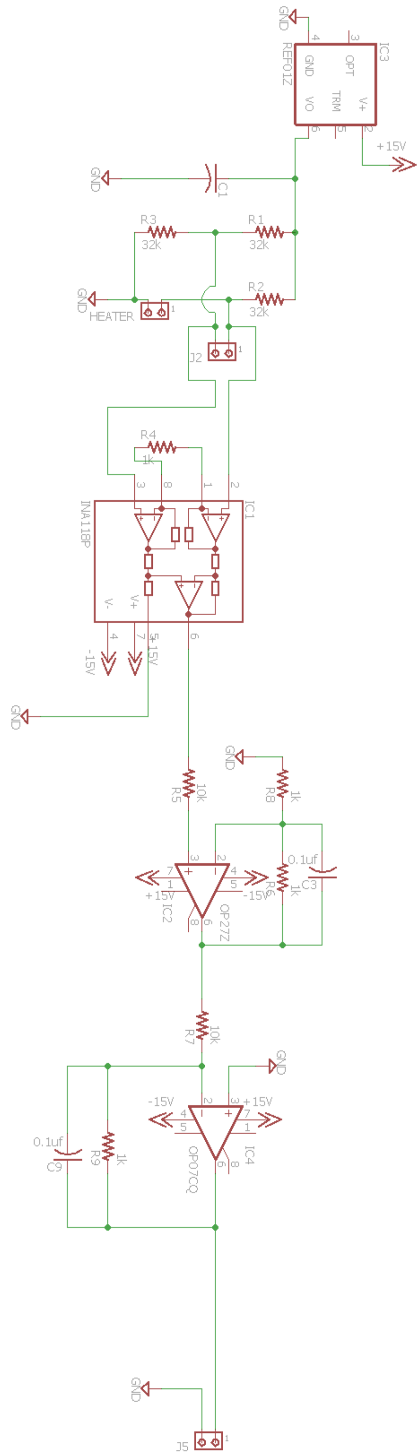
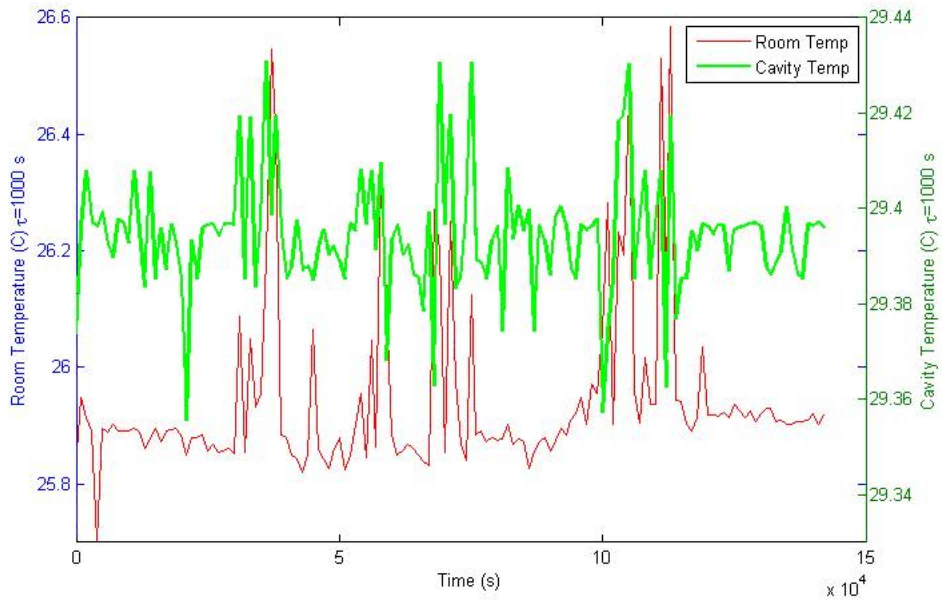


Figure 4.5. Schematic of the instrumental amplifier to generate the error signal. IC1 is an instrumental amplifier INA128. IC2 and IC4 are the op amps OP07. IC3 is the regulator REF01.

4.2. Temperature Performance

After the introduction of the design of the temperature controller, this section will demonstrate the temperature stability performance by using those designs. Fig. 4.6 shows the temperature controller performance. In the top figure, there are two plots, the red line is the room temperature which is uncontrolled, and the green line is the cavity temperature controlled by the temperature controller. The data shows the temperature fluctuations of the cavity is roughly 1 mK, which means if things are going well we can stabilize the frequency within 10 kHz. The bottom plot shows the Allan deviation of the cavity temperature, which means over a long time, this temperature controller can still work well and temperature is kept very stable.

From the top plot in the Fig. 4.6, we also notice that the correlation of measured cavity temperature to room temperature is quite strong. As the room temperature goes up, the cavity temperature will increase, which is normal and explainable. Therefore, in the future if we want to increase the temperature stability we can transfer this system to a small isolated room or build another isolated box to cover this system.



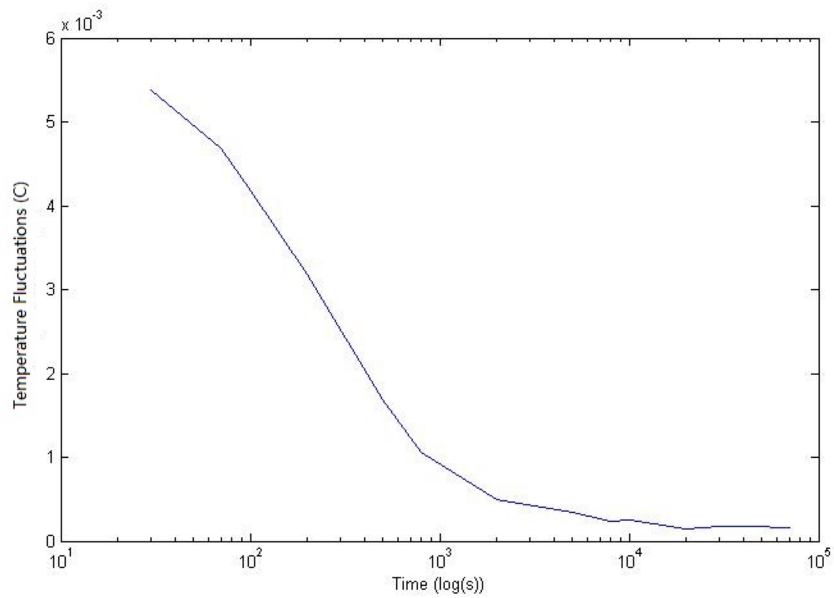


Figure 4.6. Figures of temperature performance. The top one shows the room temperature and cavity temperature drift (time constant 1000s). The bottom one shows the allan deviation of the cavity temperature.

CHAPTER 5

Coupling Laser into the Cavity

After temperature controlling the cavity, we need to couple the laser into the cavity. In this chapter, we describe how to choose and align the optics used for coupling light into the optical cavity. The optimization of this procedure requires consideration of an important concept, mode-matching. Mode-matching refers to the adjustment of the input beam's size, shape and wavefront curvature to match the cavity mode. If the ideal mode-matching is achieved, the reflection of a perfectly spatially matched input beam will interfere completely with the cavity wave transmitted back through the input mirror. Therefore, no power will be reflected off the input mirror and the laser will be on resonance with cavity. Usually this condition cannot be met and even a perfectly spatially matched beam will not couple all the power into the cavity, so there will still be some reflected net power. Thus, the reflected signal from the cavity on resonance will show a dip to a minimum. but not a dip to zero, shown in the Fig. 6.1.

5.1. Mode Matching

To do the mode-matching, firstly we need to think of a beam emitting from a waist in the cavity towards the laser, we can call this "cavity wave". The beam waist and radius of curvature of the cavity may be calculated from the mirror geometry [6].The general equation is

$$\omega_{s1} = \sqrt{\frac{\lambda L}{\pi}}[\frac{R_1^2(R_2 - L)}{L(R_1 - L)(R_1 + R_2 - L)}]^{1/4} \tag{5.1}$$

$$\omega_{s2} = \sqrt{\frac{\lambda L}{\pi}}[\frac{R_2^2(R_1 - L)}{L(R_2 - L)(R_1 + R_2 - L)}]^{1/4}, \tag{5.2}$$

where ω_{s1} and ω_{s2} are the beam waist of the first mirror and second mirror, and R_1, R_2 are the radius of curvature of two mirrors. Therefore, in our case, the geometry of the cavity(B1 and B2) is plane-concave so we let $R_1 \to \infty$ and calculate the beam waist of the cavity. Then, we need to shape and focus the diode laser beam to make it approach the size of the cavity wave. To do this, we need to know the beam size after the diode laser, which is the laser beam after the fiber showing in the Fig. 2.5. Here, we used the 657 nm diode laser, P3-630PM fiber and CFC-2X-B fiber coupler (from Thorlabs), so the waist of the beam after the fiber is roughly 0.19 mm. Also from Eq. 5.2, we get the beam waist of the first mirror is 0.19 mm, which means we don't need to enlarge or shrink the beam after the fiber to meet the mode-matching condition. However, we know laser beams propagate like Gaussian waves, so the waist will increase as the wave propagate, only certain ranges can be considered as parallel light given by

$$\frac{Z}{2} = \frac{\pi\omega_0^2}{\lambda}, \tag{5.3}$$

where ω_0 is the central waist of the beam. For $\omega_0 = 0.19$ mm, the parallel range is roughly 180 mm, but there is almost 600 mm between the cavity and the fiber. Therefore, if we don't use any lens between the fiber and the cavity, the beam will diverge and we cannot get mode-matching. To solve this, we can use a telescope to make the beam after

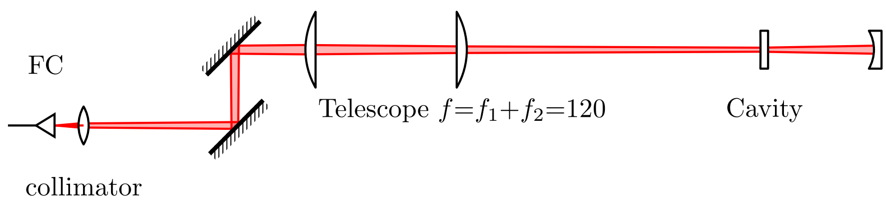


Figure 5.1. Mode-Matching setup. This telescope is made of two identical convex lens with f = 60mm. The two parallel mirrors in this figure are used for aligning beam to hit the center of the first mirror of the cavity.

proporgating a long distance still has the same size as before. The final setup shows in the Fig. 5.1.The two parallel mirrors in this figure are used to align beam to hit the center of the first mirror of the cavity. First mirror control the direction of up and down, second mirror control the left and right direction.

5.2. Examine Mode Matching

Even if we choose the appropriate lens, we still may not achieve mode-matching. We need to examine the performance of the alignment. To do this, we usually place a camera just after the cavity, so one can monitor the shape of laser mode on a computer. We also can place a photodetector to monitor the cavity transmission on an oscilloscope. Meanwhile, we should sweep the laser frequency ($\approx$ 10Hz) with a triangle drive signal generated by a function generator fed to the PZT-controlled laser mirror to find the resonance. Once modes are observed to be present, the laser's wavelength sweep should be adjusted so that about two cavity free-spectral-ranges are coverd. Fine adjustment of the alignment should lead to good coupling to the fundamental TEM_{00} mode of the cavity, which is a round and bright beam spot shown in the Fig. 5.2. When you see

Figure 5.2. Laser Mode. This round and bright spot is the fundamental TEM_{00} mode, we usually couple laser to this mode.

that the mode on the screen, and flash to other higher mode, then you can believe the mode-matching is correct.

CHAPTER 6

Locking Laser

6.1. Generating the Error Signal

After the adjustment of the alignment, we can then generate error signals while sweeping the laser frequency. Firstly, we need to modulate the laser frequency with a radio frequency, generated by a DDS board to create two sidebands. Based on experience, we find that ususal modulation frequency range from 15 MHz to 40MHz should work well. Here we used 25 MHz to modulate the laser. We also need to choose an appropriate modulation amplitude, which is usually less than 0.5 and we used 0.15. The DDS board can also play the role of phase shifter, after we monitor the signal we need to fine adjust the phase delay to make the signal better. Next, we need to place a photodetector after the PBS to monitor the reflected beam and measured the error signal, as the Fig. 2.5 showed. Then we feed this error signal coming from the photodetector into a mixer with another cosine signal generated by a DDS board, as we introduced in the chapter 2. After the mixer, we will use a low pass filter to isolate the DC signal, this process usually called error signal demodulation. We also find that it will be beneficial to add an band-pass filter after the photodetector. Additionally, to make the final signal easy to use, we can also add an amplifier before the servo loop. After doing these things, we get the error signal which qualitatively resembles the shape that the PDH principle predicted, shown in

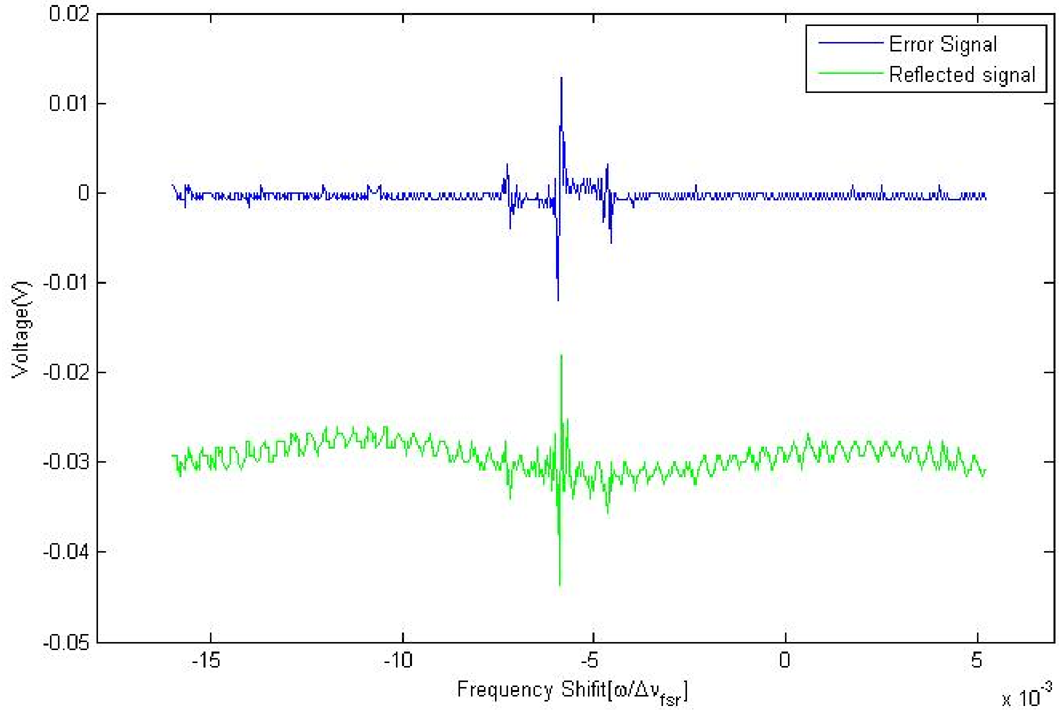


Figure 6.1. Error signal and reflected beam signal. The blue line in this figure shows the error signal coming from the mixer and the green line is the reflected beam signal measured directly after the photodetector.

Fig. 6.1. The dip in the green line means the laser gets transmitted, which corresspondes to the signal in the blue line.

6.2. Servo Loop Circuit Design

Since we successfully obtained the error signal, we then can try laser locking. As we introduced before, we should feed this error signal into a PID circuit to do a series of calculation and then use the output of the PID circuit to drive the laser frequency to a setpoint, and keep it stable. Therefore, we need to design and build this kind of PID circuit to meet our needs. In the previous chapter, we indicated that using a microcontroller to play the role of a PID, but when we try to lock the laser we cannot use a microcontroller anymore, because we need a very fast response. Comparing to the analog circuit, digital circuits one cannot provide a very fast response, so we need to build another PID circuit. In this circuit, we will need a power supply, a setpoint voltage, an instrcumental amplifier, a PID stage and an invertor. Therefore, we get the schematic shown in Fig. 6.3. In this figure, the right part are the power supplies that provide voltage for all the chips. In the main circuit, the REF is a voltage reference with IC1 and potentiometer R1 serving as the setpoint voltage. You can adjust R1 to get an appropriate setpoint voltage and you can also pick an appropriate REF chip to provide voltage reference. The IC2-IC4 chips consist of a instrumental amplifier, where one compares the error signal with the setpoint. The error signal goes into IC3. Then the result of the instrumental amplifer goes into PID part, but we normally only use P and I stage. The switch S1 enables us to control the I stage, when we don't need I we can switch it off. The potentiometers R2 and R3 are used to fine adjust the P and I parameters. After the PID calculation, we use the IC8 to sum them together. IC9 is an invertor, and switch S2 can enable or disable this invertor depending on the real situation. The IC10 is a buffer chip which can prevent the circuit from backwards current and make the circuit more stable.

The challenge of this PID circuit is to determine the phase and gain of this circuit. Firstly, we don't want any phase in the circuit, but as the signal frequency increases, the phase will accumulate caused by the capacitors and resistors. If the phase accumulates to 180 degree, then this PID circuit will totally reverse the result, and the system will become more unstable. Therefore, we need to reduce the phase of our circuit at high frequency. From experience, we know our system will work at roughly 100 KHz, then we reduce the values of capacitors and resistors around each chip in this circuit to meet our needs.

Secondly, we should also determine the appropriate gain. The goal of this is to ensure that there is sufficient gain at low frequency while keeping gain is small at high frequency. There is a way to roughly estimate the gain of this circuit. First, we should look into the error signal. As we introduced in Chapter. 2, the error signal is linear with offset frequency, so the slope of this signal has the unit of Voltage/Frequency. Then we need to determine the slope of the laser with the help of a function generator. As we introduced before, we apply a triangle wave to the laser to sweep the laser frequency, so we can find how far the laser frequency will be shifted by an applied voltage. Thus, the unit of the slope of the laser should be Frequency/Voltage. Finally, we can simply divide the slope of the laser response by the error signal's slope, to get the gain of the PID circuit, which we experimentally found to be roughly -20dB. After determining the gain, we change several resistors and capacitors in the circuit to meet our needs. For instance, if we change the resistor of the P stage to a smaller value, then the gain will be reduced, similar to the I stage. Besides, if we change the capacitors of the I stage to a smaller values, we will cause the I gain meets the P gain at higher frequency. Then we plot the transfer function of this circuit, shown in Fig. 6.2. Notice in this figure, I meets P at roughly 100 KHz, which means the total gain is -20 dB. Also note at relative high frequency, the phase of this circuit is still very small. Therefore, these two features meet our needs as explained above, and we can apply the PID circuit to lock the laser.

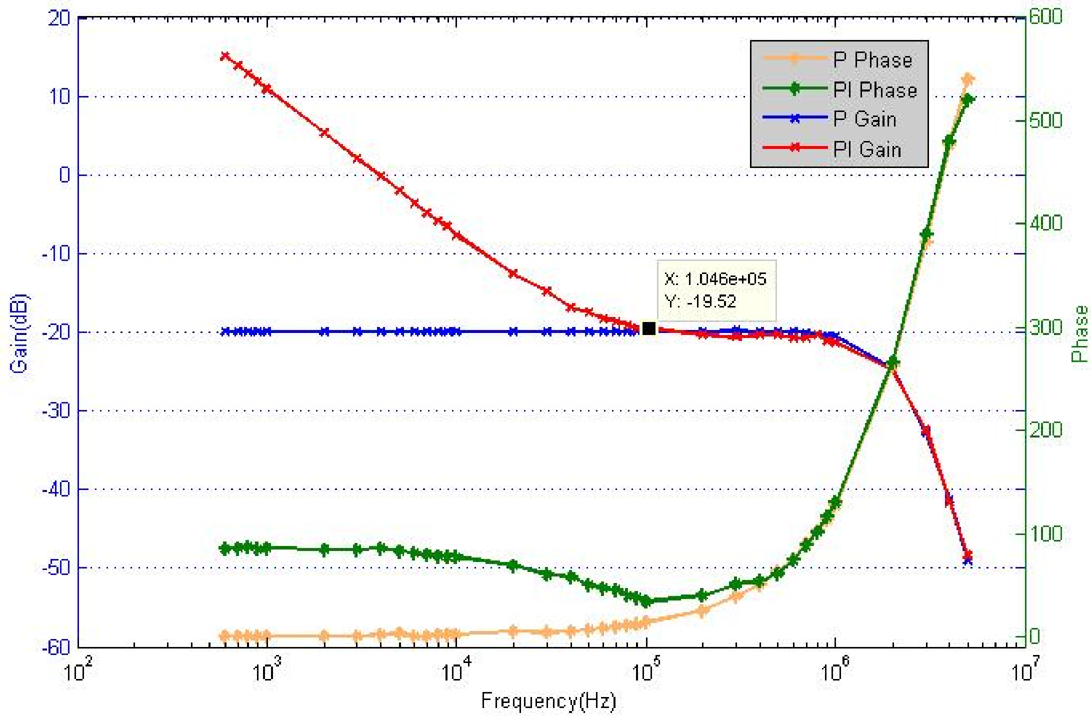


Figure 6.2. PID circuit performance. The blue line represents the P gain, and the red line represents PI gain, corresponding to the left axis. The yellow line represents the phase of the circuit only when P stage is working. The green line represents the phase of PI both working.

6.3. Locking the laser

With the loop filter designed, all the resistors and capacitors are set, we then can lock the laser to the cavity mode. At first, we should check the locking polarity by closing switch S2 and turning down potentiometer R2. If we see an increase in transmission, then the polarity of this system is correct. If not, we should open S2 and enable the invertor. If the servo perturbs the laser but no locking action is observed, the gain may be too low and the circuit is unstable, then we should turn down the potentiometer R2 to increase the gain until the laser is locked to the cavity. When we increase the gain past the optimum

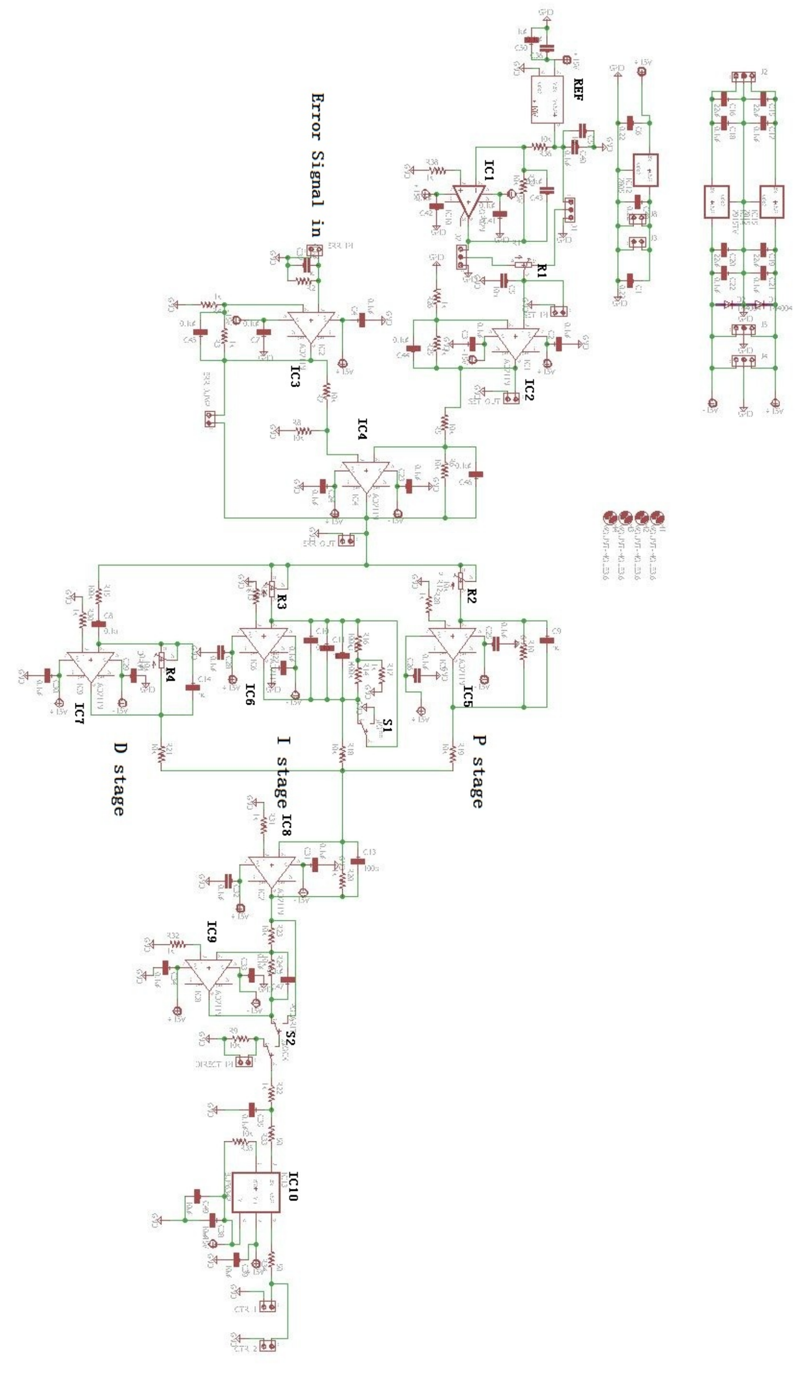


Figure 6.3. Schematic of PID circuit. REF is REF01, which provides the setpoint voltage. IC1-IC9 are all AD911N, which is faster than OP07. IC10 is a buffer chip. R1-R4 are the potentiometers.

point, we will see a oscillation on the error signal. One thing you should notice is that the error signal we feed into the circuit is very close to zero, so we need to change the REF in the circuit to REF03 and replace R1 with a large poteniometer, here it is 100 KΩ. If not, it will be so diffcult to make sure the setpoint voltage is close to zero, so there will be a large offset between error signal and setpoint, which will make locking out of action after a set of calculations with that large offset. After finding the appropriate gain and setpoint, we locked the laser to the TEM_{00} mode and observed it as pretty robust.

Next, we should measure the linewidth of the locked laser and see how good the performance of the lock is. The best way is to beat it against a more stable laser source on a photodiode and evaluate the resulting fluctuations. However, in our case we cannot beat our diode laser against a HeNe laser with wavelength of 632.8 nm, because our laser is 657 nm, so the wavelength difference is too large to tune our laser to beat with the HeNe laser. We can use another method to test the stability by sending our laser to an Iodine cell to perform spectroscopy and see the frequency fluctuations [7]. Unfortunately, this test is not included in this thesis, because this cavity right now is placed in an open environment (passway) and near the lab door, people need to go in and out of this lab and pass by this system causing huge influence on this system, which makes it very diffcult to conduct a long term measurment of frequency fluctuations. Also due to my lack of time, I cannot clean some room for this new setup and build this setup. Therefore, the frequency fluctuations measurment is not included in this thesis. What we know so far is the locking result seems very good. The future plan will be discussed in next chapter.

CHAPTER 7

Future Plan

First, I wish this system could be transfered to a isolated place and near the laser that needed to be locked. An isolated room will reduce the effect from a big surrounding and improve the locking result, and a nearby laser source will also improve the result, because if the laser if far from the locking system, you will need a long fiber to couple light into the cavity which will add a lot of phase and noise to the incident beam.

Secondly, although we observed the lock as robust, the acoustic noise still has a huge influence on this system, for example when we speak very loudly, the lock will disappear. I think that is because the acoustics will vibrate the arm that is holding the laser mirror in the diode laser, and this will cause the laser frequency to drift so that the servo loop cannot drive the frequency back. To solve this, I think we should put some rubber under the laser system and build a box to cover the laser. Also the chamber needs to be covered.

After these are done or only the chamber is transfered to a new place, the frequency fluctuations measurment could be conducted.

Finally, other cavities in this system also should be tested before putting in use, although in theory they will work as well.

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APPENDIX A

Mirror Holder and Support System Design

This appendix will present the design of the mirror holders and the cavity support system.

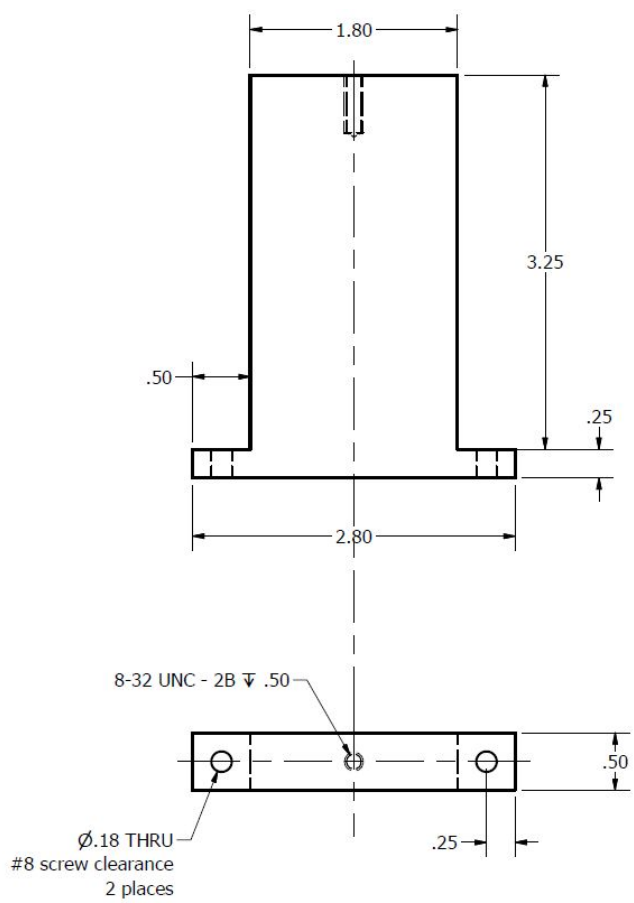

Figure A.1. Design of the stand used to support the cavity in the chamber.

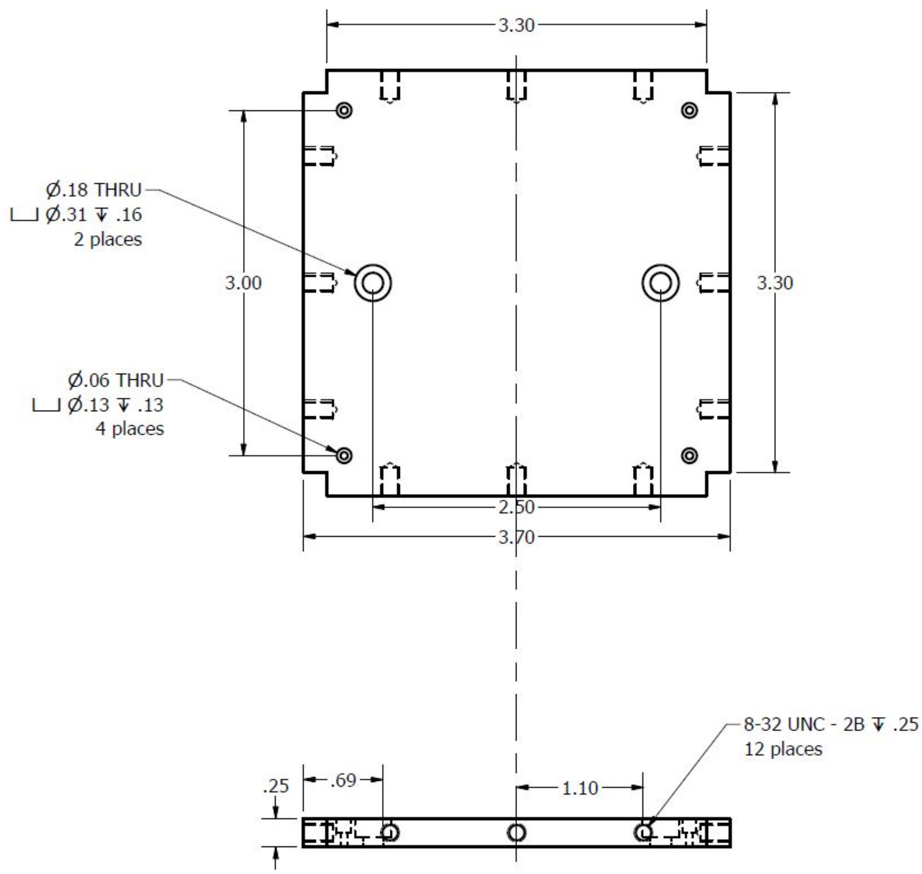

Figure A.2. Design of the baseplate connected to the stand and used to attach the mirror holders.

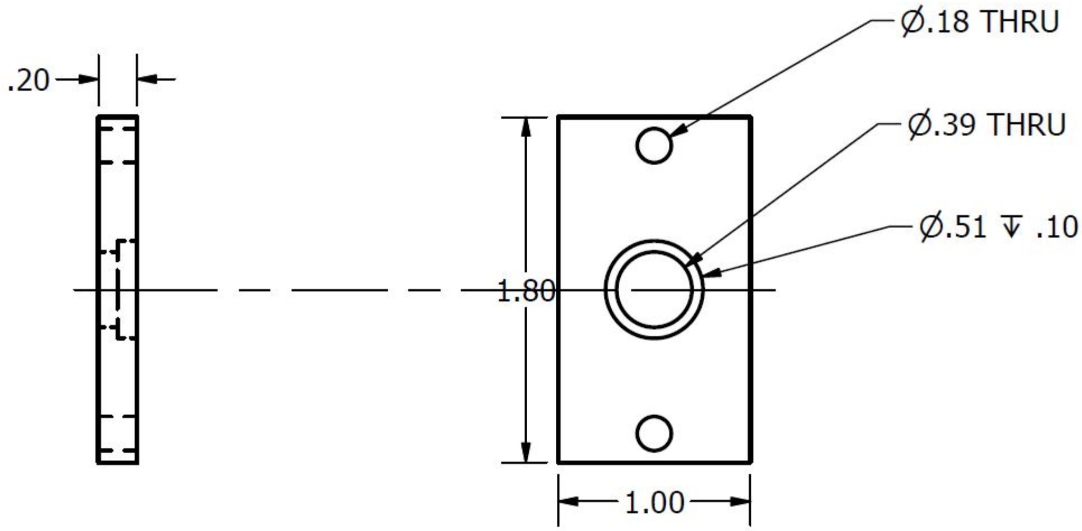

Figure A.3. Design of the mirror holder attached to the baseplate and hold the cavity mirrors.

APPENDIX B

Wire Connection in the Temperature Controller

This appendix will show you the wire connections in the temperature controller. Fig. B.1 and B.2 show the photo of the instrucmental amplifier part and inside wire connections. Fig. B.3 and B.4 show the photo of the current driver part and inside wire connections. You can find the arm number and the face number in the Fig. B.5.

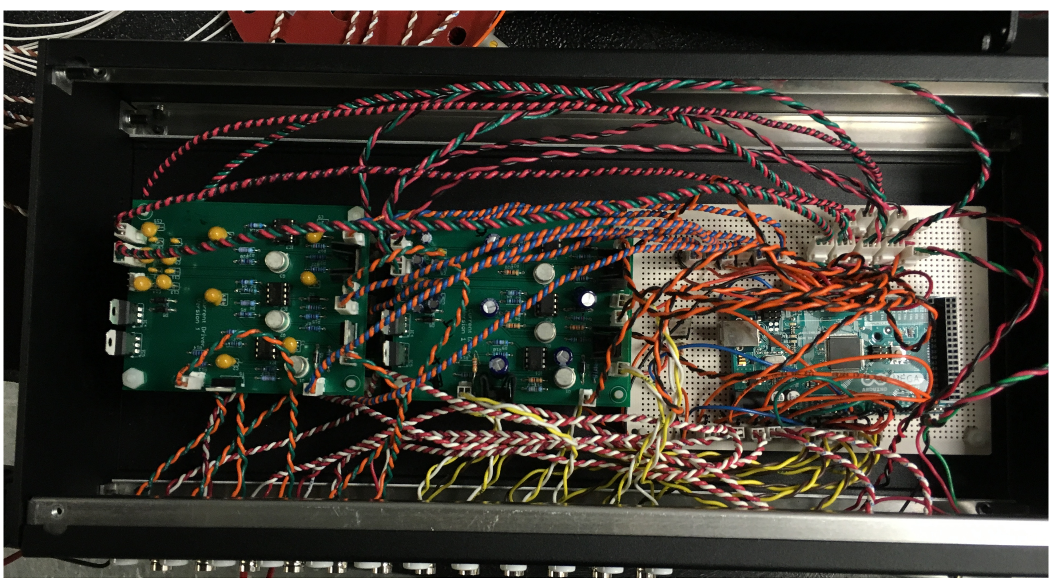

Figure B.1. Photo of the instrucmental amplifier electronic.

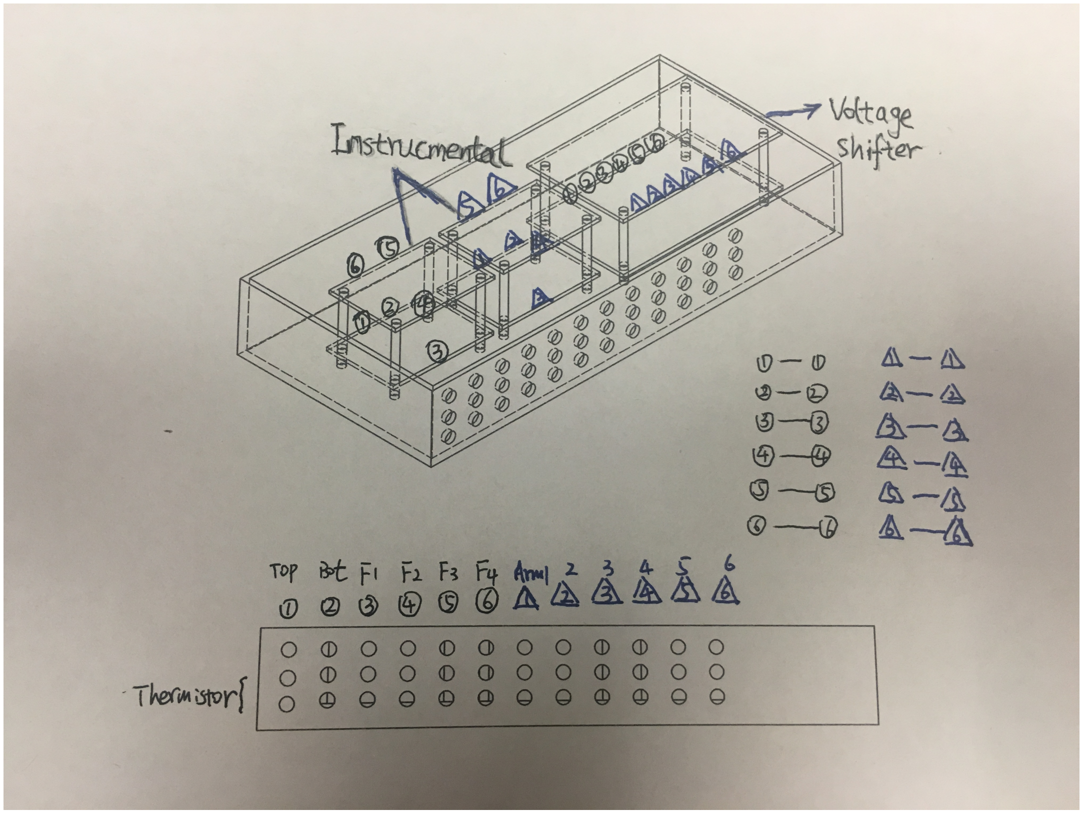

Figure B.2. Schematic of the wire connections of instrucmental amplifier electronic.

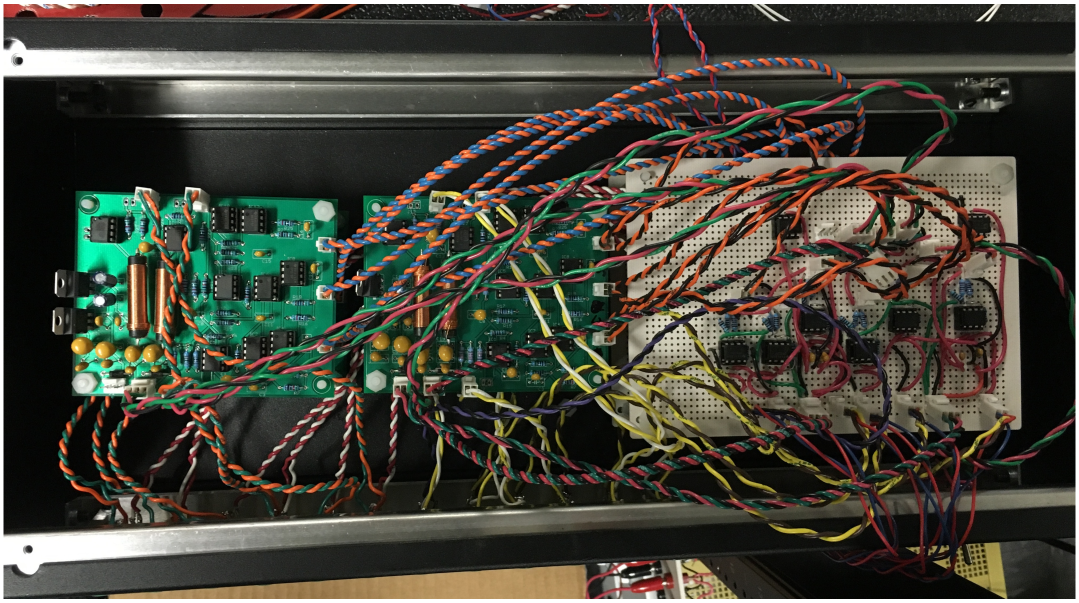

Figure B.3. Photo of the current driver electronic and the microcontroller.

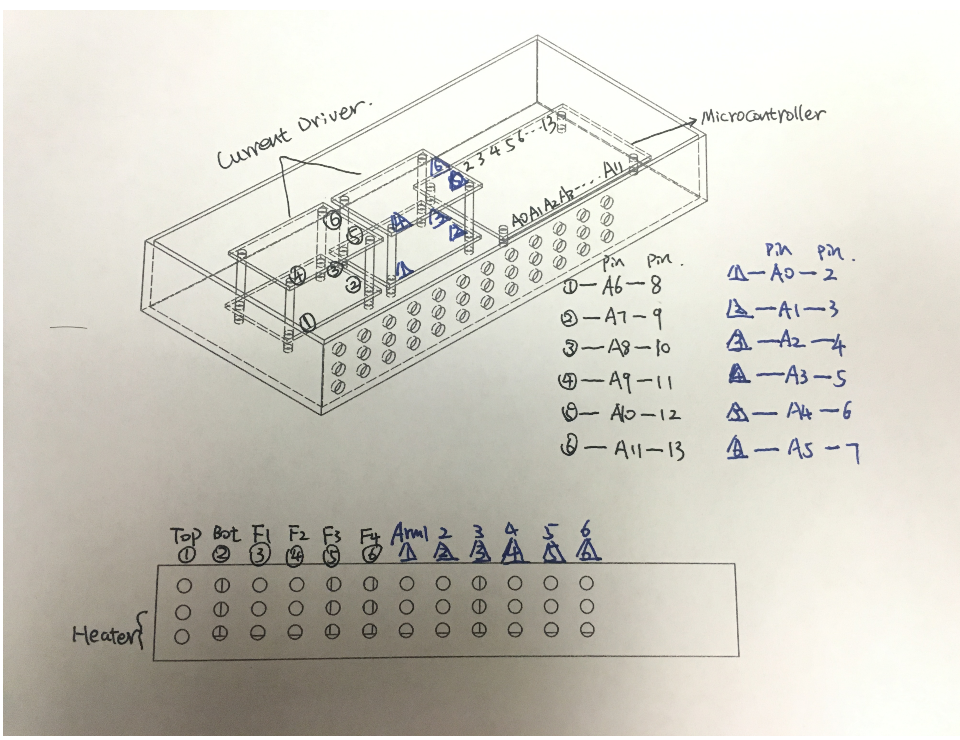

Figure B.4. Schematic of the wire connections of current driver electronic and the microcontroller.

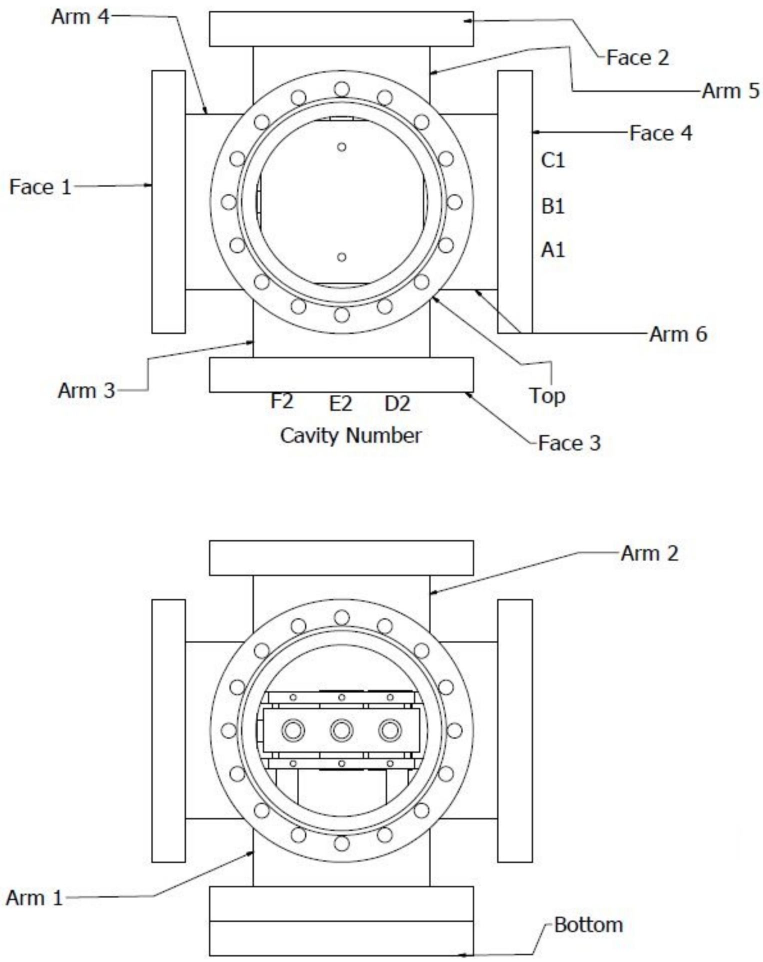

Figure B.5. Schematic of chamber's arm number and face number.

APPENDIX C

PID Codes

This is the PID codes for the microcontroller

```
const int Driverpin[]={2,3,4,5,6,7,8,9,10,11,12,13};
// assign output pins
const int Amppins[]={A0,A1,A2,A3,A4,A5,A6,A7,A8,A9,A10,A11};
// assign input pins
const int numerror=36;
const int maxvoltage=1023;
float setVol[]={512,512,512,512,512,512,512,512,512,512,512,512};
// setpoint voltage
float realVol[]={0,0,0,0,0,0,0,0,0,0,0,0};
float error[numerror];
float Error[]={0,0,0};
double Sumerror[12];
float PID_Kp[]={2.3,2.3,2.3,2,2,2,2,2,2,2,2.3,2.3};
float PID_Ki[]={0.01,0.01,0.01,0.009,0.009,0.009,0.01,
0.01,0.01,0.01,0.01,0.01};
float PID_Kd[]={0,0,0,0,0,0,0,0,0,0,0,0};
```

```
// all above need to be set and adjust

float Voloutput[]={0,0,0,0,0,0,0,0,0,0,0,0};
float mininput=0;
float maxinput=1023;
float minoutput=0;
float maxoutput=255;
// maximum output is 5V

void setup() {
  // put your setup code here, to run once:
  Serial.begin(9600);
  for (int thisReading = 0; thisReading < numerror; thisReading++){
   error[thisReading] = 0;
   Sumerror[thisReading]=0;
  }

}
void loop() {
  for (int armnumber = 0; armnumber < 12; armnumber++ ){
    realVol[armnumber]=analogRead(Amppins[armnumber]);
    error[2+3*armnumber]=error[1+3*armnumber];
```

```
    error[1+3*armnumber]=error[0+3*armnumber];
    error[0+3*armnumber]=setVol[armnumber]-realVol[armnumber];
    // get error signal
    Serial.print(error[0]);
    Serial.print("\t");
    Serial.print(error[9]);
    Serial.print("\t");
    Serial.print(error[18]);
    Serial.print("\t");
    Serial.print(error[21]);
    Serial.print("\t");
    Serial.print(error[24]);
    Serial.print("\t");
    Serial.print(error[27]);
    Serial.print("\t");
    Serial.print(error[30]);
    Serial.print("\t");
    Serial.println(error[33]);
// print values on the screen

    Sumerror[armnumber] = constrain(Sumerror[armnumber]+error[0+3*armnumber]
// constrain sumerror
```

```
    Error[0]=error[0+3*armnumber];
    Error[1]=error[1+3*armnumber];
    Error[2]=error[2+3*armnumber];
    realVol[armnumber]=PID_Kp[armnumber]*Error[0]+PID_Ki[armnumber]*Sumerror
// do the PID calculation


    if (realVol[armnumber]>=maxvoltage){
       Voloutput[armnumber]=maxvoltage;
   }
   else if (realVol[armnumber]<=0){
       Voloutput[armnumber]=0;
    }
    else{
      Voloutput[armnumber]=realVol[armnumber];
      }
      Voloutput[armnumber]=map(Voloutput[armnumber],mininput,maxinput,minout
// binary to decimal conversion
      analogWrite(Driverpin[armnumber], Voloutput[armnumber]);
// output the voltage
     }
}
```