Distributing Frequency Stabilized Light via Fiber Optics: Final Report

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Abstract: A laser beam with low frequency noise is desired in LIGO labs to act as a reference signal. The purpose of the project is to distribute a laser that has been frequency stabilized to a Fabry-Perot cavity to various labs via fiber optics and characterize the noise added by the fiber. To distribute the laser, we have mode matched the laser beam into the fiber in order to obtain the highest power output. The noise from the fiber would first be measured using self-homodyne detection. If the noise level is satisfactory, we would distribute the beam and measure the noise using a phase-locked loop. If the noise level above the labs requirements, then various techniques will be used to reduce that noise. Here, we outline the techniques used to mode match and determine the noise from the fiber and laser beam.

1 Introduction

The Coating Thermal Noise (CTN) lab is trying to determine the thermal noise of the coatings on mirrors in a Fabry-Perot cavity. This noise is caused by molecules jostling around at $k_B T$ at room temperature. In order to do so, they have two 1064 mm NPRO lasers which are each frequency locked to a cavity with a length of 1.45 inches (0.037 m). The frequency noise is determined by the displacement noise of the cavity, in other words, its change in length. The noise is examined by combining the two beams to get a beat frequency. Because the lasers are frequency locked to cavities, they should have low frequency noise. Theoretically, the noise level should be about $\frac{0.2}{\sqrt{f}}\frac{Hz}{\sqrt{Hz}}$ from $\sim$ 30 Hz to 1 kHz [1]. Because of this low noise level, we will be distributing the laser beams to other labs to serve as a reference for the noise in their setups. This will be done via fiber optics. The main part of my project is to set up the fiber optic distribution network and to make sure the noise of the laser is still below the requirement of each lab it is distributed to. I will need to characterize the noise added due to the fiber. If we determine the noise level is too high, we will implement methods to reduce the noise.

2 Background

2.1 Laboratories and Noise Requirements

We will be sending the frequency stabilized beam to various labs. Each experiment is different in nature as well as having different noise budgets.

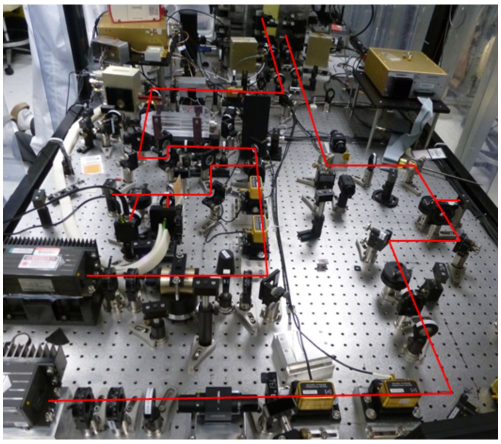

Figure 1: The setup in the CTN lab. The laser is a Nd:YAG 1064 nm NPRO laser.

- **GYRO:** LIGO's goal is to detect gravitational waves by measuring the change in the length of the arms of Michelson interferometers. These interferometers are subjected to different types of noise on Earth which can mask the signal from gravitational waves, one of them being seismic noise. Seismometers are used compensate for such noise by sending a signal to actuators in the interferometer whenever it detects motion, and a different type of signal is sent for each type of motion. However, these seismometers cannot differentiate between horizontal movement and tilt at low frequencies, which means wrong signals can be sent to the interferometers. This results in incorrect compensation for noise.

  GYRO's setup can resolve this problem, utilizing the Sagnac effect. Their setup consists of a single laser that is split so that each beam travels in opposite directions around a cavity and then recombined to determine whether the movement is a change in tilt or horizontal motion. The CTN laser would be used as a reference to determine the noise of the laser in the GYRO setup. The noise level needs to be low in the GYRO setup so gravitational waves are not masked. The noise requirement for the beam from the CTN lab is $1 - 10kHz/\sqrt{Hz}$.

- **Crackle Lab:** In the interferometer at LIGO, there are mirrors that are hanging from blade springs. The laser reflects off of these mirrors; a horizontal displacement of the mirror leads to a vertical displacement of the blade spring. These blade springs are susceptible to crackling, which occurs because of crystal domains moving with respect to one another. The crackle lab seeks to quantitatively measure the crackle noise from the blade springs. The crackle lab setup is a Michelson interferometer with the mirrors placed at the end of masses hanging from blade springs. They require low noise because noise in the laser can lead to perturbations of the mirror, and therefore, perturbations of the blade springs, which can mask the crackle noise. Crackle lab requires a beam with a noise level less than $475Hz/\sqrt{Hz}$.

For both of these setups, the CTN laser would be used as a reference because of its low noise.

3 Summary

We will be distributing the laser beam from the CTN lab using a fiber optic. As the light travels along fiber, it may pick up additional noise. Noise can be induced along the fiber from acoustic disturbances [2]. Pang describes $1Hz/\sqrt{Hz}$ for 1 m of fiber exposed to 69 dB of sound. 69 dB level is on the order of the level of human speech or a vacuum cleaner. 80 dB yielded $5Hz/\sqrt{Hz}$ noise for each meter, which is about the volume of a dishwasher. Thermal fluctuations can also induce changes in the length of the fiber, which will lead to phase variations as well as frequency fluctuations [3] . Even if ambient temperature is constant, there can still be thermal dynamic fluctuations. Basically, because particles are at a finite temperature, they will still move around, causing fluctuations in fiber, which eventually appears as frequency noise [6]. Thermorefractive noise is a function of dn/dT, how the index of refraction changes in response to temperature. Thermoelastic noise is a function of the thermal coefficient of expansion for any given material, α. These two combine to form thermoconductive noise. There is also thermomechanical noise, which is basically internal friction. Also, any mechanical disturbances, such as hitting the fiber, can create noise.

First we mode matched the laser into the fiber, using lenses and modematching programs to determine which focal length should be used and the location of the lenses. Once the laser was mode matched well enough, we recombined the output beam from the fiber with the original beam, in order to measure the noise added by the fiber using the self-homodyne method. This combined beam was directed into a photodiode, which in turn was connected to an oscilloscope and a spectrum analyzer to look at the output signal. We expected and saw a cos^2 caused by fluctuations in length of the fiber. However, these fringes were occurring too quickly to take good data with the spectrum analyzer, on the order of 0.3Hz, so we tried slowing them down using various methods. We finally succeeded in having no fringing for minutes at a time by leaving the HEPA filters off overnight. These filters keep the air above the table clean of dust and particles but also may induce varying air pressure. In addition to leaving the HEPA filters off, we insulated the fiber cable by encasing the spool in foam and placing that in a plastic box. The unspooled fiber was sandwiched with foam to isolate it from table vibrations and ambient temperature. We were able to take spectral data, for the laser locked and unlocked to the cavity.

One of the major sources of noise was fluctuations in ambient temperature so we built a circuit, using an AD590, to measure the temperature. However, the noise level from the circuit was higher than the laser's noise because we neglected to convert it from current noise to frequency noise, which was higher than our desired level. We also measured the noise from the error signal from the servo loop between the laser and the cavity, shot noise for the photodiode, and noise from the spectrum analyzer itself. The error signal noise, shot noise, and noise from the spectrum analyzer is much lower than the laser's noise and therefore, is unlikely to be the major sources for its noise. Here is the noise budget developed from this summer's work:

3.1 Future Work

- Improve mode matching in order to increase power output from fiber
- Design and build another circuit with less noise to measure ambient temperature fluctuations.
- Characterize other sources of noise induced in the fiber and reduce their effects as needed to fit the noise requirements. Some methods for noise reduction include further insulation

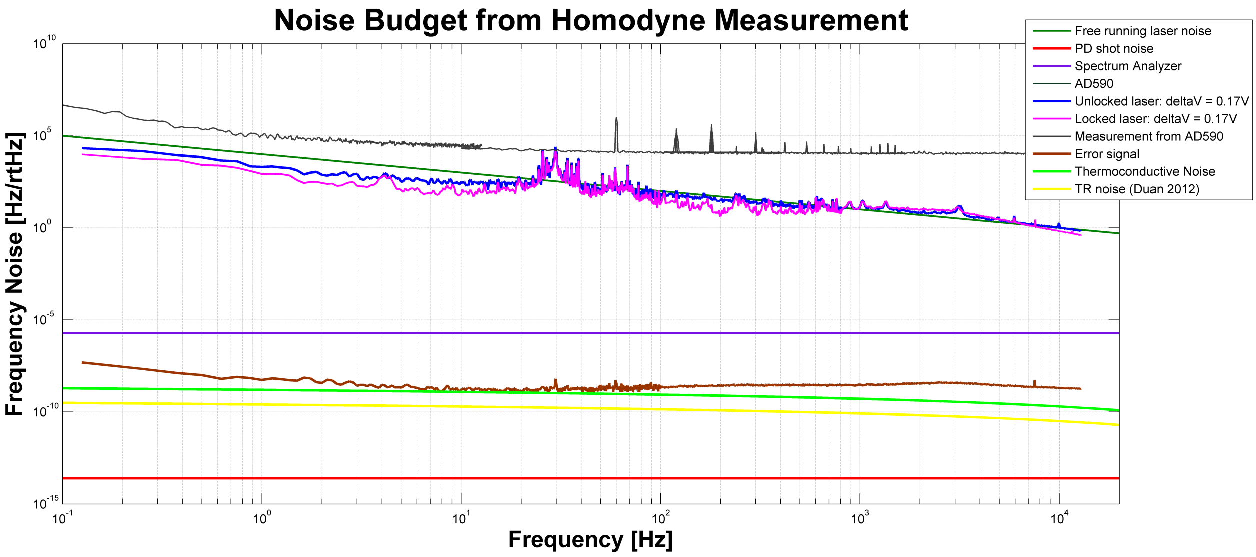

Figure 2: Noise budget for fiber optic setup

of the fiber and method described by Ma [5]

- Distribute laser to crackle and GYRO labs. This would involve insulating the fiber in between labs as well as devising ways to measure the noise at the other locations, before using the laser as a reference.
- After distributing the lasers, we will use a phase locked loop to determine noise of systems

4 Distributing Laser via Fiber Optic

Here is the setup from the CTN lab. Both lasers have a wavelength λ of 1064nm. I used the beam along the right side of the picture.

The beam emerging from the premode cleaner (PMC) has a spot size (radius) of 370 μm. This is also the beam waist because the light only diverges from the laser. A beam waist is the minimum radius of the laser beam, ω_o. The laser first has to be locked to the PMC in order to get a Gaussian profile.

4.1 Mode Matching

1. **Finding the Beam Waist**
   In distributing the laser, the laser and the fiber first need to be mode matched. This means the beam waist, ω_o, the minimum radius of the laser beam, and its location from the laser beam must match that of the fiber. This can be done by placing lenses in the beam path. To begin mode matching, I first needed to determine the waist and the location from the current setup, as shown in beam path on the right side of Figure 1. To calculate this, I needed to know the lasers wavelength (λ), spot size (radius of the beam) at the laser, the focal lengths of the lenses and their locations. I measured the distances of lenses already in the beam path to determine the beam path, which was made easier by the fact the holes in the table are 1 in. apart. The spot size (radius of the beam) from the laser was 370 μm. This is the initial beam waist, ω_o, because the radius is at its smallest

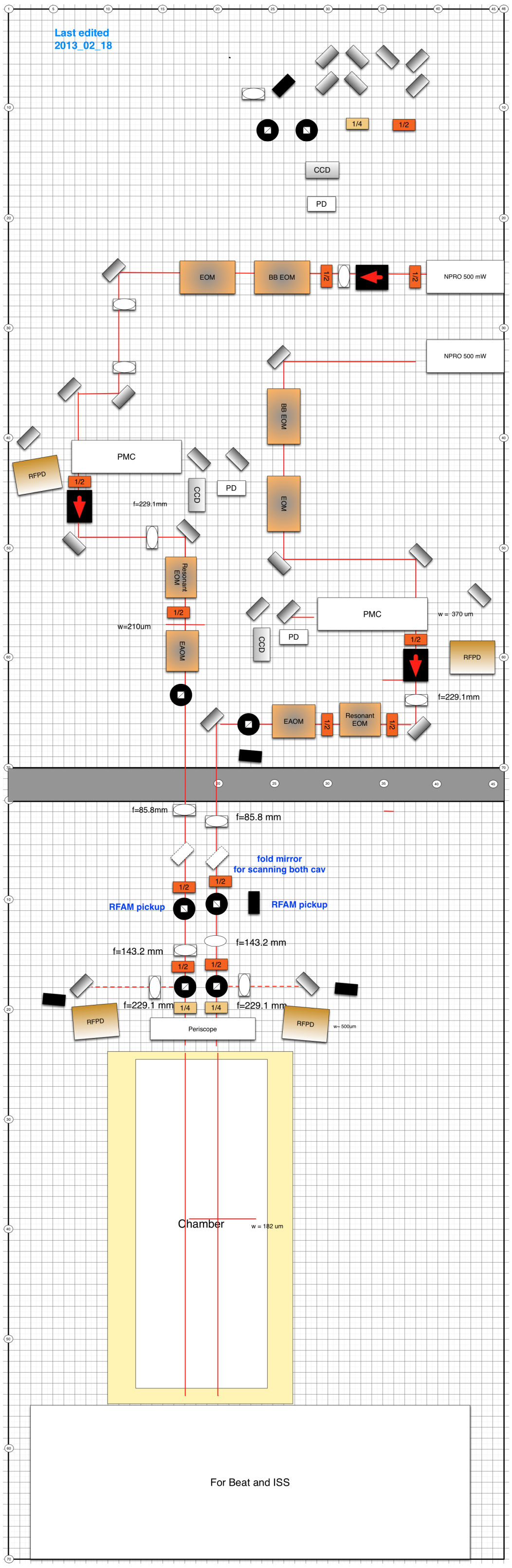

Figure 3: The setup in the CTN lab. I am utilizing the laser that has the beam path on the right. The laser is a Nd:YAG 1064 nm NPRO laser.

at the laser; the beam only diverges from there. The first lens had a focal length f = 286.5 mm and was 11.5 in (0.292 m) away from the beam. The second lens had a focal length f = 85.8 mm and was 32.6 in (0.828 m). We used the complex beam parameter q(z,R) to determine the waist and its location. The parameter q describes the Gaussian variation in beam intensity with the distance r from the optic axis, as well as the curvature of the phase front which is spherical near the axis [4]. The lenses were assumed to be thin. The complex parameter q is purely imaginary at the beam waist:

$$q_o = i\frac{\pi\omega_o^2}{\lambda}. \tag{1}$$

Since we know the complex parameter q at a certain location, we can find q distance z away, using the equation

$$q_b = q_a + z \tag{2}$$

where q_b is the output beam and q_b is the input beam. If one combines Eq. 1 and 2, he will obtain

$$q = q_o + z = i\frac{\pi\omega_o^2}{\lambda} + z \tag{3}$$

which gives q at a distance z away from the beam waist. So using Eq. 2 to find the complex parameter at the lens, q_1, we then can use the following equation to find the q value across a thin lens, q_2:

$$\frac{1}{q_2} = \frac{1}{q_1} - \frac{1}{f} \tag{4}$$

Eq. 2 and 4 can be used for each additional lens to solve for q. After the final lens, the q value will have real and imaginary parts. Looking at Eq. 3, we know the real part is the distance the second beam waist is from the last lens. This leaves us the imaginary part, which allows us to derive the beam waist, exactly like Eq. 1. I obtained a beam waist of 118.2 μm, ω_o', at a distance 0.0883m away from the lens with focal length f = 85.8mm. All these calculations were done on MatLab. All equations are found in Kogelnik[4].

The other end of the beam path is the fiber. A collimator is attached to the end of the fiber, which is basically a lens that focuses light into the fiber. I used an adjustable aspheric collimator, with focal length f = 2mm from Thorlabs. It allows the user to adjust the distance between the fiber and the lens in the collimator, which will help in mode matching. The fiber I am using is a 1064 nm PM FC/APC Patch Cable: Panda Style from Thorlabs, which is polarization maintaining and 60m long. The polarization maintaining fiber has two modes along which light that is linearly polarized will keep its polarization. For the collimator, I do the same calculations that I did with the laser, using Eqn. 1- 4, with the initial beam waist to be 3.5μm which is the radius of the fiber and the distance from the fiber to the lens to be 3.5μm. From this, I determined the waist size to be 4.67μm.

2. **Theoretical Mode Matching**

I used the program JamMT, a mode matching program, to solve for a solution that would satisfy the waist sizes we had, the length of the beam path, and the lenses that were available. Before starting the mode match, I took an inventory of the all the lenses available in the lab so I would know what I had to work with. I set the initial beam waist to be ω_o' and the initial distance z_o to be zero. I chose to use add two lenses to mode match. I set the smaller parameter for the location of the target beam waist so the two additional lenses would be on an empty space on the table while the larger parameter was chosen due to limited space on the table. We are picking up the beam from the beam splitter labeled RFAM pickup. The lenses I ended up using had focal lengths f = 143.2mm and f = 74.9mm. The distance between the two waists were 0.904m.

3. **Setting up Apparatus**

Once I obtained the solution, then I found the proper lenses and placed them at the calculated locations. Here is the setup:

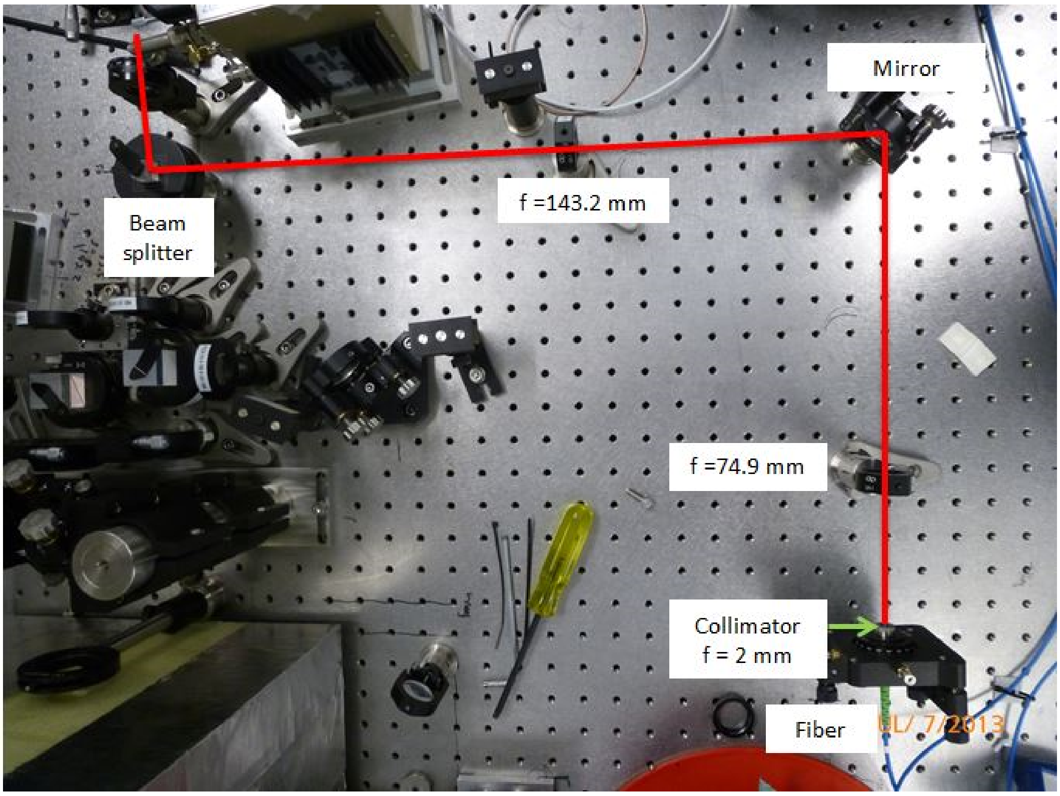

Figure 4: Setup for mode matching the beam from the PMC to the fiber. Lenses used have a focal length of f = 143.2 mm and f = 74.9 mm.

Before placing the lenses, I placed the mirror so that I could be sure that the beam was level, at the right height, and was aligned with the holes in the table. Then I placed each lens, aligning the beam before adding the second lens. The beam was 3 inches off the table. Once everything was in place, then I adjusted the knobs on the stand that the collimator was held in. To observe the power coming through the cable, I initially had a camera on the opposite end of the cable. Once I saw the spot on the screen from the laser and optimized it as much as I could, I attached the fiber to a power meter instead, so I could have a quantitative value. I changed the locations of the lenses and collimator to see if I could obtain higher values. The highest output I could obtain with this setup was about 10% of the input beam.

4. Redetermining a New Waist and Setup

We placed a collimator on the other end of the fiber optic and noted that the beam entering the fiber optic did not have the same profile as that exiting the fiber, despite using a collimator with the same focal length. This partly may have to do with the lenses being placed at different distances from the fiber, but even when we adjusted the distance, it still did not match. We used a WinCam and and a program DataRay to look at the Gaussian profile of the beam at various distances from the collimator, recording the radius of the beam.

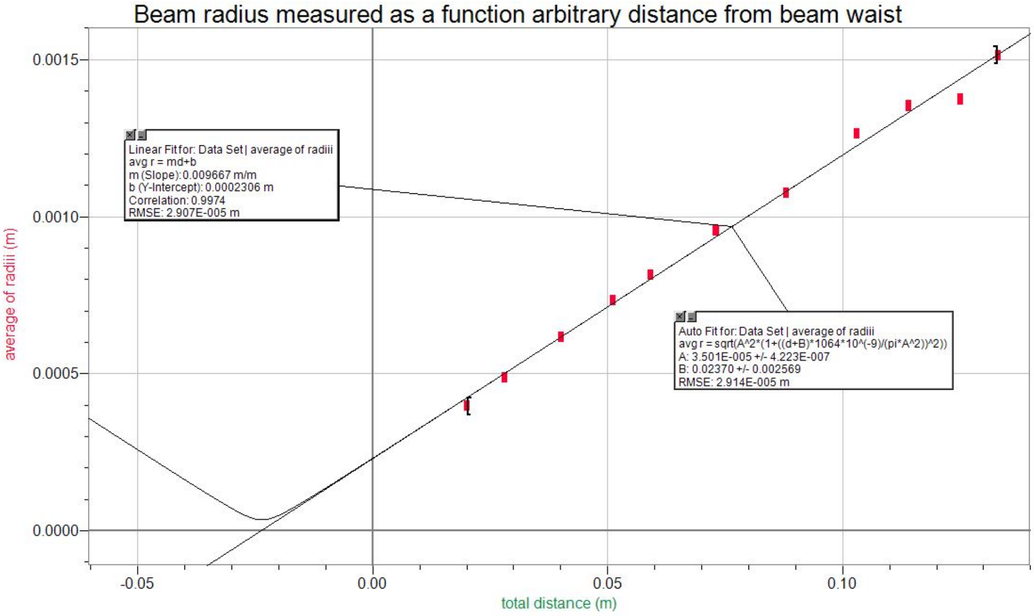

Figure 5: Gaussian profiling of output beam from fiber optic. Fit with $\omega^2 = \omega_o^2[1 + (\frac{\lambda z}{\pi \omega_o^2})^2]$. [4]

I used the following equation to find the waist size and its location [4]:

$$\omega^2 = \omega_o^2[1 + (\frac{\lambda z}{\pi \omega_o^2})^2] \tag{5}$$

I determined the waist size, ω_o, to be $35\mu m$ and its location about 2 cm from where I placed the collimator in relation to the last lens. I also used the equation $\theta = \frac{\lambda}{\pi \omega_o}$ where θ is the divergence angle, and the slope of the linear part of the graph, to check for the waist size and the two methods agreed. The newly determined waist size is slightly smaller than the waist size I calculated earlier.

Using this new waist measurement, I used JamMT and was able to find a solution with the same lenses.

With the new setup, the best output we were able to obtain was 5% which was lower than the previous setup. However, the location of the waist and its profile was much better than the previous setup. There was a possibility of error in the calculations and we could have improved on the beam alignment. Since the beam was visible, we would have gone ahead to measure the noise from the fiber but the location of lenses upstream had to be changed since a mistake was found upstream for locking the beam to the cavity so I had to redo the calculations.

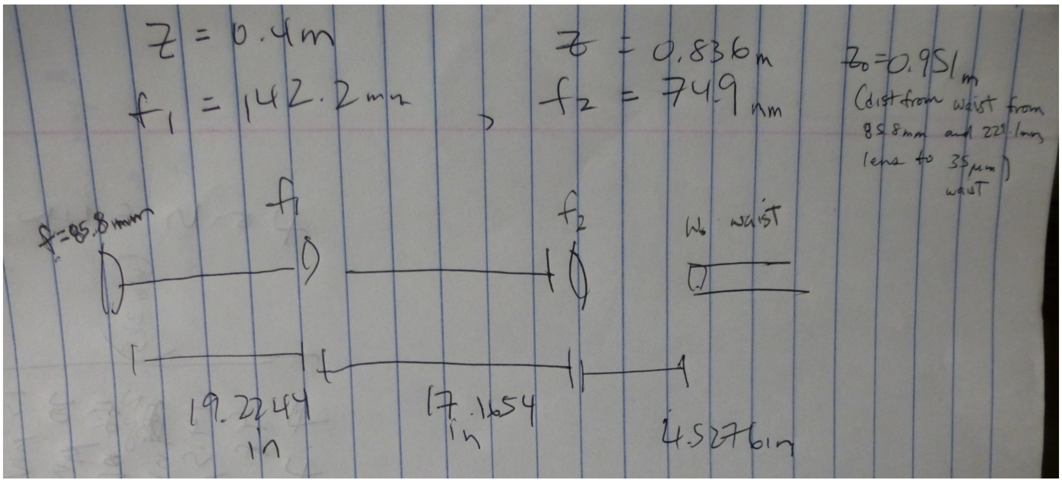

Figure 6: Calculated setup for mode matching between beam from the PMC and the fiber

There were still questions about what radius exactly should we be using for the ending spot size so we decided to experimentally determine the waist. We had the beam enter the output end of the fiber and used the methods described in item 4 of this section to determine the waist, which was $21.49\mu m$. The waist after the two mirrors (f = 286.5 mm and f = 85.8mm) was calculated theoretically and measured. Simplified Eq.5, since the second part of the sum is much greater than 1, and rearranged to obtain the equation

$$\omega = (\frac{\lambda}{\pi\omega_o})z + b. \tag{6}$$

The waist was determined to be $59.6\mu m$ from the slope, which is the divergence angle θ, where $\theta = \frac{\lambda}{\pi\omega_o}$. The location of the waist was $z_o = 0.284m$ from the testing lens (f = 127.1 mm). Then we calculated the waist in between the testing lens and the previous lens, f= 85.8 mm but the location of the waist was off by several inches. Upon closer inspection, we realized that the lens we used was not made of fused silica but BK7, which we found has a different focal length for a given radius of curvature. The lens we thought had a focal length of f=143.2mm had a focal length of f=127.1 mm. This was a major reason for why the mode matching was poor. Once this correction was made, then our calculations matched the observed waist and we proceeded to calculate and place two more lenses using methods described earlier in this section. We were able to obtain an output of 15%. Here is our final setup:

5 Measuring the Noise from the Fiber

Since we now have a visible beam, we will try to determine the noise due to the fiber using self-homodyne detection. This will be done by recombining the original beam split off earlier on the beam with the output beam from the fiber. Once we recombine the beams, we will be able to read off the beat frequency and determine the noise.

5.1 Theory

The self-homohomodyne measurement can be modeled as a Michelson interferometer with arms of unequal length, where one arm is the beam fed through the fiber and the other arm is picked off from the original beam. We want to know the change in power due to the difference in length. The electric field from each arm as a function of the length of the arm can be described as a sinusoidal wave, but it is easier to use exponentials: $E_x = E_o e^{-ikx}$ where k is the wavenumber and x is the distance the light travels independent of the the other beam. Because of the beam splitter, the electric field from each arm is halved, so the total electric field at the photodetector is the sum of the beams from each arm:

$$E = \frac{1}{2}E_o(e^{-i2kL_x} + e^{-i2kL_y}) \tag{7}$$

where L_x and L_y are the lengths of the arms. Because we are interested in the difference in the lengths, let us define new variables for the sum and difference of the the arm lengths,$L_D = L_x - L_y$ and $L_S = L_x + L_y$. The equation 7 can be rearranged and using Euler's formula to equal

$$E = E_o e^{-ikL_S}(cos(kL_D)). \tag{8}$$

To calculate the power, we multiply the electric field with its complex conjugate to obtain the following:

$$P = E^*E = {E_o}^2 cos^2(kL_D) \tag{9}$$

We should expect to see a cos^2 relation in the signal. With the spectrum analyzer, we will try to measure the noise along the linear part of the plot.

5.2 General Setup

We split off the original beam by placing a half wave plate (HWP) and then a polarizing beam splitter(PBS) into the beam path, right before the PMC. The half wave plate is to rotate the beam's angle of polarization controlling the amount of power going into this setup. This initial PBS supposed to reflect s-polarization and transmit p-polarization but the extinction ratio is 100:1, so that means some p-polarization can be transmitted if the beam is very messy, so a second PBS is used to clean up the recombined beam. The output end of the fiber is placed on a translational stage which will allow us to observe fringes by changing the length of the output beam path, and therefore, the phase of the beam. We used a lens right before the photodetector (PDA100A) to focus the beams and make it easier to see if they are aligned. The lens placed right after the output is to make the output beam profile similar to the split off beam. We are using a 45S beam splitter to recombine the beams because the light both from the original beam and the fiber are supposed to be s-polarized. This recombined beam is directed into a photodetector, which will be connected to a oscilloscope and digital signal analyzer to determine the beat frequency. The actual frequency of the laser, which is $\sim 10^{14}$ Hz will be filtered out and just the beat frequency which is much lower, ~10 kHz, will remain.

To align the beams, we tried to ensure each beam was 3 in. off the table throughout its path before it recombining with the other beam and the beams were overlapping both in the near and far field. Once we were able to see fringes on the oscilloscope, then we could tell we were getting aligned. This can be seen just by tapping on the mirrors because it causes fluctuations in alignment and path length. The larger the amplitude of the fringes, the more aligned the beams are.

On the input side of the fiber, we tested the beam using a PBS to determine it was s-polarized going into the fiber. Then we placed a HWP right before the fiber to ensure the

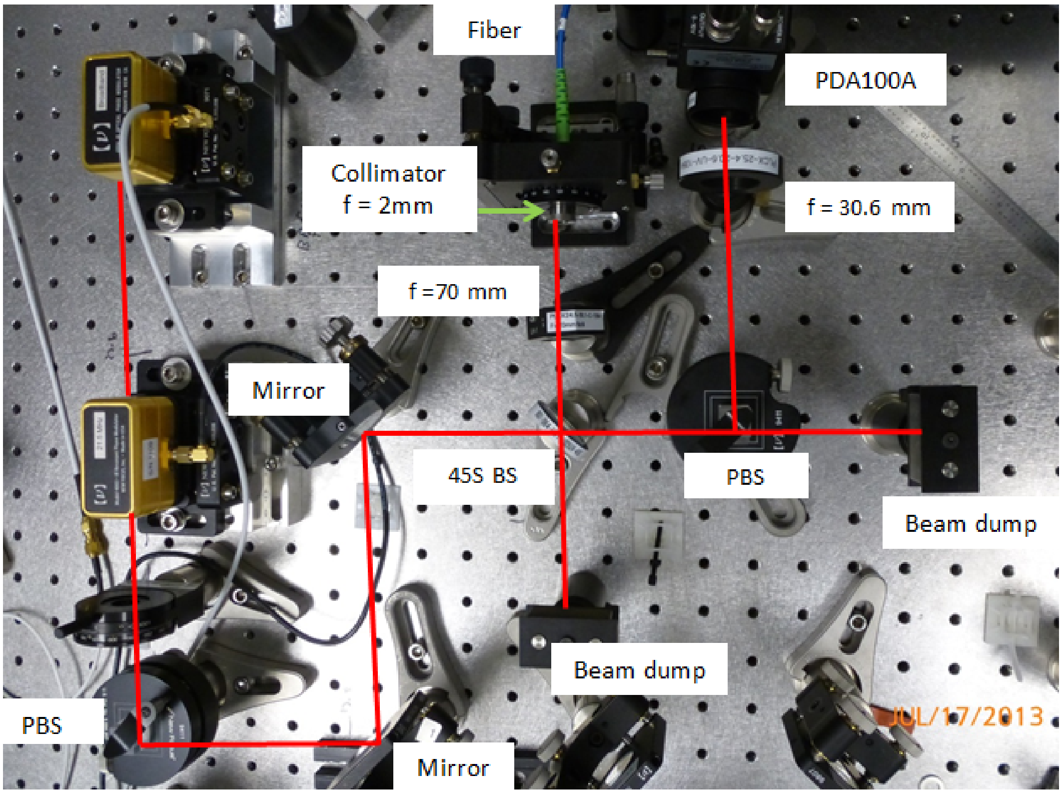

Figure 7: Setup for beam recombination of the original beam and output from the fiber

polarization of the input beam was aligned with one of the axes of the fiber, which means the output beam will be s-polarized.

To determine the angle of the HWP, we placed another HWP before the final PBS before the beams enter the photodetector. The input HWP was rotated in 5° increments over a 60° range. At each rotation, the output HWP was rotated back and forth to induce fringes in the signal, and the peak to peak voltage of the fringes observed on the oscilloscope were recorded. The more consistent the peak to peak voltage, the more aligned the polarization was to an axis. We determined a maximum alignment for the HWP was at 30 °, set the input HWP there, and removed the output HWP. We were able to translate the stage underneath the output fiber and and see the cos^2 fringes as described in the theory section.

Ideally, we would not have to use the HWP because there is a notch on the collimator that is aligned with one of the major axes of the fiber (you can determine this when they order the fiber). However, you cannot see the notch once it is attached to the stand so I made the screws attaching the collimator to the stand perpendicular but it is possible they shifted a little when we were attaching the collimator to the stand.

5.3 Reducing Fringing Frequency

We were able to observe the expected cos^2 function. Holding the fiber, therefore increasing the temperature and lengthening the fiber, would increase the frequency of the fringes. The signal's frequency would drift, going anywhere from 0.03 to 1 Hz or having a period of 10 to 30s when we left it alone. This is much too fast to use the spectrum analyzer so we tried various methods to reduce the frequency of the oscillations. We turned off the HEPA filters for the tables for

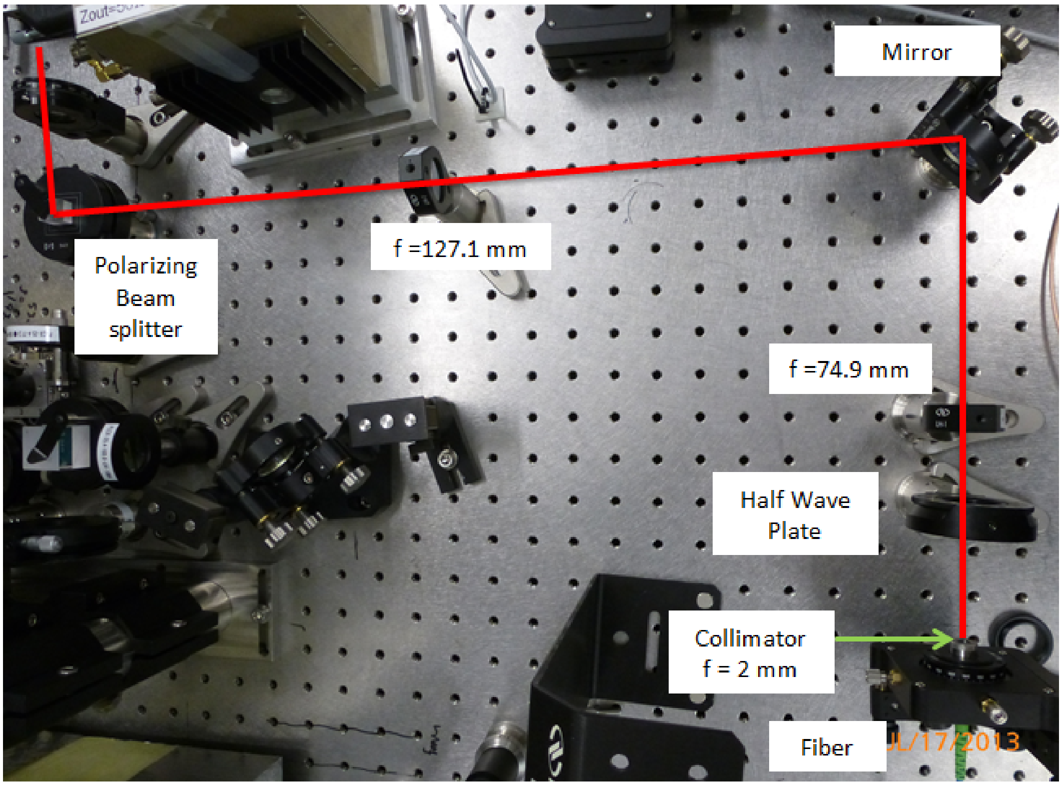

Figure 8: Setup on input side of fiber

several hours in case the changing air pressure was causing the fiber to change lengths. We covered the spool of fiber with bubble wrap, which was unsuccessful. Then we tried covering the ultra high vacuum aluminum foil to reduce air flow and acoustic noise and put the whole thing in a plastic bin, which was still unsuccessful. Unless it was acoustic noise from the lab in general, short noises would dissipate quickly. Jostling of the fiber would result in spikes in the signal and increased the frequency of the fringes for a short while but the oscillation would slow down again.

Thermal noise seemed to be the major untested source of noise, though we had wrapped the spool in bubble wrap. We calculated the temperature change required for the fiber length to change by wavelength, in other words, for the phase ϕ to change by 2π. The phase change over the length of the fiber is

$$\phi = kx, \tag{10}$$

where k is the wave number. In this case, since light is propagating through material, we know that

$$k = \frac{2\pi n}{\lambda} \tag{11}$$

where n is the index of refraction of the fiber, which is about of 1.5. Setting ϕ equal to 2π, combining equations 10 and 11, we obtain

$$x = \frac{\lambda}{n}. \tag{12}$$

We know the thermal expansion of a material can be described with the following equation

$$\frac{\Delta L}{L} = \alpha \Delta T \tag{13}$$

where α is the coefficient of thermal expansion, L is the total length of the material, and T is temperature. ΔL corresponds to x, because a change in length is what causes the signal to oscillate. Combining equations 12 and 13, solving for ΔT, the change in temperature needed for the signal to form a complete fringe:

$$\Delta T = \frac{\lambda}{n \alpha L}. \tag{14}$$

Here, the wavelength $\lambda = 1064$ nm, n is 1.5,the coefficient α is on the order of 10^{-6} for fused silica, and L the total length of the fiber is 60m. This gives a ΔT of about 10 mK.

- **Measuring temperature fluctuations on CTN table**

  We decided to measure the temperature fluctuations of the table. The plan was to build two identical circuits using temperature transducers, AD 590, which produces a current proportional to temperature, $1 \mu A/K$, to measure the temperature fluctuations. We would cross-correlate the two circuits to be confident of the results.

  First Circuit Here is the design for our initial circuit:

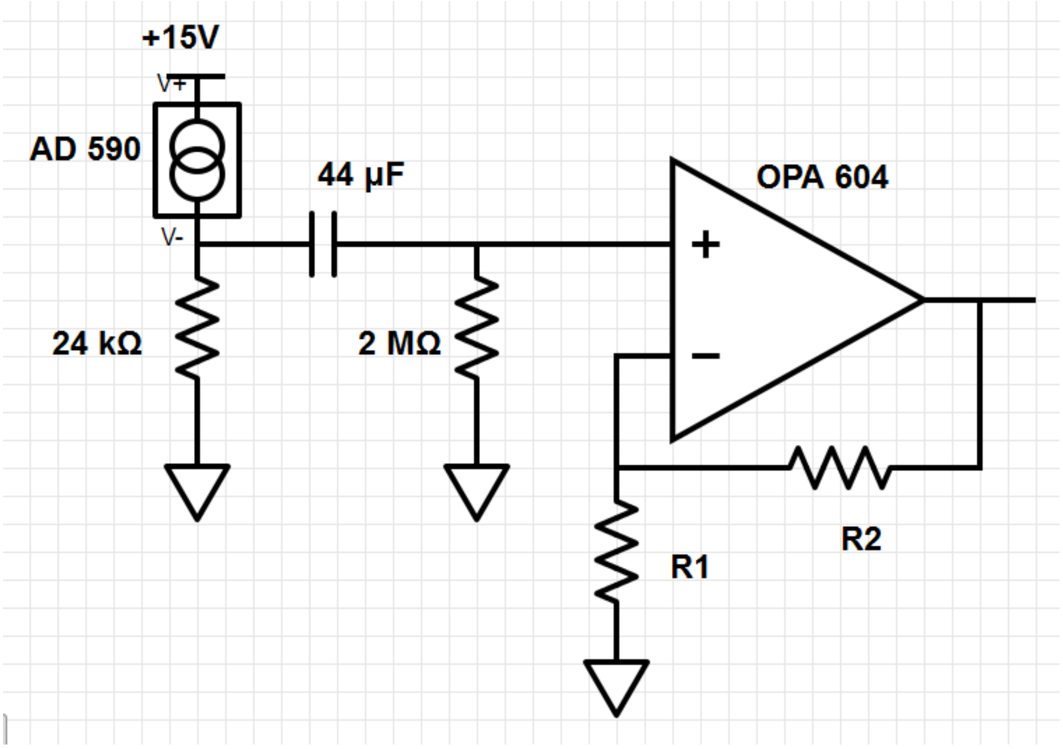

Figure 9: Initial circuit designed to measure temperature fluctuations on CTN table

The $24k\Omega$ resistor is to set the voltage going into the rest of the circuit. Room temperature is around 300K so we expect the voltage entering to be around 7V. Next is a high pass filter, with a time constant around 550s, or a cutoff frequency of 1.8 mHz. The high pass filter is to AC couple the circuit so we can better look at fluctuations on the timescales the signal oscillations are occurring and to ignore slow temperature changes in the room. We used two $22\mu F$ WIMA film capacitors which have very low noise and are non-polarized because that was the highest value capacitor of that type. We used an operational amplifier OPA 604 which produces low current noise. OPA 604 is made with field effect transistors (FET) which draw very little current and make the op amp more ideal. The OPA 604 is placed in DIP socket so that it can be reused at a later time. There are sockets for the resistor connecting the output to the negative input so we can easily change the gain on the circuit. The gain from the two resistors is about 4, which is calculated using the equation

$$Gain = \frac{R_1 + R_2}{R_1} \tag{15}$$

where R_1 is 330 Ω and R_2 is $1k\Omega$.

We tested the circuit in the electronics lab first by connecting components on a breadboard, using a function generator to input signal, and the circuit behaved as expected. The components were soldered to a Vector Circboard 8015 and tested again, with expected results. The AD 590 was then connected and the circuit saturated, which was expected because there is a large voltage change when the power supply is turned on so it takes awhile for it to decay with the long time constant so we placed a smaller resistor, on the order of 100k Ω to bring the signal to zero. The circuit responded appropriately when we placed the AD590 by warm and cool objects.

When initially setting up and testing the circuit in the CTN lab, there was a lot of high frequency noise. We discovered this was due to the longer wires connecting to ground on the power supply. There is some equipment in the lab emitting electromagnetic radiation at megahertz frequencies, which is inducing voltages at that frequency in the wires from the power supply. We used shorter wires and that dramatically reduced the noise.The signal did not saturate but drifted at various DC values, from 0.5V to 2V, when we measured the temperature on the table. We are unsure of the source of this DC signal because the signal should be centered around zero, due to the high pass filter. When we used a smaller resistor, on the order of $100k\Omega$ in parallel with the $2M\Omega$ resistor, the signal went to zero. Over a linear section, we measured the change in voltage over three fringes to be 0.112 V, which ends up being $1.16\mu K$, much smaller than the needed 13 mK for a wavelength change.

Second Circuit Because of the unknown source for the DC signal, we designed a second circuit, still using around the AD590. Instead of utilizing a high pass filter, we simply subtracted out the average expected signal from the room temperature, 7V, in order to look at the fluctuations.

This is done using the AD587, a 10V voltage source and resistors R_1 and R_2. Resistor R_4 is needed because the operational amplifier is not perfect; it will draw some current so when it does, the voltage at the two inputs of the op amp will be equal. The equation to calculate the value of R_4 is

$$R_4 = \frac{(R_1 + R_2)R_3}{R_1 + R_2 + R_3}. \tag{16}$$

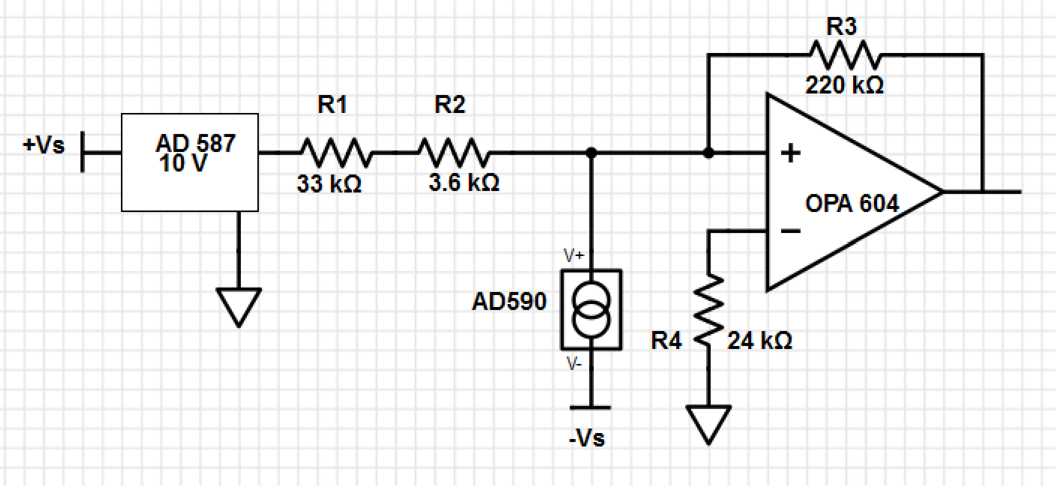

Figure 10: Second circuit used to measure

Again, we encountered high frequency noise. We realized this was due to an antennae affect, since we used long wires to attach the AD590 in order to utilize the circuit over the whole table. We wrapped the wire in aluminum foil and also connected it to the ground on the power supply, which helped tremendously but we could still see some noise. We went ahead and took data with the spectrum analyzer but as seen in the noise budget,the noise level from the AD590 circuit was much higher than the laser noise. We realized we had forgotten to convert the current noise of the AD590 and this was higher than the laser free running noise. Because the noise level from the circuit was higher than the laser's noise, we will not be able to characterize what part of the laser noise is attributed to ambient temperature fluctuations. We will need to find another device with lower noise to measure the temperature.

- **Insulating and enclosing the fiber**

  After attempting the methods listed above, we tried to slow down the fringes by insulating the fiber, since about 2m was not shielded. This was done by wrapping the exposed fiber with foam, enclosing the spool of fiber within a plastic bin, turning off the HEPA filters for several hours, and pulling all the blinds down around the table to keep air flow and acoustic noise low.

  Initially, this did not slow down the oscillations in the signal by much as seen in the figure below. The unshielded fiber yielded periods of about 20 s while the shielded fiber had a maximum period of 40s. We were able to see more noise with the shielded fiber, and the oscillations were a little slower but not as much as we expected. Locking the laser to the reference cavity, which dramatically reduces the frequency noise of the laser, does not change the frequency of the fringing.

  The cancellation is decent, with the maximum voltage at 2.5 V and the minimum at 0.5 V. However, since the minimum is not exactly at zero, the beams do not totally cancel each other out. This could be because the spot sizes are not exactly the same, which is true in the far field, or they are only partially overlapping.

  We finally left the HEPA filters off overnight and the fiber stabilized, resulting in a drift having a frequency less than 0.01 Hz. We left the foam on the exposed wire as they

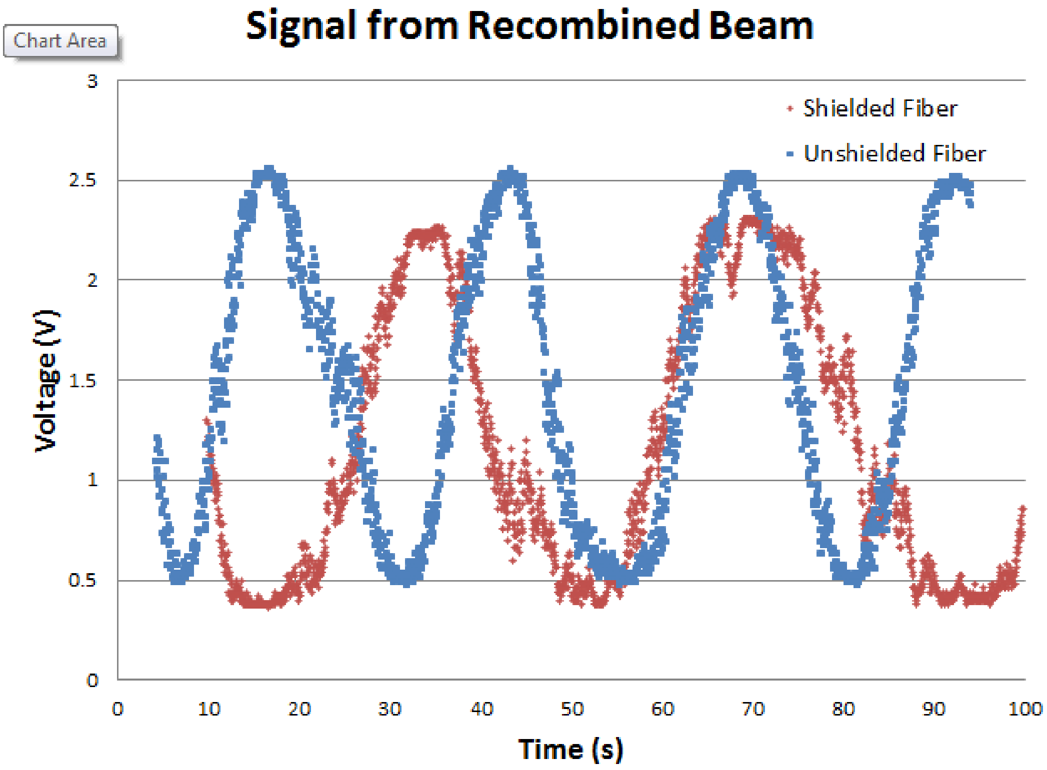

Figure 11: Comparison between signals when the fiber is insulated with foam, the spool is enclosed in a plastic bin, and HEPA filters are off and when the fiber is totally unshielded, with HEPA filters are on. The period of the oscillation is a bit longer and more noise is noticeable in the shielded fiber but it does not have as much effect as we would expect.

seemed to help with vibrations from the table and replaced the aluminum foil on the plastic container with bubble wrap. This is what the final setup looks like:

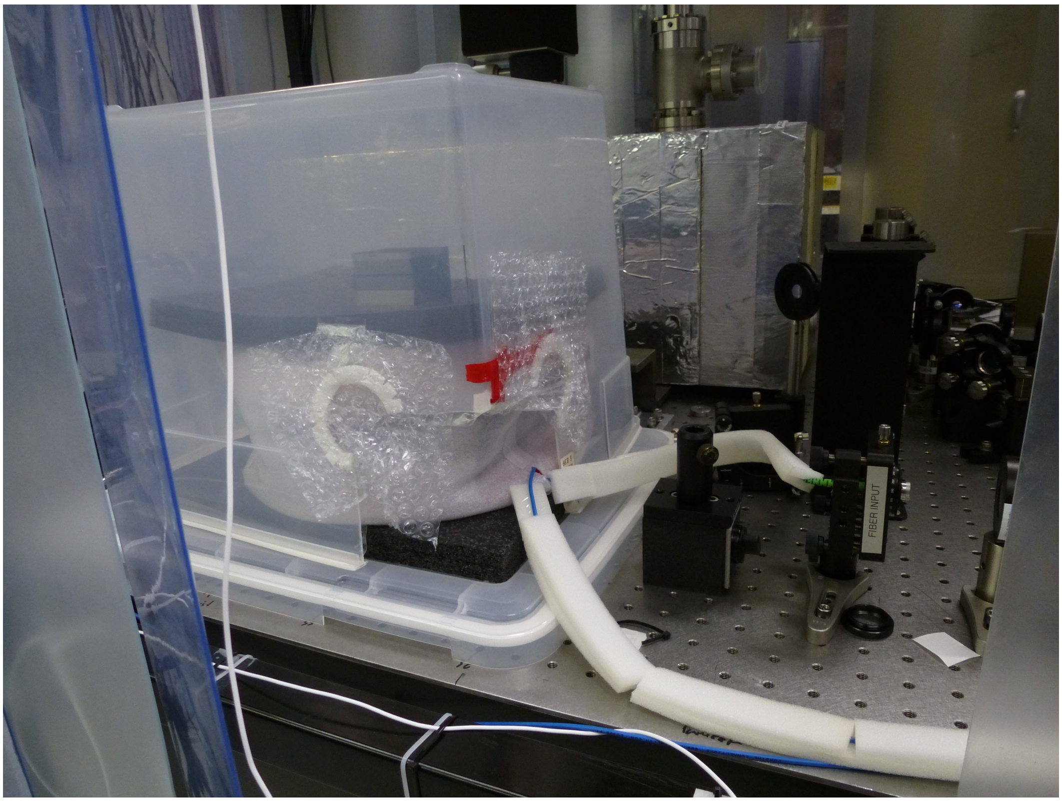

Figure 12: We used a plastic bin with the spool of fiber placed on the cap and the rest of the bin enclosing the spool. Bubble wrap was used to cover the holes in the bin, and the full length of exposed fiber was enclosed in foam.

5.4 Measuring Other Noise

- Error signal This noise was measured from the error signal that is part of the servo that feeds back from the cavity to the laser.
- Photodiode Shot Noise Noise in the photodiode is fluctuation in the power, δP. It can be described by the equation $\delta P = \sqrt{2h\nu P_o}$ where P_o is the power going into the photodiode. The output from the photodiode is in volts so we need a conversion from voltage to power. We know that the power going into the photodiode and the voltage read on the oscilloscope are linearly related, $P = \alpha V$, and therefore $\delta P = \alpha \delta V$. We solved for the conversion factor by rotating the polarizing BS that split off from the original beam to vary the power entering the photodiode and recorded the resulting voltage reading in the oscilloscope. Using a power meter, we knew there was about 0.5 W entering the photodiode on average from the combined beam so we used this as our P_o to calculate the noise.

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