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Development of Novel Lock Acquisition Procedures at the Caltech 40m Interferometer

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Abstract

A crucial step in an operational gravitational wave detector is lock acquisition, the process of bringing optical cavities to resonance and locking the detector, making it sensitive to gravitational wave signals. The narrow bandwidth of the feedback system makes the process of lock acquisition at LIGO a challenge; chance is largely relied on to bring degrees of freedom into range of the servo. In Advanced LIGO, acquiring lock will become even more challenging with addition of a fifth degree of freedom, so a reliable auxiliary lock acquisition system becomes crucial for operation. This report describes an auxiliary lock method that uses laser light distinct from the main beam to control arm cavity lengths via frequency doubled Pound Drever Hall locking. The accuracy required of the system is set by required cavity length precision, and noise limits of components of the system are presented and analyzed in this context. Optical fiber transferring laser light to the point of injection into detector arms is the limiting noise source. Fiber noise levels were measured with a Mach Zehnder interferometer and found to exceed limits set by desired locking precision. A fiber noise cancellation scheme is being implemented, and is expected to reduce noise below desired levels.

Contents

1 Background and Motivation 3
1.1 Outline 3
2 Auxiliary Locking 5
2.1 Locking Methods 5
2.2 Noise Sources 5
3 Fiber Stabilization 7
3.1 Measuring Fiber Noise 7
3.1.1 Experimental Setup 7
3.1.2 Noise Sources 7
3.1.3 Fiber noise measurements 11
3.2 Cancelling Fiber Noise 12
4 Future Work 12
5 Summary and Conclusion 13
6 Methods 13
6.1 Derivation of Mach Zehnder output signals 13

1 Background and Motivation

The Caltech LIGO 40m interferometer prototype gravitational wave detector, operated by the LIGO Laboratory, is designed for optimizing techniques and modeling the performance of the LIGO detectors and for developing and testing new elements for the Advanced LIGO design. Prior to operation of the detector, the system is in an uncontrolled state; in order to collect data, the optical elements must be brought close to resonance and locked. Once the system is locked, feedback signals to the optics can maintain each degree of freedom (DOF) at the operating point, making the detector sensitive to the length perturbations caused by gravitational waves. Currently, the random motion of each of the test masses is relied on to bring each of the four DOF within range of the locking mechanism. With the upgrade to Advanced LIGO, another DOF will be added to the system, making this technique much more inefficient than it is even today. It is important that the time required for lock acquisition is short, such that the time the detector is available for taking data is not significantly affected [1]. To achieve this, the process of acquiring lock must be made more deterministic and robust. The lock acquisition work at the 40m interferometer will determine how the Advanced LIGO interferometers are locked.

The method of lock acquisition is based on a procedure in which the five different DOF of the system in the plan for Advanced LIGO (Figure 1) are sequentially brought to resonance [2]. As the states of the DOF cannot be independently measured in the output signals available, it is difficult to calculate the required feedback from this information. Mathematically, solving the lock acquisition problem means dynamically finding the inverse of the sensing matrix $\mathbf{G}$, defined by the equation $O = \mathbf{G}D$, where D is the vector of the displacement of the DOF and O the detectable output signals[2]. In order to make the process more reliable, it is important to diagonalize the matrix $\mathbf{G}$ as much as possible.

There are several proposed techniques for sensing and controlling the DOF [3]. One of these schemes, frequency shifted Pound Drever Hall (PDH), is presented below.

1.1 Outline

The first section of this paper describes the steps required in the frequency shifted PDH scheme for auxiliary locking presented in [3]. The potential noise sources and their effect on the auxiliary lock system are discussed.

The second section of the paper describes the technique and impementation of cancelling phase noise caused by transferring laser light over long distances via optical fiber. This is necessary for our method of lock acquisition, as the stable PSL reference must be transferred to the end stations 4km away for Advanced LIGO for injection into the arms. The characteristics of the fiber noise are presented. The technique for phase cancellation described in [4] will be tested and implemented for a 50m fiber and the results will be described.

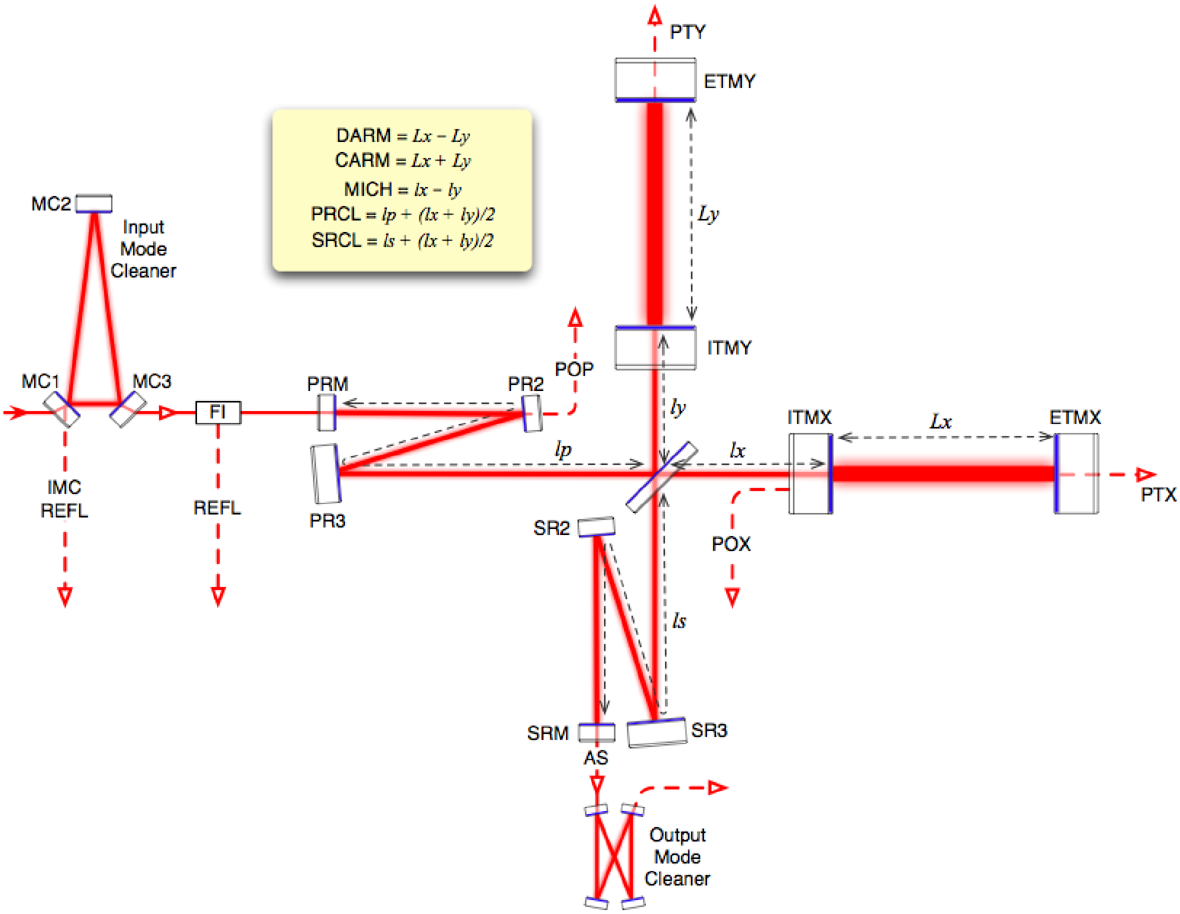


Figure 1: LIGO interferometer[1]. The five degrees of freedom are shown. The goal of this auxiliary locking scheme is to independently lock arm cavity lengths L_x and L_y.

2 Auxiliary Locking

In order to improve the lock acquisition procedure, an auxiliary locking technique will be used - a novel approach in which auxiliary laser light, distinct from the main laser beam, is injected into the interferometer to obtain better length sensing signals to aid in lock acquisition. In the proposed method, green light (wavelength 532nm) injected into the end test masses will be used in the Pound Drever Hall technique of locking a cavity to a stable frequency laser[5]. The signal will provide a means of sensing and controlling the arm cavity lengths. Several other methods of auxiliary locking are also described in [3].

2.1 Locking Methods

In the proposed method, the auxiliary beam is frequency doubled to 532nm with respect to the main beam. This prevents interaction of the auxiliary laser light with the PSL and enables an independent measurement of arm cavity lengths without interaction with the power recycling cavity [3]. The light will be injected through the end test masses (ETMs) into the arm cavities (Figure 1), thereby decoupling the arms from the rest of the system. The main challenge is to obtain a stable frequency reference at the end stations for use in PDH. In order to achieve this, pickoffs from the PSL will be sent via optical fiber to ETMX and ETMY. At the end stations, the light delivered through fiber will be used in a phaselock loop to stabilize a 1W 1064nm laser. The 1W laser will subsequently be frequency doubled to obtain $10mW(?)$ of 532nm light, which will be used to control the arm lengths (L_x and L_y in Fig 1) using a feedback signal generated by the Pound Drever Hall technique[5]. Independently sensing and controlling L_x and L_y provides a direct method to lock two of the degrees of freedom of the interferometer, and is a key step in bringing the entire system into lock and able to perform measurements.

DIAGRAM OF ALL THIS POTENTIALLY GOES HERE

2.2 Noise Sources

The required precision of cavity lengths is set by the linewidth of the Fabry-Perot cavity transmission resonances, which is given by $\lambda/\mathcal{F}$, where λ is the wavelength of the light and $\mathcal{F}$ is the finesse of the cavity. For Advanced LIGO, $\lambda = 1064nm$ and $\mathcal{F} = 400$ (?), which gives a total arm length motion of $2.7nm$. Keeping the cavities within a half linewidth of resonance sets a limit on the rms arm length motion of approximately $1nm$. This provides a limit for the total rms frequency noise in the laser to be used in Pound Drever Hall locking, given by:

$$\delta f = f \cdot \frac{\delta L}{L}$$

where L is the cavity length, f is the laser frequency, and δL is the desired maximum deviation of cavity length from resonance. For Advanced LIGO arm lengths of $L = 4km$, which gives a maximum frequency noise of $\delta f = 75Hz$ rms.

(also should probably calculate for 40m specs)

Although the PSL laser frequency is stablized to within (???), there are multiple noise sources in the auxiliary locking system which reduce the precision of the laser and put a limit on the effectiveness of PDH locking stability. The main noise sources are outlined below, and the major concern of fiber phase noise is then treated in more detail in the following section.

- Fiber phase noise

  The transmission of a stable frequency reference through a fiber introduces phase noise, as the fiber's phase is very sensitive to environmental perturbations [4]. The stability of the laser to be used for PDH sets a limit of $75Hz$ rms on the amount of frequency noise that can be generated by transmission of the stable PSL pickoff through the fiber. It has been shown that it is possible to effectively cancel the fiber induced phase noise [4]. The technique of noise cancellation will be tested and implemented in the context of the auxiliary lock system.

  The methods of fiber noise cancellation [4] may introduce an additional source of frequency noise. The stability of the system is limited by the effectiveness of phase noise cancellation, as well as by the stability of the drive frequency of the AOM to be used in the phase cancellation loop (Figure **??**).

- Phaselock Loops

  A phase lock loop will be used to stabilize a $1W$, $1064nm$ laser at the end station to the light transmitted through the fiber. This process is expected to introduce minimal noise into the system.

  (diagram of PLL? and some more detail possibly...)

- Frequency Doubling

  There is an additional amount of frequency noise that may be caused by the process of frequency doubling the laser to $532nm$ prior to injecting into the ETMs. The amount of noise is as yet unknown; a system similar to the Mach Zehnder interferometer which is being used to detect fiber noise will be implemented to measure the frequency noise introduced by this process.

- Shot Noise

  The shot noise limited sensitivity in a Pound Drever Hall locking system is given by [5]:

$$S_L = \frac{\sqrt{hc}}{8} \frac{\sqrt{\lambda}}{\mathcal{F}\sqrt{P_c}}$$

  where λ is the light wavelength, $\mathcal{F}$ is the finesse of the cavity and P_c is the power of the carrier in PDH locking. For $\mathcal{F} = 400$ and $P_c = 10mW$, the shot noise limited length sensitivity is $1.4 \times 10^{-18}m$, which will not affect the stability goal of $1nm$.

3 Fiber Stabilization

As sending stabilized light via optical fiber to the end stations over a distance of 4 km greatly increases the amount of phase noise, it is necessary to employ noise cancelling techniques [4]. The measurements of phase noise introduced by the fiber and noise cancellation methods are described below.

3.1 Measuring Fiber Noise

3.1.1 Experimental Setup

A Mach Zehnder interferometer is used to measure the amount of the phase noise added by the fiber by detecting the phase difference between light travelling a short distance in free space versus through a 50m fiber. In the present system, the beam of an $1064nm$ INNOLIGHT NPRO laser is incident on a 50/50 beamsplitter and is recombined using a second 50/50 beam splitter after one beam passes though a 50m fiber. The interference signals between the two beams are measured with two photodiodes (Figure 2).

The measured outputs of the two channels are given by

$$V_1 = A_1(1 + \cos(\theta))$$

$$V_2 = A_2(1 - \cos(\theta))$$

where A_1 and A_2 are the detected powers of the two initially split beams, and θ is the phase difference between the two arms of the interferometer. An accurate measurement of the phase θ provides a direct measure of phase noise in the system.

Due to imperfections of the beam splitters and differences between the two photodiodes, initially the DC signals and the amplitudes of phase fluctuation in the two channels are not equal, that is, $A_1 \neq A_2$. However, if the outputs are balanced such that $A_1 = A_2 = A$, the amplitude and phase noise signals can be decoupled. Letting

$$S_+ = V_1 + V_2 = 2A \quad S_- = V_1 - V_2 = 2A\cos(\theta)$$

the signals can be digitally divided to give

$$\frac{S_-}{S_+} = \cos(\theta)$$

which is a direct measurement of phase, independent of laser amplitude. To balance the two outputs, the gain on one of the detectors is reduced by inserting a potentiometer in series with the output of one of the detectors. This adjustable gain in one of the detectors can vary the output from 100% to 0.1% with a precision of 0.05%. Thus, by adjusting the gain, the detectors can be balanced to within 0.05%.

3.1.2 Noise Sources

There are several noise sources in homodyne detection which contribute to voltage fluctuations in the diodes and can be interpreted as effective phase noise fluctuations, thus raising

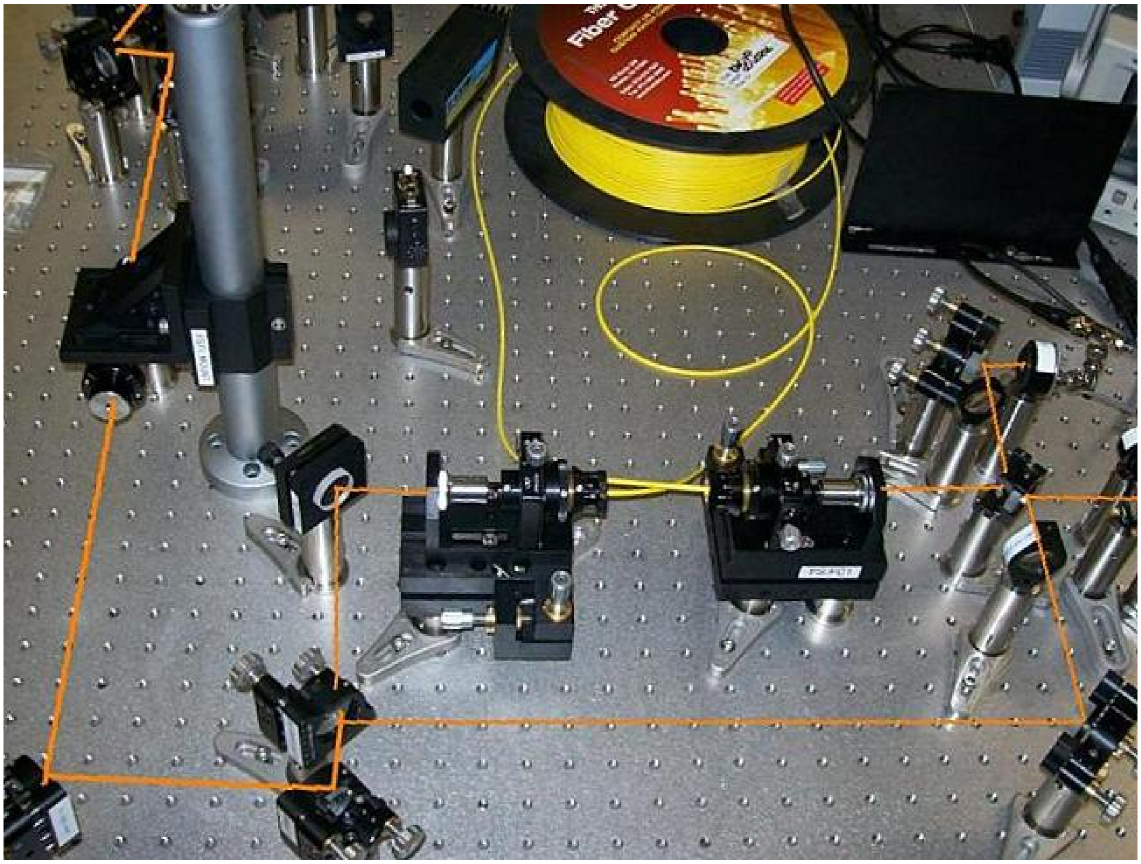


Figure 2: Fiber noise measurement setup: Mach Zehnder interferometer. The laser beam passes through a Faraday Isolation to prevent back reflection into the laser, and is incident on a 50/50 beamsplitter. Half the light passes through a MX10 lens and is coupled into the fiber. The two beams recombine in a second 50/50 beamsplitter and are focused to onto two PDA255 photodiodes, maximizing the response of the diodes to the detected signal.

the minimum amount of fiber phase noise detectable by the system. The main candidates for noise contributions are detailed below, and the calculated and measured spectra are presented in Figure 3.

- **Laser amplitude noise and detector imbalance**

  If the detectors are not properly balanced, additional noise is introduced into the measurement. For balanced detection, as discussed above, $\frac{S_-}{S_+} = \cos(\theta)$. However, if the total detected power is $A_{tot} = A_1 + A_2$ and there is an imbalance in the detected power of $\delta A = A_1 - A_2$, then

$$\begin{aligned}\frac{S_-}{S_+} &= \frac{\delta A + A_{tot}\cos(\theta)}{\delta A\cos(\theta) + A_{tot}} \\ &\approx \cos(\theta) + \frac{\delta A}{A_{tot}}(1+\cos^2(\theta))\end{aligned}$$

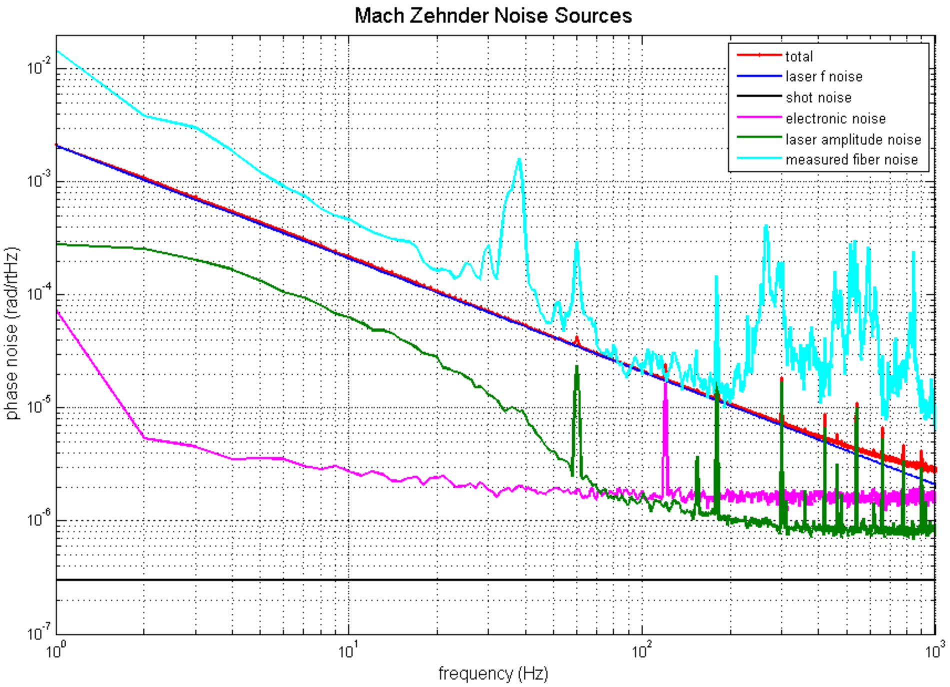


Figure 3: Equivalent phase noise in one Mach Zehnder channel. The laser frequency spectrum for a path length difference of $50m$ and an assumed $1/f$ laser f noise profile, which is likely an overestimate [6]. Electronics noise is detector dark noise, measured by blocking the laser. Relative laser amplitude noise was measured by blocking the fiber arm to leave out interference effects, divided by total DC voltage. Shot noise is a negligible noise source; the total predicted noise limit is shown in red and dominated by laser f noise. The interference signal is shown as fiber noise, which exceeds background noise sources at most frequencies.

to first order in $\frac{\delta A}{A_{tot}}$. If the system is locked at $\theta \approx \pi/2$, then we have

$$\frac{S_-}{S_+} \approx \theta + \frac{\delta A}{A_{tot}}(1+\theta^2)$$

Thus the detectors must be balanced well enough such that $\frac{\delta A}{A_{tot}}$ is lower in magnitude than the other noise sources in the system (Figure 3). This method will also cancel the common mode noise due to the fluctuation of beam position at the laser to fiber coupling, which results in intensity fluctuations in light transmitted through the fiber. To do so, we can consider the sum signal

$$S_+ = \delta A \cos(\theta) + A_{tot}$$

and vary the relative gains of the photodiodes to make S_+ independent of fluctuations in θ to a precision allowed by the potentiometer.

- **Laser frequency noise**

As the path lengths of the arms of the Mach Zehnder differ by the length of the fiber, fluctuations in the laser frequency are no longer common mode and thus are not cancelled in the detection. The equivalent length noise due to a relative laser frequency noise spectrum of $\frac{\nu(f)}{\nu}$ is given by

$$l_{freq}(f) = \Delta L \frac{\nu(f)}{\nu}$$

where ΔL is the path length difference between the arms [7]. This gives an equivalent phase noise of

$$\theta_{freq}(f) = \Delta L \frac{\nu(f)}{\nu} \cdot \frac{\pi}{\lambda}$$

The difference in path length is assumed to be approximately equal to the fiber length, $\Delta L = 50m$. The frequency noise spectrum of the laser has not been directly measured, so a typical spectrum of $\nu(f) \propto 1/f$, with $\nu(100Hz) = 100\frac{Hz}{\sqrt{Hz}}$ is assumed for concreteness.

- **Shot noise**

  Shot noise in the photodiodes is given by

  $$V_{shot}(f) = Z\sqrt{2eRP_{laser}}$$

  where P is the incident laser power, e is the charge of the electron, and Z and R are the diode's transimpedance and responsivity, respectively [7]. At the operating laser power, a π shift in phase corresponds to a voltage difference of $0.66V$, so the equivalent phase noise is (Figure 3):

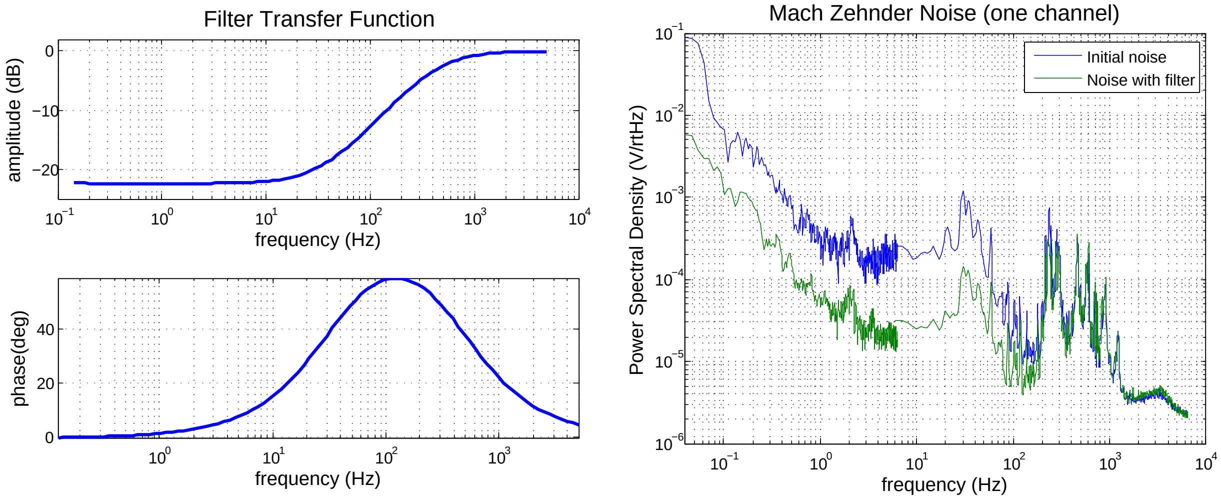
  $$\theta_{shot}(f) = Z\sqrt{2eRP_{laser}} \cdot \frac{\pi}{0.66V}$$

- **Photodetector and electronics noise**

  The noise of the photodiodes themselves was measured directly by blocking the incident light and measuring the spectrum of one of the channels (Figure 3). The noise level of $< 2 \times 10^{-6} radians/\sqrt{Hz}$ above a frequency of $20Hz$ is consistent with the detector specifications of a noise equivalent power of $NEP = 3\times10^{-11}W/\sqrt{Hz}$, which translates to a noise floor of $2.9 \times 10^{-7}V/\sqrt{Hz}$ or $1.4 \times 10^{-6} radians/\sqrt{Hz}$. The peak at $120Hz$ is from power line pickups.

- **ADC noise**

  As the cancellation of fiber noise requires a control and feedback system, a digital data acquisition and control system will be used for feedback and signal readout. The conversion to a digital signal will be performed using a ?? bit analog to digital converter. This process introduces noise due to the finite full scale range and bin size of the ADC. In order to reduce the effect of ADC noise, an electronic filter was designed and built. The transfer function of the filter taken using a swept sine measurement is shown in Figure 4(a). The corner frequencies are $34Hz$ and $413Hz$. The effect of the filter is to whiten the spectra of the Mach Zehnder channels before input into the ADC (Figure 4(b)). The spectra are subsequently amplified to maximize the resolution and input in a high pass anti aliasing filter prior to input into the ADC.



(a) Transfer function (b) Effect on spectrum

Figure 4: High pass filters will be used to whiten the output spectra prior to input into the ADC. The swept sine response of the filter is shown in (a). A typical MZ spectrum taken from one channel with and without the filter (b).

- **Other noise sources**

  Other noise sources present in homodyne detection systems may include beam jitter noise, scattered light, and temperature noise of the photodiode [8]. The contribution of these sources to the noise budget is unknown, but is thought to be small compared to the dominant sources listed above.

3.1.3 Fiber noise measurements

The signal from the Mach Zehnder channel is high enough above the noise sources (Figure 3) to make a preliminary judgement about the amount of frequency noise introduced by the 50m fiber. The phase noise spectrum $\theta(f)$ can be converted to a frequency noise spectrum $\nu(f)$ by

$$\nu(f) = 2\pi f \cdot \theta(f)$$

The measured phase noise is converted into frequency (Figure 5). It is compared to a similar setup, without the fiber in one arm. This spectrum, taken for balanced path lengths, has insignificant laser frequency noise levels. The main sources of noise in the balanced path length system are thought to arise in large part from phase fluctuations due to environmental (seismic, acoustic, etc.) noise. The total rms frequency noise for the fiber spectrum is $30Hz$, as compared to $7Hz$ rms for the equal arm MZ, so the fiber signal is well above the environmental noise level.

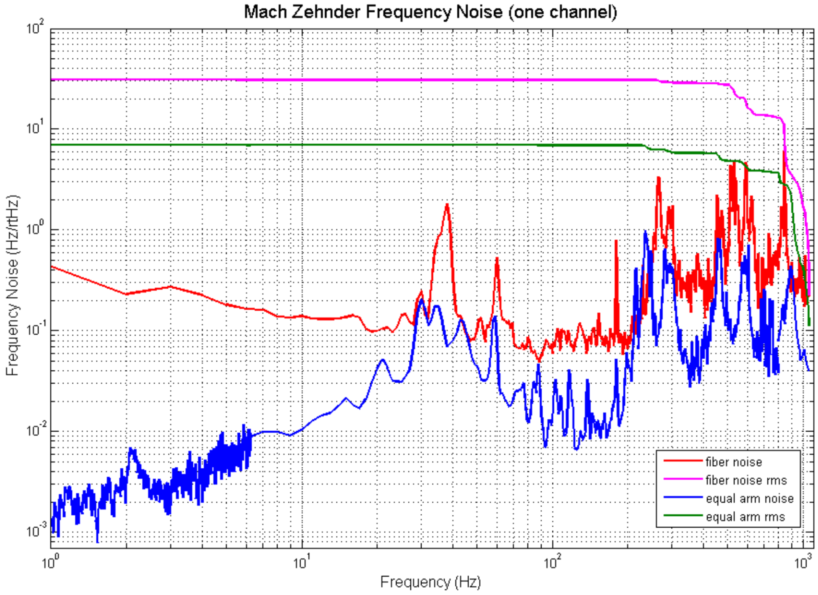


Figure 5: Frequency noise in a Mach Zehnder interferometer with equal arms (no laser frequency noise contribution), compared to the noise caused by adding a 50m fiber in one arm. The total rms noise values are $7Hz$ and $30Hz$, respectively.

The phase noise induced in the fiber by environmental perturbations is considered approximately linear ([4]), so the noise can scale linearly with fiber length depending on the environmental conditions. This would result in a frequency noise of up to $2.4kHz$ rms for a $4km$ long fiber to be used in Advanced LIGO. This far exceeds the noise limit of $75Hz$ for effective lock aquisition presented in the previous section, necessitating the implementation of fiber induced phase noise cancellation techniques.

3.2 Cancelling Fiber Noise

FIBER CANCELLATION SETUP

4 Future Work

The future goals of the project are as follows:

- **Improving the Mach Zehnder system**

To further improve the signal to noise ratio of the phase noise sensing system, several changes will be made to the present Mach Zehnder interferometer:

- Environmental noise: The vibrational modes of the mounts for the optical elements of the Mach Zehnder are thought to contribute to the environmental noise. Making mounts with fewer degrees of freedom will lower the noise in the system. The MZ will also be better shielded from acoustic and seismic noise with a box.
- Mode matching: To increase the amount of transmisson through the fiber, laser light should be coupled into the fiber with maximal overlap between the beam and the fiber modes. Also, to maximize the interference signal between the two arms of the Mach Zehnder, the output of the fiber must be modematched with the beam propagating through free space. Gaussian beam propagation calculations will be used to optimize the placement of optical elements for this purpose, and several lenses to alter the beam parameters will be added to the setup as necessary.
- Amplitude noise cancellation: The method of amplitude noise cancellation presented above will be implemented.

- **Implementing fiber noise cancellation**

  As of this report, the noise level of the fiber will significantly affect the transfer of a stable laser reference across a distance of 4km necessary for Advanced LIGO. The phase cancellation technique described in [4] will be tested and implemented. Revisions to the scheme described may be developed if necessary.

- **Modeling and testing auxiliary locking techniques**

  If a sufficiently stable frequency reference is shown to be reliably transmitted via fiber, it will be used in a frequency shifted PDH locking technique to control the length of the degrees of freedom of the interferometer.

5 Summary and Conclusion

6 Methods

6.1 Derivation of Mach Zehnder output signals

If the electric field incident on the first beamsplitter is given by

$$E_{laser} = Ee^{i\omega t}$$

then assuming the free space path has zero phaseshift while the fiber path has a phaseshift of θ with respect to the free space path, then the beam is split into E_1 and E_2:

$$E_1 = -\frac{1}{\sqrt{2}}Ee^{i\omega t}, \qquad E_2 = \frac{1}{\sqrt{2}}Ee^{i\omega t}$$

After the beam passes through the fiber, it gains a relative phase θ,

$$E_3 = -\frac{1}{\sqrt{2}} E e^{i(\omega t + \theta)}$$

The fields E_2 and E_3 recombine at the second beamsplitter to give two interfering fields E_A and E_B incident on the photodetector.

$$E_A = \frac{1}{\sqrt{2}}(E_2 - E_3), \qquad E_B = \frac{1}{\sqrt{2}}(E_2 + E_3)$$

Taking the magnitudes gives the output power

$$P_A = |E_A|^2 = \frac{1}{2}E^2(1 + \cos(\theta)) \quad P_B = |E_B|^2 = \frac{1}{2}E^2(1 - \cos(\theta))$$

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