LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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Stabilization of a 2μm Laser Using an all-Fiber Delay Line Mach-Zehnder Interferometer

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1 Introduction and Context

The Advanced LIGO interferometers are amongst the most sensitive instruments ever constructed. Even as these observatories progress towards achieving their design sensitivity, work is under way in planning even more sensitive successors[4][5][6]. These will incorporate the the state of the art in materials, control and sensing technology. Key to reaching these improved design sensitivities will be the implementation of cryogenic test masses[4]. These will likely be made from crystalline silicon and will be probed with longer wavelengths in the range of 1550-2000 nm. The choice of 2 m laser light is a strong candidate wave length given the transparency window of the materials and reduced scatter[7]. Less well known is the performance limitations of lasers of this type and how they might be pre-stablized for use in demanding interferometric experiments.

While NPRO style lasers, previously used at 1064 nm in LIGO, offered inherently narrow line width light, newer fiber coupled technologies such as Discrete-Mode diode lasers are now commercial available at competitive prices. Direct stabilization of these seed laser sources using all fiber assemblies may offer a compact, affordable and low maintenance alternative to more traditional reference cavity pre- stabilization schemes. The characterization of an all fiber stabilized diode laser source will be an important step for delivering 2 m light to table top experiments used in testing various 2 m devices for future LIGO use. It will also be an important first step for building a test bed for assessing the goodness of candidate laser sources for future long wavelength laser interferometers.

Laser stabilization is important for reducing frequency and intensity noise in optic systems. In a system involving a single-frequency laser, there is always noise associated with its output, causing its monochromatic nature to be broadened in its spectral output. Noise in laser sources can originate from a multitude of sources including external acoustic disturbances, internal thermal drift, and spontaneous emission within the laser's gain medium(i.e. quantum noise). Understanding and accounting for these sources is a crucial aspect in obtaining a low noise light source for interferometric experiments. Current LIGO technology uses a 125W laser of 1064nm light and one of the modifications for the LIGO Voyager upgrade is a longer wavelength laser of 2004nm. (This experiment aims to demonstrate all fiber optic stabilization of a relatively noisy (2 MHz linewidth) diode laser source and establish performance limits of such as simple system.)

2 Objectives

The goal of this all-fibered Mach-Zehnder intereferometer(shown in Figure 1) project is to actively stabilize a 2 μm laser and characterize both its *frequency* and *intensity* noise. We will use a path length difference in the intereferometer to make a frequency discriminator and an InGaAs photodiode to measure intensity noise. This project is motivated by the current stage in the LIGO3 PSL Timeline, Noise Characterization and Long-term Stability[4].

Furthermore, we will employ a closed loop feedback control system in our set-up to stabilize the frequency of our laser under test. Additionally, we will design an encasement around our intereferometer to passively supress as much thermal and acoustic perturbations as possible. Depending on the progress of the project, we will conclude by investigate the usage of an acousto-optic modulator for intensity noise stabilization. The ideal conclusion of our experiment would be additional data that can support the usage of a longer wavelength laser on the new generation LIGO Voyager.

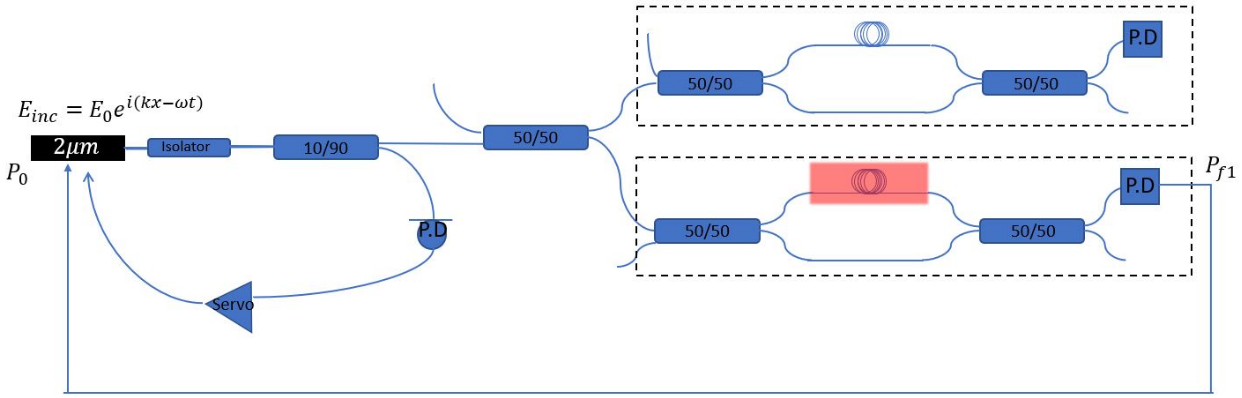


Figure 1: Experiment set-up, with Mach-Zehnder interferometer delay line and its reference

3 Experiment overview and approach

3.1 Laser Stabilization

The optical delay line present in the mismatched fiber cable will be used to stabilize the frequency of our 2 μm laser. Essentially the long intereferometer arm will act as a time-delayed reference when compared with the identical intereferometer. The variations in power output convert the interferometer's slope response in frequency to a use as an error signal in a closed feedback loop. To use this mid-fringe locked frequency stabilization, we would use the thermal feedback from one interferometer. Such a control loop would be constructed using a PID Controller. The error signal of this loop would subsequently be used to characterize the frequency noise present in the laser under test.

We can have an idea of the required path length difference by considering the Free Spectral Range (FSR) of the interferometer, $\Delta\nu \approx \frac{c}{\Delta x}$. For an FSR comparible to the linewidth of 2MHz, we need an arm legnth mismatch on the order of 150m. This quantity represents a free spectral range of 2MHz present in the laser under test of a full fringe. However, since we want to stabilize the frequency to half fringe, we would need to seek a length that corresponds to the linear region near the turning point of the fringe, roughly halfway. Thus, we predict the path length difference should be within an order of magnitude of the calculated value, approximately 15m. We can also come to similar conclusion by analyzing the incoming laser electric field and comparing its power input and output. Considering the proportionality between the electric field squared with the magnitude of power:

$$P_{f1} = (E_{inc}^2/2)(1 + \cos(\Delta\phi)) \tag{1}$$

Representing the phase difference in terms of the path imbalance and wavelength:

$$P_{f1} = (|P_0|/2)(1 + \cos((2\pi\Delta L)/\lambda) \quad (2)$$

For the case when the output power at the photodiode is equal to the input power, the path imbalance becomes, in terms of c (depedent on refractive index of fiber optic cable) and frequency:

$$P_{f1} = |P_0| \quad (3)$$

$$\Delta L = nc/f \quad (4)$$

$$n = 1, 2, 3, ... \quad (5)$$

A challenge that is likely to arise would be the losses that come from pertubations within the optic cable that can affect polarization. This issue can be addressed either by putting a deliberate ”stress” on fiber, thus shortening the length of polarization, or by incorporating Faraday Mirrors into the interferometer. The latter would ensure that the output polarization state in the fiber optic cable is orthogonal to the entering state[2].

3.2 Characterizing Frequency and Intensity Noise

Frequency noise is often described in terms of its linewidth, which can be measured in a variety of ways. In our project, we will measure the frequency noise present in the output of the interferometer by converting its fluctuations into amplitude fluctuations. This will be achieved by having an optical frequency discriminator created by a path difference between the arms of the interferometer. In the process of characterizing the noise from the laser under test, we will develop acoustic and thermal isolation methods to prevent unwanted perturbations that could affect our measurements. We will measure and characterize the intensity noise of the laser under test with the output readings from the available InGaAs photodiode. These measurements will be performed with an electronic spectrum analyzer[3].

In order to prevent external noise (e.g. thermal and acoustic) that can affect the fiber optic cables and the laser under test itself, we will construct an encasement around the fiber optic cable spool and other parts of the experiment. The material used is still to be determined but a similar project had success using Sorbothane shock absorbing padding to account for acoustic vibrations and a simple Stryofoam case for passive thermal isolation[1][2]. The estimated noise budget of the LIGO Voyager is shown below.

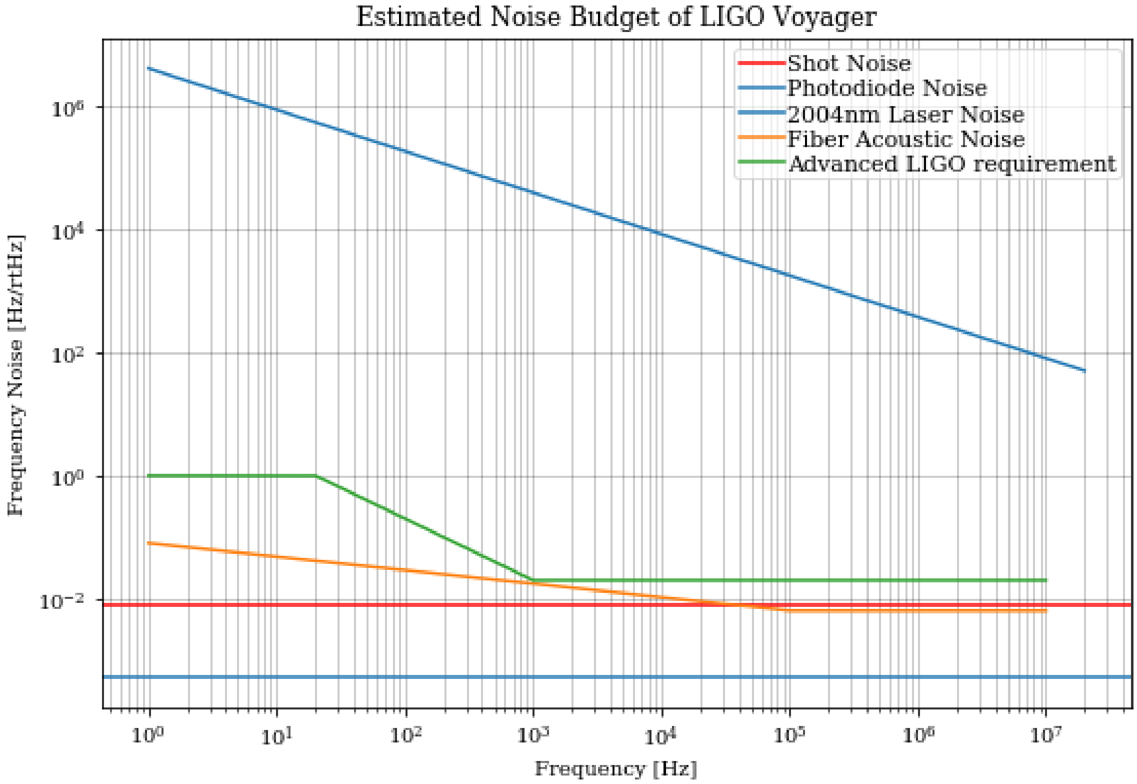
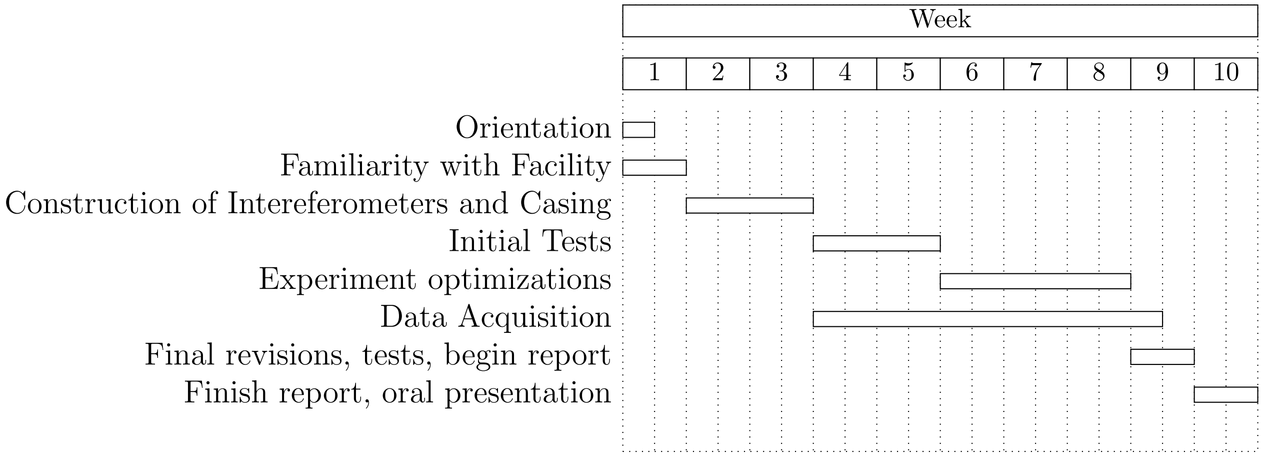


Figure 2: **Noise Budget for LIGO Voyager**, *Shown are the estimated amplitude spectral density of the frequency noise of various sources in the overall set-up. Together they contribute into our system's noise budget, and are compared with the estimated frequency noise requirement of the Voyager 2μm laser, which itself comes from the 1kHz linewidth NPRO frequency noise spectrum scaled by 2000. Based on the laser's wavelength and input power, the shot noise was calculated to be* $2.276 \times 10^{-11}\,\mathrm{W/Hz^{1/2}}$. *From manufacture documentation, the value of the photodiode NEP is* $1.50 \times 10^{-12}\,\mathrm{W/Hz^{1/2}}$. *Assuming a 15m arm length mismatch, the frequency noise equivalent power was calculated to be* $8.144 \times 10^{-3}\,\mathrm{Hz/Hz^{1/2}}$ *and* $5.358 \times 10^{-4}\,\mathrm{Hz/Hz^{1/2}}$ *for the shot noise and photodiode respectively.*

4 Project timeline

In this ten-week program the first and last weeks will be reserved primarily for orientation and project reports, respectively. Once a familiarity with the facility and its equipment has been established in the first week, we will spend the following week or two to begin constructing the Mach-Zehnder intereferometer and order any additional parts if needed. Following the setting up of the intereferometer, the next week can be spent putting together its encasement to prevent outside sources of noise affecting the desired laser noise we wish to characterize. Due to the intervals of time between each run of the experiment, which can take roughly a whole day, a significant part of the project will be reserved to data compilation and analysis. This data analysis will run alongside the experiments, particularly when the lab must be vacant for testing.



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