LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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Frequency Stabilization of 2 Micron Lasers Using Optical Delay Self-Heterodyne Interferometry

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1 Introduction

In the current LIGO design, 1064 nm light propagates through a Michelson interferometer and reflects off test masses [3]. Measurements of gravitational waves are made by analyzing the interference pattern that is output from the interferometer. The output is dependent on the phase difference between the beams in the two arms in the interferometer, and the lengths of the interferometer arms determine this phase shift. In order to accurately measure minuscule changes in the lengths of the interferometer arms, it is crucial to reduce various types of noise in the system, such as frequency noise. If a substantial amount of frequency noise is present in the laser that propagates through the system, it is difficult to differentiate changes in the interferometer output caused by gravitational waves from those caused by variations in the laser frequency.

Another source of noise in LIGO's data originates from the thermal noise of the test masses. LIGO's current test masses are made of fused silica, but mirrors made of crystalline silicon have demonstrated lower levels of mechanical loss than fused silica mirrors [4]. Crystalline silicon is highly absorbent of 1064 nm light, but demonstrates low absorption when tested with a longer wavelength of 2 μm [1]. Therefore, the next generation of LIGO detectors will likely switch to crystalline silicon mirrors and will use a wavelength of about 2 μm in the interferometer.

Access to low-cost sources of stable 2 μm light is crucial for researchers to develop the next generation of LIGO detectors. This work will address the stabilization of a 2050 nm laser, and will focus on reducing the frequency noise of the laser with a self-delayed heterodyne interferometry technique. This low-cost method has the potential to facilitate further testing and development of 2 μm light for gravitational-wave detection.

2 Objectives

Through self-delayed interferometry, I intend to narrow the linewidth of a 2050 nm laser. Previous work on self-delayed interferometry has demonstrated that the linewidth of a 1550 nm laser can be reduced from 2.2 MHz to 3.1 kHz. Current off-the-shelf 2 μm lasers have a linewidth of about 50 kHz, and I intend to stabilize my laser to 0.1 Hz [2]. I will first investigate the stability of the system without isolation from the environment of the laboratory, and then further attempt to improve the stability by placing the system in an isolation box to reduce acoustic noise.

3 Approach

My setup is similar to the setup used to stabilize a 1550 nm laser through self-delayed interferometry [2]. A general overview of my setup is displayed in Figure 1. First, a laser output will be split with a 90:10 fiber coupler. The 90% output will then be fed into a delay fiber while the 10% output will be fed into a fiber Mach-Zehnder interferometer. In this interferometer, the input is again split with a 75:25 coupler, with the 25% output being fed into a 50:50 coupler while the 75% output is fed through a piezo-driven fiber stretcher (FS) and then into the 50:50 coupler. The two outputs from the 50:50 coupler are transmitted to a pair of photodetectors (PD). From the photodetector signals, I will obtain a signal that will be fed into an electro-optic modulator (EOM) to produce a phase-corrected output, along with a signal that will be used to continually shift the FS such that the output of the interferometer is at a midpoint between constructive and destructive interference. The phase of the output from the EOM will be measured with another Mach-Zehnder interferometer setup.

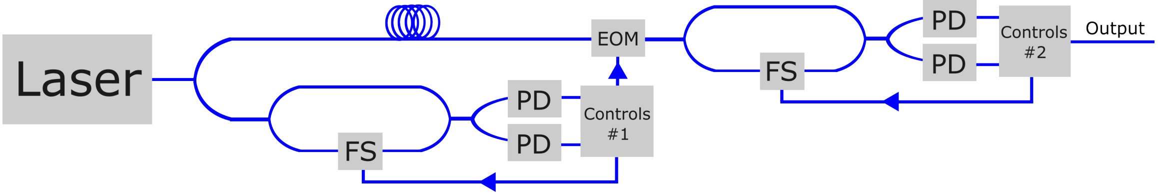

Figure 1: A diagram of my setup.

4 Locking the Laser

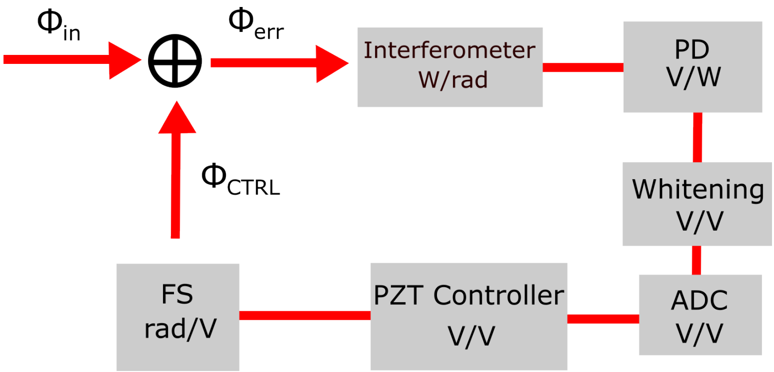

Figure 2: A diagram of the control loop we are using the lock the laser.

Currently, we are using the PID Controller instrument on our analog-to-digital converter (ADC) to create the signal to the piezo (PZT) controller. In the controller, we are simply using an integrator filter with a unity gain frequency of around 1 - 10 Hz, which allows us to correct the low-frequency drift of the output while suppressing extraneous signals at high frequencies. We then use a PZT controller to amplify the signal from the ADC by a factor of 15 in order to access the maximum range of our FS. However, the signal produced by the ADC is in the range of ±5 V, and the PZT controller takes inputs of 0-150 V. Therefore, we constucted a simple summing amplifier circuit to translate the ADC output signal to a signal in the range of 0 - 10 V. We are still in the process of building our whitening filter, which aims to amplify the signal from the PD and reduce the impact of the ADC noise floor on our noise budget.

5 Noise Budget

One of our main objectives over the past few weeks has been creating a noise budget which depicts how different sources of noise in our system appear as frequency noise from the laser. In order to calibrate each noise source to frequency noise, we constructed transfer functions that relate the laser frequency noise to the measured voltage on the ADC, and then used those transfer functions in order to translate the voltage we measure from other noise sources into frequency noise. We are interested in comparing frequency noise with the sum of all other sources of noise in order to determine the extent to which we can suppress the frequency noise with our later use of feed-forward correction. In order to find the sum of all noise sources other than the frequency noise, we added these sources in quadrature.

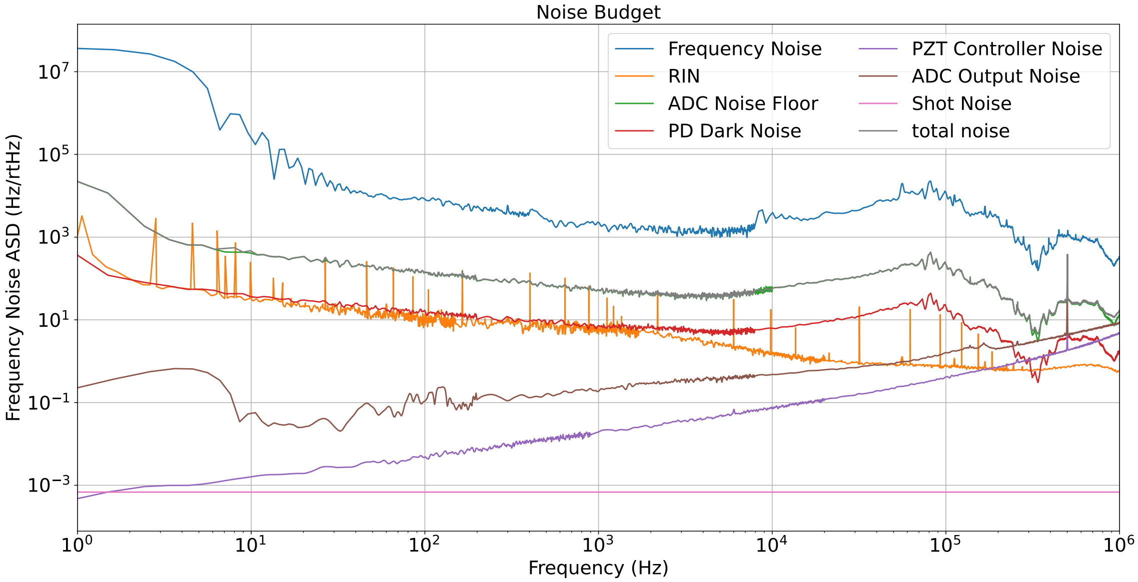

Figure 3: All sources of noise that we are considering.

5.1 Frequency Noise

Once our interferometer output was locked to the middle of a fringe, we measured the frequency noise of the laser by calibrating the signal we measured at the end of the interferometer with the photodiode to frequency fluctuations of the laser.

5.2 Relative Intensity Noise

The other notable source of noise arising from the laser output is the relative intensity noise (RIN). We measured the RIN of our laser by simply measuring the direct output of the laser with a photodiode without any delay from the interferometer. From this measurement, we calculated how the intensity fluctuations would translate to voltage fluctuations at the output of the interferometer, and then converted the voltage fluctuations back to frequency noise.

5.3 ADC Noise Floor

There is noise present in the output of our ADC, which is a Moku:Go from Liquid Instruments. This noise arises from the fact that there is noise inherent in the internal electronics. We found the equivalent frequency noise of our ADC noise floor by terminating all of its inputs and outputs and then converting the measured output voltage back into frequency noise. It is clear in Figure 3 that the ADC noise floor is one of the most prominent noise sources in our system. We are in the process of designing a whitening filter that will amplify the signal output by the photodiode so that the ADC noise floor will not be a limiting factor going forward.

5.4 PD Noise

There is also noise present in our system due to the fact that when we apply a bias voltage to the photodidoe, there is a small amount of current leakage in the detector which manifests as small voltage fluctuations measured on the Moku. This noise is called PD dark noise and is present regardless of if the laser is on or off. We measured the dark noise of our PD by turning the detector on with the laser off, and monitoring the output on the Moku.

5.5 Shot Noise

Shot noise arises in our photodetector due the fact that the photocurrent is comprised of the flow of discrete electrons, and thus there are variations in the number of electrons flowing per unit time as governed by Poisson statistics. We can calculate the amplitude spectral density of the shot noise that is present in our photodiode across all frequencies with $\sqrt{2qI}$ where I is average photocurrent in the photodiode.

5.6 PZT Controller and ADC Output Noise

We have noise in our system arising from the process of creating a signal that drives our PZT. One source of this noise is from creating a control signal with our Moku. We measured this small signal noise by feeding a small signal into the Moku and then measuring the output. In addition, there is noise in the output of the PZT controller. We measured this noise by inputting a DC signal into the controller and measuring the spectrum of the output.

6 Future Work

Our next steps consist of constructing the filters I previously discussed and setting up the EOM in order to correct the frequency noise of the laser. We also need to construct a second interferometer that will enable us to measure the remaining frequency noise after correction.

7 Timeline

Week 1: Gain familiarity with the lab and the components of the experiment, begin constructing setup

Week 2: Finish constructing the initial setup

Week 3 - 4: Take data with initial setup and determine how different sources of noise are affecting the system

Week 5: Continue to take data and improve the design to reduce sources of noise

Week 6 - 8: Transfer the setup into an isolating chamber to further reduce noise, quantify the improvement in laser stability, and continue to improve the system

Week 9: Collect any last necessary pieces of data, begin writing final report

Week 10: Finalize report and presentation

References

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[4] J. Steinlechner, I. W. Martin, A. S. Bell, J. Hough, M. Fletcher, P. G. Murray, R. Robie, S. Rowan, and R. Schnabel. Silicon-based optical mirror coatings for ultrahigh precision metrology and sensing. *Phys. Rev. Lett.*, 120:263602, Jun 2018.