LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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Technical Note **LIGO-T2300208–vX** 2023/07/10

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.

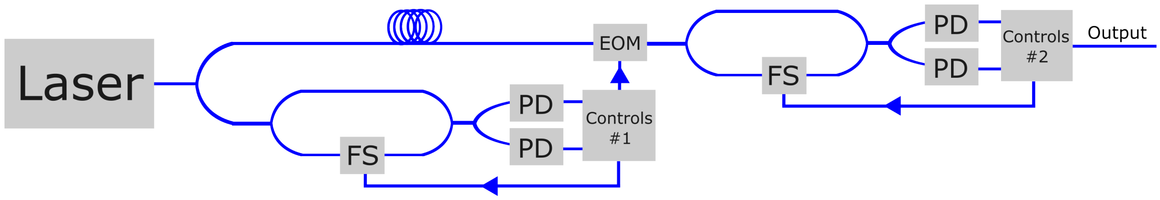

Figure 1: A diagram of my setup.

4 Progress

In order to minimize the linewidth of the laser, it is necessary to characterize different sources of noise in our system. We measured the noise of our analog-to-digital converter (ADC) which is a Moku:Go from Liquid Instruments. This characterization is crucial so that we can develop filters that distinguish signals from the noise floor.

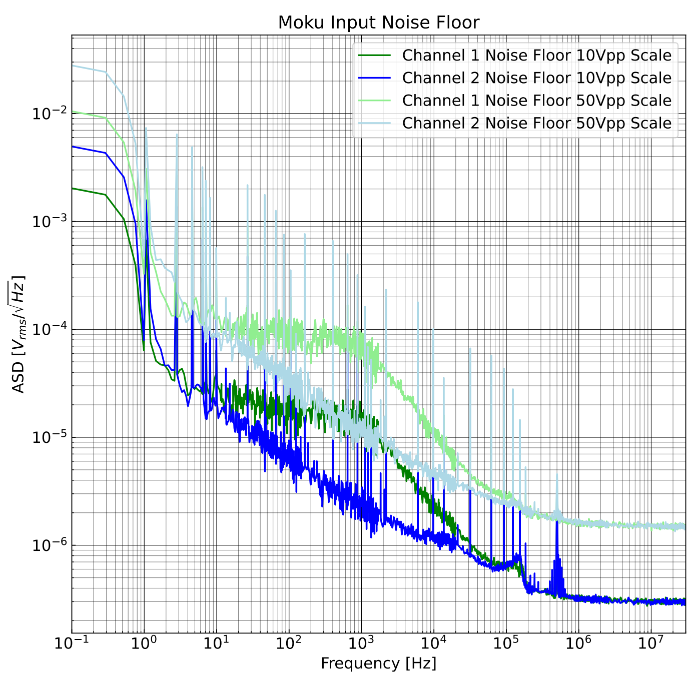

Figure 2: The amplitude spectral density of the ADC noise floor.

Additionally, we have measured the frequency response curves of the instruments in our experiment. This step is essential for understanding how signals of different frequencies are detected or modified. We have obtained frequency response plots for our laser diode controller (LDC) and a photodiode coupled with a transimpedance amplifier.

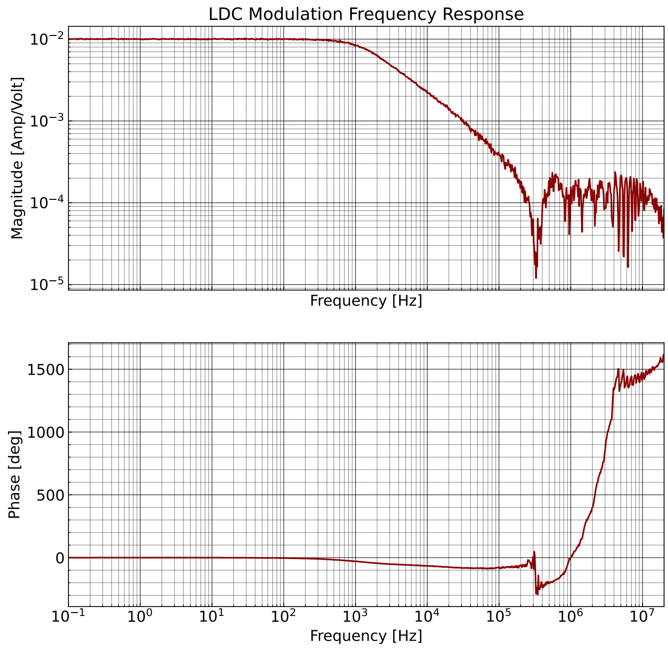

Figure 3: Frequency response curve of laser diode controller.

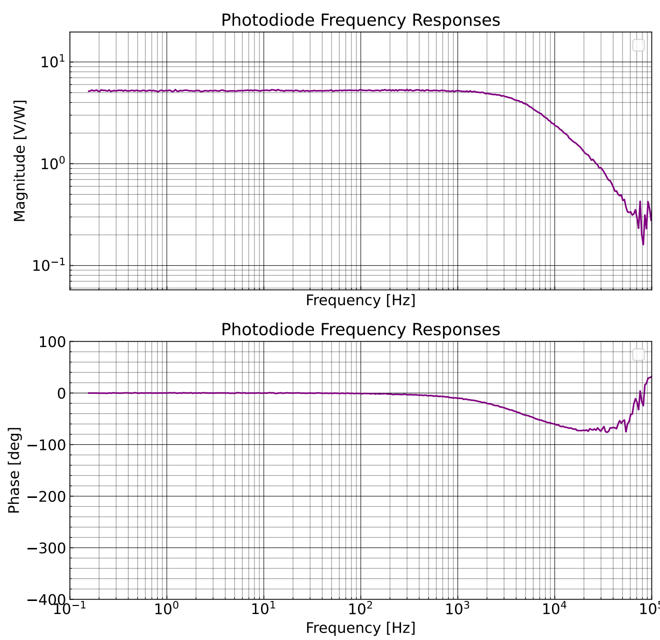

Figure 4: Frequency response curve of photodetector with amplifier.

One modification we made to our initial setup is that we originally planned to use a 50:50 coupler before the FS instead of a 75:25 coupler. However, we measured a significant power loss of around 5.7 dB in the FS. Since we intend to have signals of similar powers entering the 50:50 coupler, we decided to increase the power of the signal that is sent into the FS.

5 Future Work

We are currently working on designing filters that will amplify signals at high frequencies and creating a feedback loop that will control our FS. We are also working on a design to potentially lock the interferometer output in the linear regime by modulating the temperature of the fiber in the interferometer.

6 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

[1] R X Adhikari et al. A cryogenic silicon interferometer for gravitational-wave detection. *Classical and Quantum Gravity*, 37(16):165003, Jul 2020.

[2] Jiageng Chen, Qingwen Liu, and Zuyuan He. Feedforward laser linewidth narrowing scheme using acousto-optic frequency shifter and direct digital synthesizer. *Journal of Lightwave Technology*, 37(18):4657–4664, 2019.

[3] LIGO Scientific Collaboration. Advanced LIGO. *Classical and Quantum Gravity*, 32(7):074001, Mar 2015.

[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.