LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
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Feed Forward Frequency Stabilization of 2 Micron Lasers Using Optical Delay Homodyne Interferometry

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Contents

1 Introduction 2

2 Approach 3

3 Progress 3

4 Challenges 5

5 Next Steps 5

6 Acknowledgements 6

1 Introduction

From LIGO's observation of gravitational waves to timing experiments, laser systems are critical to modern precision measurement. Currently, LIGO utilizes a 1064 nm laser in a Fabry-Perot Michelson interferometer to measure the perturbations to lengths resulting from a passing gravitational wave[1][2]. However, the exceedingly small amplitude of these perturbations requires an exceedingly careful attention to sources of noise in the detectors, even after scaling the interferometer up to 4 km. A substantial component of LIGO's current noise budget is the thermal noise of the fused silica 'test masses' (mirrors)[2]. To reduce the contribution of thermal noise in the detector, a shift to cryogenic optics after the O5 observing run has been proposed in the LIGO Voyager upgrade to the LIGO Hanford and Livingston Observatories[3]. Additionally, KAGRA and proposed 3rd Generation Observatories such as the Einstein Telescope and advanced models of LIGO Cosmic Explorer are designed using cryogenic optics for the reduction in thermal noise[2]. Unfortunately, the transition to cryogenic optics requires modifications to a number of existing design choices. The fused silica currently used as the test mass substrate is incompatible with the cryogenic system, requiring a transition to another substrate. KAGRA uses saphire as its substrate, but the favored substrate is crystalline silicon. Crystalline silicon has favorable thermal characteristics, but is unusably absorbant to light at 1 µm, requiring a transition to 1.5 µm-2 µm lasers[2]. For Voyager, the primary contender is 2050 nm[4].

The 2 µm laser is additionally of interest to LIDAR and carbon dioxide measurements for its transparancy in atmosphere while being absorbed by carbon dioxide[5][6]. However, the state of technology at the 2 µm wavelength is notably behind that which has been developed at 1064 nm[2]. Particularly for the precision of interferometric measurements, the lasers must have narrow linewidths (range of light frequencies output) to reduce noise coming from other wavelengths. Current 2050nm lasers reach linewidths around 50kHz at low power, with more powerful lasers demonstrating much broader linewidths[4]. To achieve narrower linewidths suitable for more precise measurements, the laser phase noise must be reduced using a control circuit. A common method involves selecting out the primary frequency using a resonant cavity, and returning a control feedback loop to the laser source to lock the laser to the resonant mode of the cavity. Under the right circumstances, this can achieve linewidths less than a millihertz in the optical range, yet requires costly precision optics[7]. In the 2018 LIGO SURF Program, Vinicius Wagner demonstrated this approach during to phase noise reduction at 2 µm[8]

This experiment serves to investigate an alternate method of phase noise reduction, feedforward. In this mode, The phase noise is measured in real time on a sample of the beam using an interferometer and a correction term is calculated while the bulk laser is propagating through a delay line. Then, the adjustment is applied to the bulk laser following the delay line to correct for the measured phase noise. This approach has the benefit of being able to directly respond to the deviations in phase, while having the drawback of a more open control system, making the system more vulnerable to drifts in component gain.

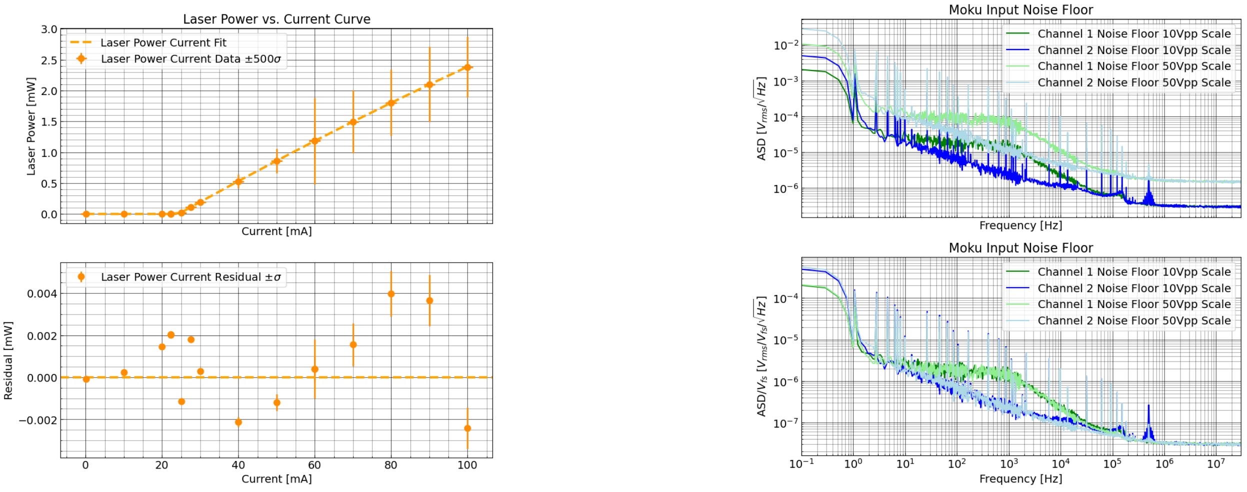
2 Approach

This work draws substantively from previous work in feedforward linewidth stabilization[9][10]. The beam from a 2 µm laser (e.g. [11]) will be split in two via a 90:10 beam splitter, with the bulk of the beam being sent into a fibre-optic delay line of approximately 100m (approximately 400ns delay). While the light propogates through the delay line, the remaining fraction of the beam is sent into a homodyne interferometer to measure its phase error. The interferometer consists of splitting the incoming beam in half, passing one half through a delay line, and interfering the delayed half with the direct beam in a 90° optical hybrid. To maintain the interferometer response in the linear regime around 45° phase difference between legs, a control element on the delay line will adjust the delay to compensate for drifting. Both a piezoelectric fiber stretcher and thermoelectric expansion of the fiber are being considered for this control element, driven by the Moku analog outputs through a control circuit. As the fiber stretcher fiber has notable attenuation at 2 µm, the split between the delayed and direct paths may be adjusted to 75:25 to provide a more balanced input at the 50:50 recombination. The light output of the hybrid is then converted into electrical signals using a single or pair of balanced photo-detectors. A whitening filter between the photodetectors and the ADC suppresses the contribution of the ADC noise to the measurement by increasing the magnitude of high-frequency components which are lower amplitude without amplifying the DC component such that it saturates the ADC. The balanced photodetectors allow for an increased rejection of intensity noise in the phase noise measurement if the intensity noise proves to be a limiting error source in the accurate phase noise measurement. Digital and/or analog circuitry then processes this measured phase noise into a phase correction RF signal to control an electro-optic modulator at the end of the primary branch's delay line. Folowing the application of this correcting frequency shift, the resultant laser output is expected to be of a much narrower linewidth. The final laser output is then reassessed for phase noise using another stage of homodyne interferometry as described before to quantify the reduction in noise.

3 Progress

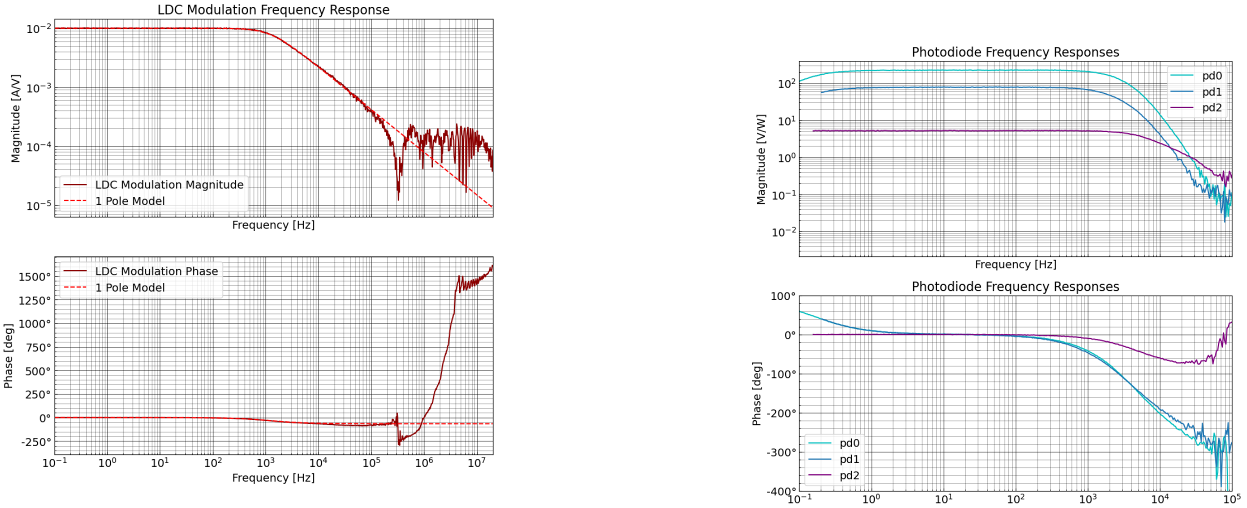
A significant portion of the previous three weeks has been spent familiarizing myself with working with fiber lasers, the data acquisitions tools used in the lab (the Moku:Go from Liquid Instruments), and relavent python libraries to control the data acquisition and process the resultant data. Additionally, we have been taking baseline measurements of noise sources and transfer functions to aid the modeling of the system. This has included measurements and modeling of the laser diode PI curve (Fig. 1a), the noise floor of the Moku:Go ADC (Fig. 1b), the response of the laser diode controller to analog modulation (Fig. 1c), the AC and DC responses of the various photodiodes (Figs. 1d,1e)

In gathering this data, I have written scripts alongside noting the necessary connections to redo the measurements, either to check for fluxuations over time or to take similar measurements of e.g. a new photodiode. I have also been working towards consistently storing data in files containing important metadata e.g. proper descriptions of the measurement taken, units, and relavent details of data acquisition.



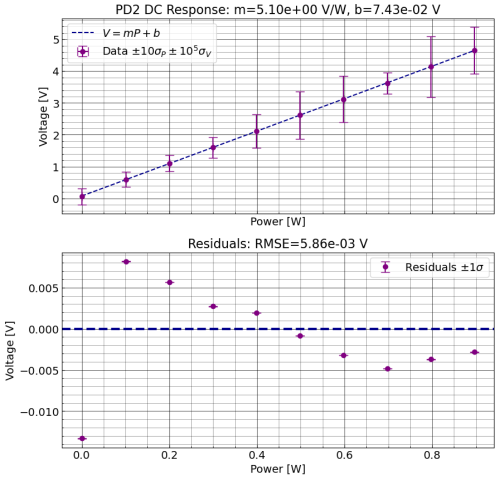
(a) DXS0174 PI Curve

(b) Moku:Go Noise Floor



(c) Laser Diode Controller Modulation Transfer Function

(d) Photodiode Response Curves



(e) Photodiode DC Response

Figure 1: Plots of Baseline Data

4 Challenges

Largely, my challenges have been the broad-scale difficulty of orienting myself in a new system of experimentation and analysis, using different tools than those with which I had previously been familiar. Specifically, I have found some of the documetation I've searched for cryptic, in particular the Moku Python API. I believe this to be a combination of the sometimes sparse nature of the documentation and my lack of experience with how the information is formatted in these sources. This is naturally expected to ease as I become more experienced, and has lessened over the previous couple weeks.

Another difficulty is an inability to self-evaluate my proficiency with the systems, particularly the laser system. The recent failure of the laser diode, while not expected to be a large delay in the project timetable, happened largely unpredictably from my perspective, indicating a blind-spot in my confidence in operating the laser, and I remain without clear insight into the failure. I believe it would be beneficial to more thoroughly discuss what safeguards could have lessened the probability of the failure.

Finally, I've found it difficult to determine what should be measured directly and what can be extrapolated from a simpler measurement/datasheet and a few assumptions/models.

5 Next Steps

- Creating and characterizing a whitening filter for the photodiode signal before digitization
- Implementing digital inverse whitening filter in Moku
- Creating and characterizing a thermoelectric fiber length modulator and associated control circuitry
- Creating a model of the system sufficient to produce noise budgets of the RIN and Phase noise measurements and the expected performance of the frequency stabilization.
  - Measuring/modeling attenuation in a fiber
  - Measuring/modeling attenuation/noise in a coupling
  - Compare noise budget with single and dual photodetectors
- Characterizing the new laser
  - Measuring PI curve
  - Measuring RIN and Phase Noise
  - Measuring temperature dependence of frequency
- Characterizing electric optical modulator
- Achieving reduced frequency noise via feedforward stabilization

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