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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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 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 incorporate cryogenic optics for the reduction in thermal noise[2]. Unfortunately, the transition to cryogenic optics requires modifications to several 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 transparency in air and absorption 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 and cannot operate at high frequencies where the control delay exceeds the correlation time of the noise[7]. In the 2018 LIGO SURF Program, Vinicius Wagner demonstrated this approach 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. The direct response decreases the latency from measurement to actuation with respect to the signal, allowing for performance at frequencies outside the capacity of typical feedback systems, into the MHz range.

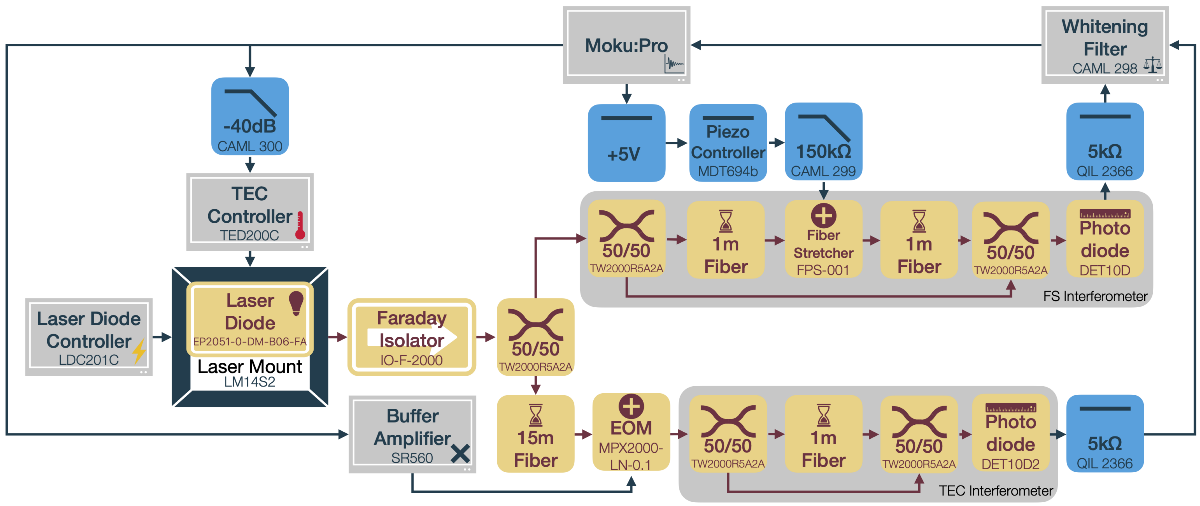

Figure 1: Diagram of the Optical Setup

2 Approach

This work draws substantively from previous work in feedforward linewidth stabilization[9][10]. As detailed in Fig. 1, the beam from a 2 µm laser (e.g. [11]) will be split in two via a 50:50 beam splitter, with the bulk of the beam being sent into a fiber-optic delay line of approximately 15 m (approximately 75 ns delay). While the light propagates through the delay line, the other fraction of the beam is sent into a homodyne Mach-Zehnder 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. Additionally, feedback to the temperature of the laser diode may be used to retain the frequency locked to an interferometer. The light output of the hybrid is then converted into electrical signals using a photo-detector, and decomposed into component frequencies by the Moku Spectrum Analyzer. This is normalized by the bandwidth of each frequency bin to yield an amplitude spectral density, or the root mean square noise power spectrum. Via a measurement of the amplitude of the fringe over a full 2π sweep, this is converted from volts to radians. This equates to a measurement of the correlation of the phase deviations between the direct and delayed beams, allowing for a measurement of the frequency noise, related by $\phi(t) = 2\pi f(t)/\tau$, with τ representing the relative delay between the two arms.

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. A pair of 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

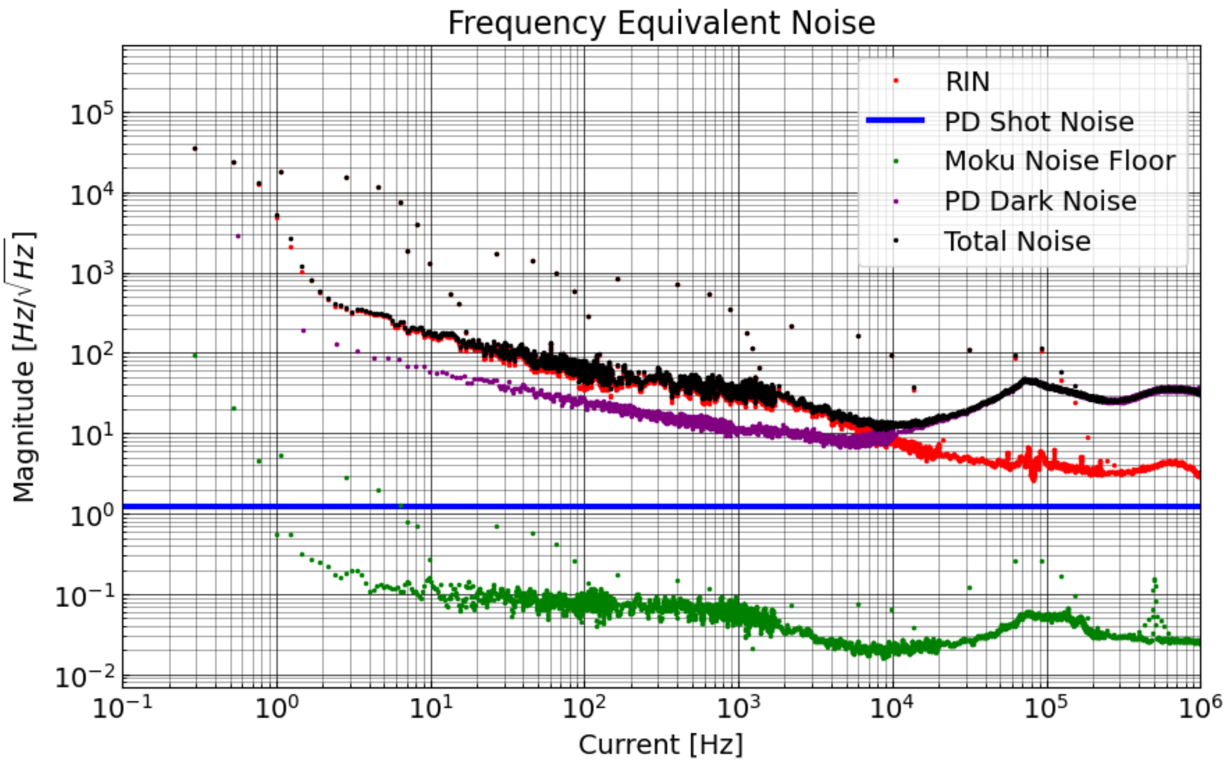

Figure 2: Noise Budget of First Interferometer

in the accurate phase noise measurement. Digital circuitry in the Moku then processes this measured phase noise to apply the stabilizing signals to the locking actuators and into a phase correction RF signal to control an electro-optic modulator at the end of the primary branch's delay line. Following the application of this correcting frequency shift, the resultant laser output is expected to contain reduced phase noise. The final laser output is then re-assessed for phase noise using another stage of homodyne interferometry as described before to quantify the reduction in noise.

3 Progress

An important segment of the summer has been spent working on modeling the system's transfer functions and noise sources, resulting in the production of a noise budget for the system, Fig. 2. This involves first measuring and/or theoretically modeling transfer functions between points in the system. Then, measurements of the amplitudes of the noise sources across the frequency domain are moved through the system via these transfer functions to produce their equivalent frequency noise. This model is then used to predict the limiting factors for the measurement of the initial and final noise and the expected amount of noise reduction. We have physically constructed and characterized several analog circuits for the whitening of signals and processing of outputs from the signal output by the Moku to the form required by the actuator (increased current, shifted zero point, reduced magnitude, etc.). The setup for the feedforward experiment is constructed as in Fig. 1, and we have a preliminary example of a reduction in phase noise, Fig. 3, although in a small frequency

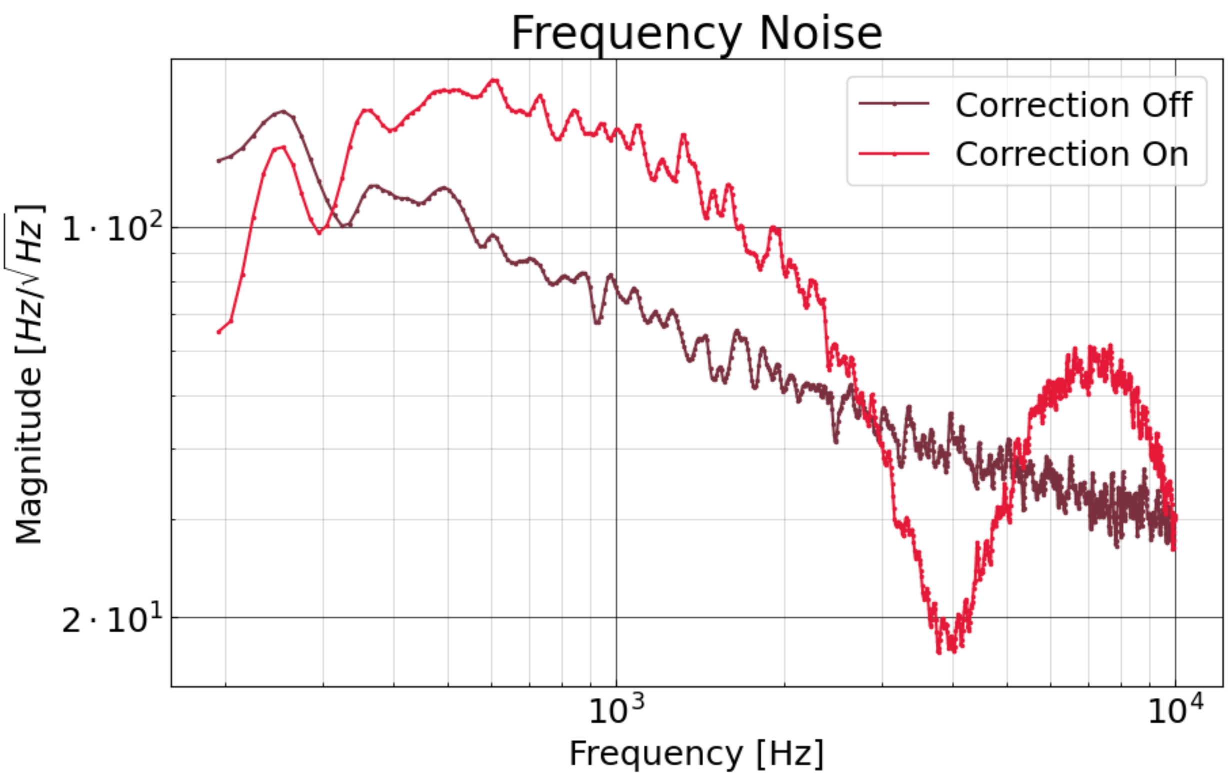

Figure 3: Decreased Phase Noise

band and only 50% while the noise is increased in the nearby range. Finally, we have found some approaches that were less fruitful, such as the Peltier element as an actuator to lock one of the interferometers, as the frequency range was not sufficient to maintain lock in the current setup.

4 Challenges

Working with the Moku continues to be a moderate challenge. Principally following from my lack of familiarity with the system, combined with occasionally vague documentation, configuring the Moku to perform its required tasks has been difficult. The output appears to have unfiltered digitization on the order of 1 mV, which I was not aware of, leading me to become confused by the noise appearing in my characterization of the whitening filter. Additionally, the pre configured instruments of the Moku often do not contain the combination of features I wish to use for a given task, causing me to spend extra time looking through the set of instruments available and then chaining multiple together in the Multi-Instrument mode to approximate the desired responses. Finally, these instruments often do not contain useful features, such as a sufficiently low gain on the PID integrator, or the ability to specify the desired sample rate. Additionally, it has been difficult to keep the system models in sync with the current optics setup as it continues to change and I have lacked the time to gather data on components such as the losses in a fiber.

5 Next Steps

- Ensure the model for the system is accurate for the current setup.
- Take more justified measurements of the feedforward noise reduction.
  - Calibrate meausements to phase noise.
- Compile results into final report/presentation.

6 Acknowledgements

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