LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
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Technical Note **LIGO-T1600153–v1** 2016/05/15

Reference System for Cryogenic Coating Noise Measurements SURF Project 2016

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1 Introduction

The Laser Interferometer Gravitational-Wave Observatory (LIGO) is a large scale project aimed at detection and study of Gravitational Waves. The current Advanced LIGO Detectors are some of the most sophisticated and sensitive sensors for length fluctuations ever made. These interferometers measure strain in their arms in the order of a few 10^{-24} in the frequency range of 10Hz to a few kHz. Instruments that aim at such delicate measurements are inherently prone to a wide range of noises.

One such source of noise is the Brownian noise in the coating of the test masses which arises from the coupling between macroscopic degrees of freedom and the thermal energy in the mirrors according to the fluctuation dissipation theorem[1]. While Brownian noise also emerges in the substrates and suspensions, the coating contribution presents a severe limitation to the achievable instrument performance between 40 and 200 Hz[2].

It is thus important to improve the mirror coatings and reduce the effects of this noise. A possible approach in doing so is cryogenically cooling the test masses so as to lower the thermal energy in the test mass, in turn lowering the Brownian noise. Due to the fact that fused silica is not well-behaved towards lower temperatures, silicon is an attractive alternative for its mechanical properties and thermal characteristics[3].

During this summer, I will work on a pre-existing work bench designed to measure the coating thermal noise in sample mirrors at cryogenic temperatures. The bench consists of two nominally identical optical cavities with independent lasers locked to them. Using this setup for a differential measurement of the resonance frequency fluctuations in the two cavities, one can directly measure the coating thermal noise that dominates these cavities by design.

The next generation of test cavities will only be several centimeters long, which enhances the conversion from length to frequency fluctuations. It however also carries a risk of too high beat frequencies for the low-noise photo detectors used in the experiment. The measurement becomes simpler if each of these two setups is compared with a third reference setup, which features lower intrinsic noise in its cavity. I will be setting up this reference bench and incorporate it into the existing work bench.

2 Objective

The goal of my work for the summer is to set up an optical frequency reference to aid the characterization of coating noise in cryogenically cooled silicon cavity optics.

Unlike LIGO in its current state, the experiment uses silicon optics because fused silica is not well-suited as a substrate material at cryogenic temperatures due to increased mechanical loss and low thermal conductivity. This in turn requires that we transition to 1550 nm lasers, because silicon is too absorptive at 1064nm.

Due to manufacturing tolerances, the relative location of the resonances in the test cavities are somewhat uncertain. Since they are very short by design, they have large free spectral ranges in the GHz range, and upon differential measurement, in case the locking frequencies are far apart, the beating output will be too fast to be detectable by the photo detector. As a contingency plan for beat measurements and a diagnostic tool for debugging the original test bench, the proposed modification of the setup is the addition of an external reference system.

Thus, I will be setting up the reference bench, which features an independent laser and a third optical cavity. The silica reference cavity exists from the early stages of the cryogenic test bench. This cavity will be placed inside a separate vacuum tank on a separate optical table. Feedback controls, which need to be optimized, will keep the laser system on resonance with the cavity. The stabilized transmitted light will be guided to the test bench with an optical fiber.

3 Approach

In the early stages of the experiment a fused silica cavity for initial testing of the laser feedback was assembled, shown in Figure 1. It is much longer than the next generation of test cavities and supports larger beams, which dilutes the impact of coating noise. The cavity is therefore intrinsically less noisy, and can be used as a frequency reference for the coating noise induced frequency fluctuations in the test cavities. Similar cavities have been used in the past for room temperature measurements of coating thermal noise[4].

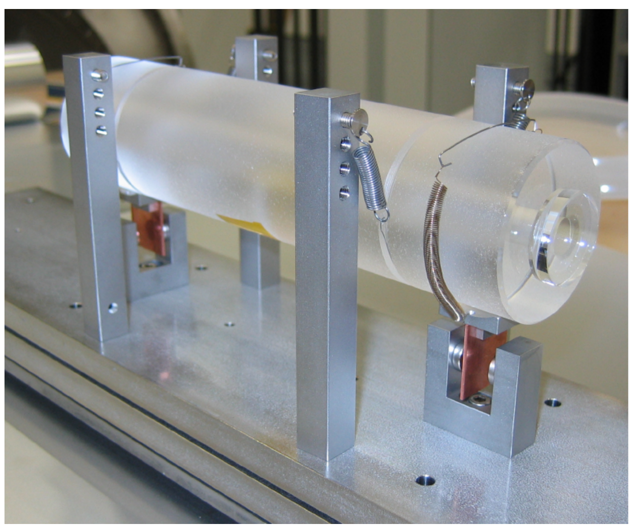

Figure 1: The Fused-Silica Reference Cavity.

To build this reference system, I will characterize the additional fibre-coupled laser system (electronic response, spatial profile) and find a lens solution to match the spatial mode supported by the cavity. With a laser system probing the reference cavity I will then determine its optical properties and use the measurements to establish and optimize the feedback to the laser frequency using the Pound-Drever Hall[5] technique. This locks the laser frequency to the cavity resonance and causes the majority of the laser light to be transmitted in the cavitys fundamental mode.

I will then direct the output of this setup to the work-bench, which is located on a different table, via an optical fibre. On the test bench, I will modify the existing setup such that the beams transmitted by either test cavity are additionally interfered with the stabilized reference laser, which enables the differential frequency noise readings. Figure 2 shows the arrangement of the existing bench and the proposed reference bench.

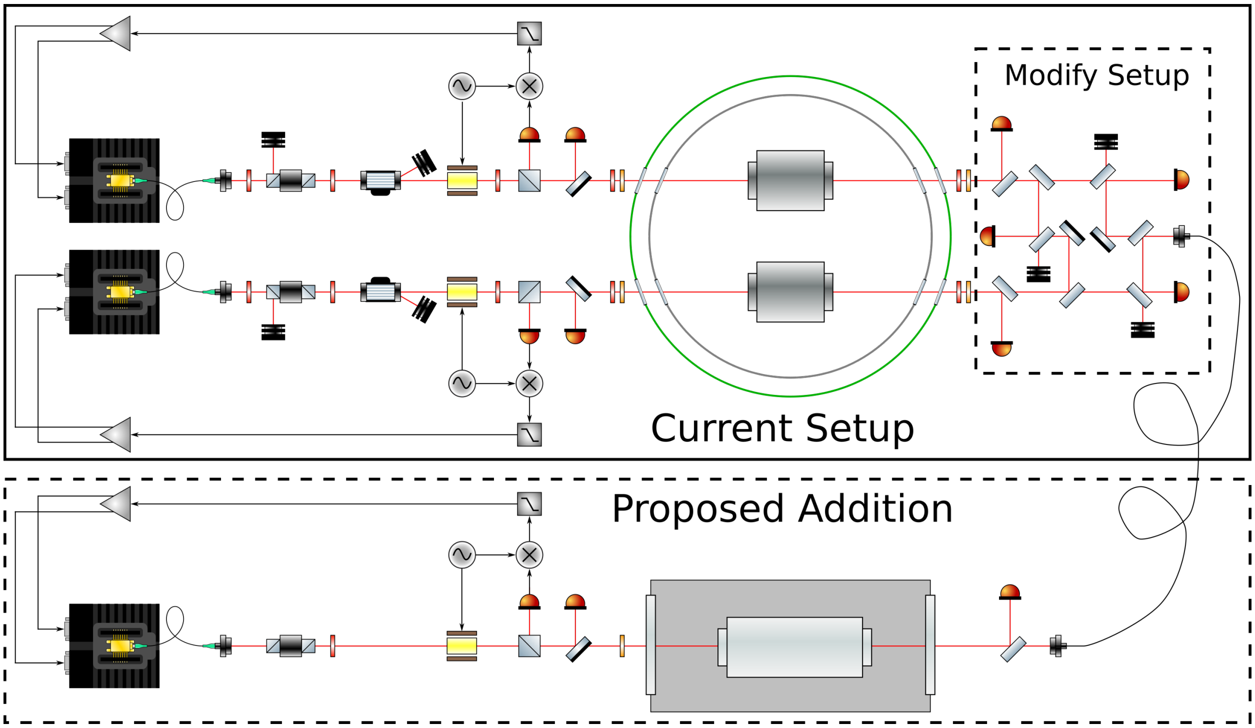

Figure 2: Diagram Showing the Final Setup.

There are a few different methods to obtain these readings and assess the test cavity noise floor. With a well-behaved reference system one can take individual measurements of the test cavities, which requires the reference bench to be locked in separately at appropriate frequencies and therefore does not provide a coherent measurement between the test cavities. More complex, coherent methods exist which involve sideband modulation and do not require locking the reference multiple times. Certain combinations of the data streams can potentially cancel the residual noise output of the reference setup, only measuring the noise from the test optics. The conclusion to my work will be to explore the applicability of some of these extraction techniques.

Upon completion of my tasks, the Cryolab at Caltech will have a valuable diagnostic instrument for LIGO optics which streamlines coating noise measurements and can help identifying problems in the setup.

4 Program Schedule

Week	Task Focus
1	Becoming familiar with laser operation and beam diagnostics
2	Mode measurements and matching with lens solutions
3	Setting up the front optics guiding the beam into the cavity
4	Cavity characterization and initial feedback setup
5	Place cavity in vacuum tank, evacuate; feedback optimization
6	Back optics setup and fiber-coupling of transmitted light
7	Test bench modifications
8	Beat note setup with primary lasers; contrast optimization
9	Measure frequency noise with different electronic demodulation techniques
10	Application of advanced high frequency demodulation techniques

References

[1] Y. Levin, "Internal thermal noise in the LIGO test masses: A direct approach," Phys. Rev. D **57**, 659–663 (1998).

[2] T. Hong, H. Yang, E. K. Gustafson, R. X. Adhikari, and Y. Chen, "Brownian thermal noise in multilayer coated mirrors," Phys. Rev. D **87**, 082001 (2013).

[3] J. Franc, N. Morgado, R. Flaminio, R. Nawrodt, I. Martin, L. Cunningham, A. Cumming, S. Rowan, and J. Hough, "Mirror thermal noise in laser interferometer gravitational wave detectors operating at room and cryogenic temperature," arXiv (2009). http://arxiv.org/abs/1506.07088.

[4] T. Chalermsongsak, F. Seifert, E. D. Hall, K. Arai, E. K. Gustafson, and R. X. Adhikari, "Broadband measurement of coating thermal noise in rigid Fabry-Pèrot cavities," Metrologia **52**, 17 (2015).

[5] E. D. Black, "An introduction to Pound-Drever-Hall laser frequency stabilization," American Journal of Physics **69**, 79–87 (2001).