LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
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2024 LIGO SURF Project Proposal: 40m ALS / SFG

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1 Introduction

The LIGO (Laser Interferometer Gravitational-Wave Observatory) detectors are essentially large scale Michelson interferometers which are designed to sense variations in space-time strain induced by passing Gravitational Waves (GWs). The LVK (LIGO-Virgo-KAGRA) detector network currently consists of two Advanced LIGO detectors in the U.S.; the Advanced Virgo detector in Italy; and the Japanese detector, KAGRA. A third Advanced LIGO detector is to be located in India.

The 40m prototype of LIGO at Caltech is a 1:100 scale model of the LIGO facility. It serves as a testing ground for upgrades aimed at enhancing the Advanced LIGO (aLIGO) detectors. The primary objective of this project is to study the implementation of upgrades that significantly improve the sensitivity of the GW detectors. Currently, the detector faces challenges related to quantum efficiency (QE) in photodetection and laser feedback stabilization.

The significance of the SFG project lies in the pivotal role of quantum efficiency enhancement for the transition to longer wavelengths (> 1 um) in next-generation LIGO detectors. Even ∼15% improvement in quantum efficiency can significantly increase the observable GW range by ∼60%. In ongoing research efforts, the project aims to boost quantum efficiency through the implementation of an upconverting mode cleaner. The progress of this effort depends largely upon the procurement of necessary materials.

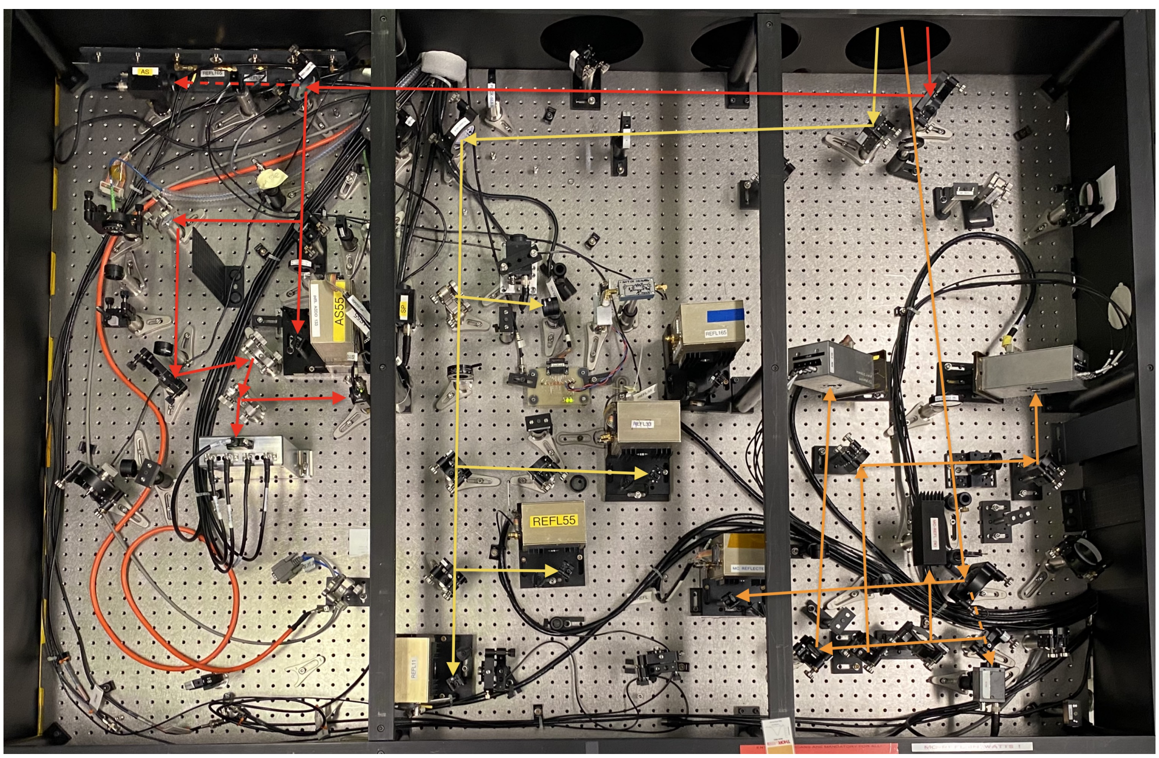

Figure 1: Arm Length Stabilization Table (as of June 10, 2022)

As for the ALS project, laser feedback stabilization plays a crucial role in maintaining stable optical cavity lengths, and decreasing the time required to get back to the observing state in case the locking breaks. Enhancing the digital control system for laser locking holds the potential to increase the number of detections significantly (∼1 per week) due to increase in the time the detector is in observing mode. Previous work on ALS at the 40m lab has focused on feasibility and initial implementations of a digital control system.

2 Objectives

- Implement an upconverting mode cleaner; using nonlinear effects to upconvert the signal into 700 nm where high (>95%) QE devices can perform the detection.
- Investigate noise coupling mechanisms and devise mitigation strategies to meet the requirements of a GW detector.
- Characterization of a feedback control system which monitors the cavity's response to the laser and makes real-time adjustments to maintain stable locking using automatic system identification (sysID) and digital IIR filters.
- FPGA based implementation of an optimal feedback transfer function that minimizes noise-induced fluctuations in the cavity length while responding quickly to external disturbances.

3 Approach

3.1 UMC Implementation

After studying nonlinear optics effects, utilize a 2050 nm light beam as the signal input and a strong 1064 nm pump to upconvert the signal into 700 nm within a nonlinear crystal inside a cavity. Upon material availability, assemble the UMC setup and conduct initial testing to validate functionality and performance. Work on how to optimize the UMC setup to achieve near unity QE.

3.2 ALS System Understanding

Gain a firm understanding of the existing ALS system deployed in the 40m lab. Investigate the noise characteristics of the laser locked to the cavity and analyze its impact on stability and measurement accuracy.

3.3 Optimize feedback transfer function

Determine the optimal feedback transfer function that satisfies a multi-objective cost function, balancing stability, responsiveness, and noise suppression. Refine the control parameters based on performance in simulations to achieve speed in laser stabilization.

3.4 Resource Utilization

Most equipment and resources are available at the 40m lab for both the SFG and ALS projects. The procurement of the nonlinear crystal for the SFG project is in process. However, the timeline for material arrival is uncertain, posing a significant challenge to the project.

3.5 Collaboration and Dependency

Work closely with mentors and the 40m lab team, comprising approximately 4 to 5 individuals, for feedback, and collaboration. The projects do not rely directly on results from other related projects.

4 Project Schedule

Below is a tentative timeline of the project.

Week 1-2:

- Fully understand the principles of nonlinear optics and UMC working.
- Familiarize with the existing ALS system and its components at the 40m lab.
- Review literature on feedback controls, sysID and IIR filters in detail.

Week 3-4:

- Familiarize by working with the lasers and other equipment to implement the UMC. Begin assembling the UMC setup based on available components.
- Study the noise characteristics of the laser locked to the cavity for the ALS project.

Week 5-6:

- Continue the assembly of the UMC setup and conduct initial testing to validate functionality if possible.
- Examine the feasibility of potential feedback transfer functions.

Week 7-8:

- Optimize the UMC setup to optimize to achieve near unity quantum efficiency.
- Further investigate noise coupling mechanisms in the ALS system and devise mitigation strategies.
- Implementation of the feedback transfer function on FPGA and optimization.

Week 9-10:

- Evaluate the performance of the ALS/UMC systems through simulations.
- Document the findings, including optimization results and recommendations for future improvements.
- Prepare presentations or reports summarizing the project outcomes.

References

[1] https://labcit.ligo.caltech.edu/~ajw/Amaldiv2_Weinstein.pdf

[2] https://wiki-40m.ligo.caltech.edu/40mHomePage

[3] https://dcc.ligo.org/DocDB/0188/T2300178/004/Reuben_Mathew_SURF23_Final_Report.pdf

[4] B P Abbott et al 2020 Class. Quantum Grav. 37 055002

[5] The plans are based on discussions with Professor Rana Adhikari (Experimental Gravitational Physics, LIGO Lab Caltech) and Radhika Bhatt (Graduate Student, Adhikari Research Group).