LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
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Technical Note **LIGO-T2300146–v1** 2023/06/02

Developing spatially-tunable adaptive optics for LIGO

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1 Introduction

Gravitational waves (GW) were first predicted by Albert Einstein in his General Theory of Relativity. Their first direct detection was in 2015 by the Laser Interferometer Gravitational-wave Observatory (LIGO), through the response of free test masses (mirrors) to the strain of spacetime. The distance between these test masses can be measured by a laser and calculated from the phase difference of the returning beam. The Advanced LIGO detectors are dual-recycled Fabry-Perot Michelson interferometers. [2]The Fabry-Perot cavities reflect the laser back and forth through the arms of the detector, extending the arms to increase the laser's interaction with the gravitational wave and for the GW signal to be amplified. This amplification is also done through signal recycling.

Sources of gravitational waves include pulsars, transients such as the mergers/inspirals of black holes and neutron stars, and binary systems. Higher sensitivity GW measurements provide more information on the origins and development of these sources, and may contribute discoveries of new astrophysical phenomena. The observation of gravitational radiation from non-discrete sources such as the cosmic expansion of the early universe and the Big Bang is one goal of developing more sensitive detectors.

Increasing stored power in the LIGO interferometers decreases quantum shot noise at high frequencies [2]; however, this gives rise to undesirable thermally-induced distortions due absorption of power. Absorptions in the coatings of the test masses results in a radial temperature gradient [2] and causes unwanted lensing effects and surface deformations. These cause wavefront distortions, which reduce amplification of the gravitational wave signal and increase noise at the readout photodiode. Such distortions are currently compensated by the Thermal Compensation System (TCS). The TCS measures the magnitude and spatial distribution of any wavefront distortions, and compensates for induced sagitta changes and wavefront distortions within the test masses.

Uniform absorption refers to the absorption of the main laser beam caused by a spatially invariant absorption coefficient across the high-reflectivity surface of the optic. [3] TCS is designed to compensate for uniform absorption. Non-uniform absorption involves higher spatial-frequency absorption caused by features such as point absorbers, or non-uniform coating absorption and emissivity. Such non-uniform absorption induces distortions causing power to scatter from the fundamental mode into higher order spatial modes [3], which can be enhanced or suppressed by arm cavity gain.

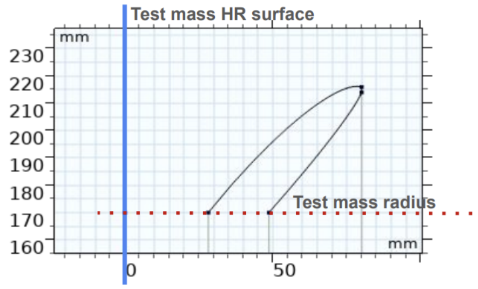

Figure 1: FroSTI Reflector System Design

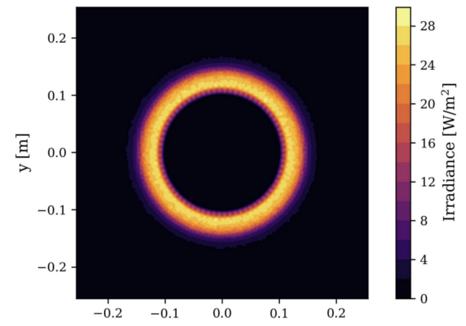

Figure 2: FroSTI Radiance Profile

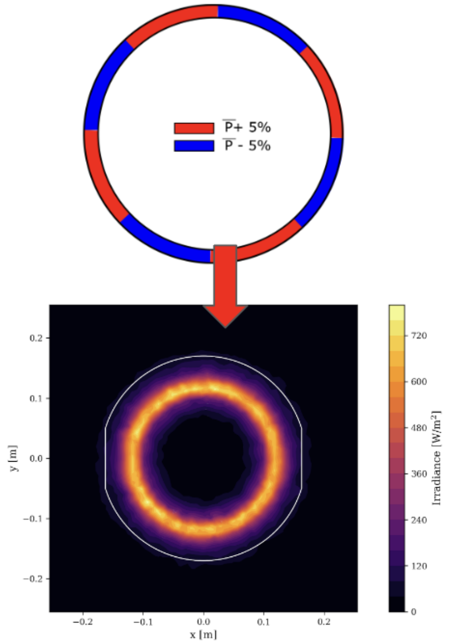

Figure 3: FroSTI Radiance Profile with Variance in Individual Heating Units

The front-surface-type irradiator (FROSTI) is a prototype actuator designed for aLIGO which consists of a ring heater mounted in front of the test masses. FROSTI's initial design targets the enhanced loss of the fundamental mode to the 7th order mode by point-absorbers.[4] FROSTI will also compensate for the non-spherical surface deformation due to coating absorption. FROSTI uses the asymmetric elliptical profile to deliver IR radiation effectively to the mirror surface, using nonimaging optics design principles (see Figure 1). FROSTI demonstrated its ability to constrain radiation radially (see Figure 2). It however does not constrain rays azimuthally, as shown in Figure 3. Simulations of the FROSTI system, which consists of multiple heating units, show that varying radiation across individual units does not produce an exact correspondence of heating in target regions.

2 Section 2: Objectives

The objective of this project is to address the non-uniform absorption-induced distortion by designing new FROSTIs to generate more complex and precise heating profiles. Such capability requires significant improvement in azimuthal confinement of the irradiation profile. This project will aim to design new geometries that allow such confinement based on existing design methods of nonimaging optics.

3 Section 3: Approach/Method

- To study the angular distribution of the heat produced by FROSTI, we first simplify ray tracing simulations of FROSTI by reducing the geometry to an octant with only one heater turned on.
- The distribution of heat from the single arc will then be analyzed to determine the best figure of merit for the reflector system confinement optimization. The goal for a redesign would be to constrain rays from the singular heater section and deposit them into the region of interest on the test mass; towards the edges of this (angular region), a sharp drop in intensity is ideal.
- Necessary design alterations of individual heating units will be identified by optimizing individual segment power.
- Once the optimal reflector system design for a single heating unit has been identified, then the entire ring heater can be simulated.
- A Monte Carlo simulation will be performed to show the distribution of residual distortion (rms) after optimization.

4 Section 4: Timeline

Weeks 1 and 2: Familiarize with COMSOL modeling software (including ray tracing tools) and with current ray tracing/thermoelastic models. Begin to make modification of current models to speed up computation time (i.e. taking out unused heater elements to simplify).

Weeks 3 and 4: Explore geometry modification design space (finish by end of Week 3). Analyze heating profile from single-heating unit and confirm efficiency/performance metrics.

Weeks 5 and 6: Finalize modeling reflector system designs for single-heating unit (finish by start of Week 6). Apply any required single-heating unit design modifications to full FROSTI design.

Weeks 7 and 8: Evaluate new full heater with modifications. Make adjustments to full heater design and analyze for possible improvements.

Week 9: Test confined FROSTI design with Monte-Carl generated non-uniform distortion and evaluate actuator efficacy in minimizing residual wavefront distortion.

Week 10: Finalize and consolidate presentation materials.

References

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