LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Technical Note **LIGO-T11XXXXX–vX** 2022/05/18

Optical contact bonding for mitigating clamping losses in silicon resonators

Ojo Akinwale

California Institute of Technology
LIGO Project, MS 18-34
Pasadena, CA 91125
Phone (626) 395-2129
Fax (626) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Project, Room NW22-295
Cambridge, MA 02139
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

LIGO Hanford Observatory
Route 10, Mile Marker 2
Richland, WA 99352
Phone (509) 372-8106
Fax (509) 372-8137
E-mail: info@ligo.caltech.edu

LIGO Livingston Observatory
19100 LIGO Lane
Livingston, LA 70754
Phone (225) 686-3100
Fax (225) 686-7189
E-mail: info@ligo.caltech.edu

http://www.ligo.caltech.edu/

1 Introduction

The indirect detection of gravitational waves with the discovery of the first binary pulsar facilitated the development of laser interferometers. In 2016, the LIGO-Virgo collaborations resulted in the first observation of gravitational waves. Gravitational-wave astrophysics makes use of propagating disturbances in the space-time medium to detect sources of gravitational waves. Gravitationaly waves offer an alternative method for astronomical observation due to not being bound by the same limitations as conventional electromagnetic waves. They don't need any type of matter present nearby the origin source and can propagate nearly all matter without being being scattered. Gravitational waves thus open up the possibility of discoveries that can't be observed using traditional observational techniques.

Accelerating masses in a relativistic field theory of gravity produces gravitational waves. Gravity is a phenomenon that comes from the curvature of spacetime. Mass creates curvature in the fabric of space-time and the amount curvature is directly affected by the amount of mass. It follows as such that we see objects with large mass having greater gravity. As objects move the curvature changes accordingly in spacetime. An accelerating object can produce fluctuations in the curvature of spacetime that propagate at the speed of light in the form of waves. This phenomena is known as gravitational waves. As a gravitational wave passes an observer, that observer will be able to detect spacetime distortion due to the strain. In resonance with the frequency of the wave the distance between objects fluctuates constantly as the wave travels past. The effect from even the most extreme gravitational waves is only detectable with a very sophisticated detector.

LIGO uses laser interferometry for gravitational wave detection. LIGO has two gravitational-wave observatories where two interferometers filter out noise from the signal. Interferometry is a technique which uses the interference of superimposed waves to extract information. The current method uses a laser beam which is split and then recombined where the interference pattern from the two beams forms a beat. Any change to the length of the paths or time taken for the beams to reach the the recombination point. The arms shift in length and those shifts are measured and analyzed.

The quality factor describes how much loss of energy there is for an oscillator or resonator in a given cycle of oscillation. The magnitude of the quality factor dictates the rate of energy loss where the oscillations deteriorate slower with a high quality factor. Thus, high quality factor translates to more sensitive gravitational wave detection in the interferometer. Losses can be sourced to radiation, dielectric material deterioration, or of the metallic resistance. Silicon was chosen for the test masses for its natural resistance to mechanical and thermal loss. The inverse quality factor Q-1 is a simple way to express energy loss in an oscillating system.

2 Objectives

LIGO's Michelson interferometer uses mirrors in its arms to reflect the laser in its beam-splitter system. Silicon provides a high mechanical quality which is needed for gravitational wave detectors, and thus functions well used in the mirrors. Thermal fluctuations require great precision to measure with accuracy. The silicon resonator will be placed inside a vacuum chamber inside a liquid nitrogen cryostat. The Q factor will be measured from the decay time in its vibration.

There exists a variety of sources of noise within the gravitational wave detector related to air damping, surface effects, material damping, and thermo-elastic damping. One important source comes from the loss of mechanical energy through radiation into the surrounding substrate which is known as clamping loss [1]. This must be reduced for more accurate signals in the cavities of the interferometer. The project will explore the testing of clamping losses in silicon resonators to mitigate a large source of internal dissipation. There aren't many methods to reduce clamping losses. Phonon tunneling is referred to as clamping losses in reference to the loss of energy associated mounting the mechanical resonator [2].

There are several methods that have been studied to mitigate clamping losses. One study found clamping losses are inversely proportional to the frictional force which is proportional to the pressure on the clamps [1]. Therefore, losses should be reduced by increasing pressure on the resonators [3]. The geometry of the resonator and support structure is a significant source of the dissipation of energy from the resonator to the Si substrate by coupling through the clamps. Assuming a weak coupling between the resonator and support structure allows for the calculation of the mechanical quality factor due to phonon tunneling losses. Therefore, the spectral overlap can be mitigated by reducing the density of states of the support, such as its effective size. The spatial overlap can be mitigated by using different symmetries of the resonator and substrate or wafer modes.

Some of the methods discussed have shown promising results in increasing the Q factor of silicon resonators but one solution can be to use optical contacted silicon stacked at the clamp. Because optical contacting has no adhesives it produces highly reflected structures. If you add material to alter the geometry near the clamp of the resonator you might introduce new sources of dissipation as in some designs such as double clamping face these issues. Optical contacting silicon stacked near the clamping point would work to increase the mechanical quality factor since it would reduce radiation losses from thermal fluctuation. The lost of elastic energy into the support of the resonator can be described by a number of terms including anchor losses, clamping losses, radiation losses, mounting losses, phonon tunneling losses. Phonons exhibit tunneling properties given that heat can flow across a gap through the phonons that act as a tunnel between two materials. With optically contacted silicon used around the clamp the tunneling will be nullified since silicon bonded with this technique acts as one body. There is no or very few scattering or absoptive losses in optically contacted silicon as well

Thermal losses can also be explained as friction converting mechanical energy to thermal energy. The fluctuation–dissipation theorem says that when there is a process that dissipates energy, turning it into heat (e.g., friction), there is a reverse process related to thermal fluctuations [4]. The goal of this project is to further explore clamping losses and determine what affect optically contacted silicon stacked at the clamp will have. This will study will expand upon this area with the aim of minimizing sources that diminish the sensitivity of the optical cavity mechanisms on LIGO detectors.

3 Project Plan

The start of the project in the first 3 weeks will include setting up an optical lever to amplify the accuracy of measurements by magnifying the small displacements of the resonator. The silicon cantilever will be clamped down with stainless steel blocks to avoid interference with the measurements from vibrational losses. To achieve the desired amount of heat transfer between the cantilever and cryostat, optically contacted silicon will be stacked a the clamping point. The clamp will be attached to the cantilever by screws which were made of silver which will be optimal in the cold environment of the cryostat.

The next 2 weeks will be used to measuring the Q factor of various cantilevers and refining testing parameters. To measure the Q factor, information about the oscillation cycle needs to be extracted. One way of initiating this process is by electrostatic driving to produce a non-uniform electrodynamic field. which, when placed near the silicon flexure, forces the cantilever to oscillate. A signal generator and high-voltage source will supply the power and allow for controlling the manual inputs of the signal's frequency and amplitude.

The rest of the project will focus on reducing clamping losses by stacking layers of silicon at the clamping point. The next 2 weeks will feature setting up the clamping experiment and the rest of the project will work on obtaining results that can help characterize the efficiency of this setup.

1.

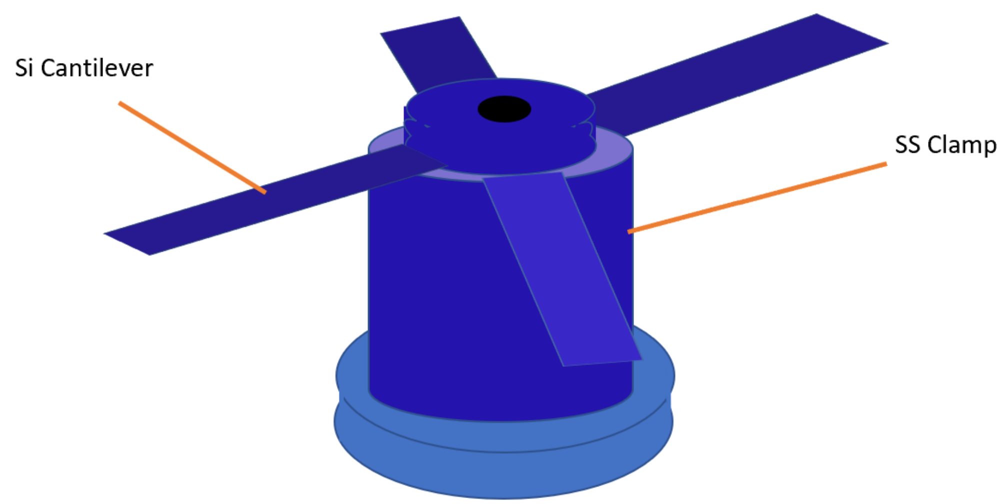

Figure 1: Experimental setup of cantilevers and clamp

References

[1] Author, Manoj Pandey *Analysis of entrainment and clamping loss in an optically actuated MEMS*. Dissertation, Cornell University, 2008.

[2] Author, Yegishe Tsaturyan *Ultracoherent soft-clamped mechanical resonators for quantum cavity optomechanics*. PHD thesis, Danish Center for Quantum Optics, Available at: https://nbi.ku.dk/english/theses/phd-theses/yeghishe-tsaturyan/Yeghishe2.pdf, 2019.

[3] Author, F. R. Blom, S. Bouwstra, M. Elwenspoek, and J .H. J. Fluitman *Dependence of the quality factor of micromachined silicon beam resonators on pressure and geometry.* J. Vac. Sci. Technol. B, 10:19–26, 1992.

[4] Author, Peter Eastman *Introduction to Statistical Mechanics*. Stanford University, Available at: https://web.stanford.edu/ peastman/statmech/index.html, 2015.