LIGO Project Proposal

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Introduction

Originally proposed in 1916 as a part the theory of general relativity, gravitational waves and their detection have been a major investment for many scientists. LIGO, the Laser Interferometer Gravitational-Wave Observatory, measures ripples in the force of gravity emitted from major cosmic events, such as the collision of binary stars and vibrations of black holes. Each burst of these waves provides a unique set of data that characterizes these events and provides more insight into the far reaches of the universe. However, there exist limitations on the accuracy of the data collected by the LIGO detectors.

The LIGO detector is essentially a Michelson interferometer, composed of a series of fused silica mirrors suspended from fibers in a pendulum. Because gravitational waves are incredibly weak, it is necessary to reduce noise sources as much as possible in order to obtain accurate results. Currently, the material for the current wires – fused silica – still contributes significant thermal noise uniformly across the noise floor, preventing the detectors from reaching their quantum mechanical sensitivity limits. Our research will focus on finding a new material for the fibers that has lower thermal fluctuations. This material will likely operate under cryogenic temperatures to minimize the mechanical dissipation of atoms vibrating from thermal fluctuations.

In reality, thermal fluctuations are incredibly small and hard to measure accurately. So instead of measuring fluctuations, the fluctuation dissipation theorem allows us to measure the mechanical dissipation of a material, which is directly related to the amount of thermal fluctuations. To derive one from the other, we start with the equation of motion of the particles inside a material, modeled by

$$m\ddot{x} = -k(1 + i\phi)(x - x_g) + F \tag{1}$$

where ϕ is the loss angle:

$$\phi = \Delta \frac{\omega\tau}{1 + \omega^2\tau^2} \tag{2}$$

The vibration transfer function is

$$\frac{x}{x_g} = \frac{\omega_0^2(1 + i\phi)}{\omega_0^2 - \omega^2 + i\phi\omega_0^2} \tag{3}$$

and a quality factor given by

$$Q = \frac{1}{\phi(\omega_0)} \tag{4}$$

To solve this, one starts with the power spectrum of the motion of the mass, given by

$$x^2(\omega) = \frac{4k_BT\sigma(\omega)}{\omega^2} \tag{5}$$

with $\sigma(\omega)$ denoting the mechanical conductance, which is also the real part of the admittance:

$$Y(\omega) \equiv \frac{\omega k\phi + i(\omega k - m\omega^3)}{(k - m\omega^2)^2 + k^2\phi^2} \tag{6}$$

Solving for $\sigma(\omega)$ and substituting into Equation (5) produces the power spectral density of the position of the mass:

$$x^2(\omega) = \frac{4k_BTk\phi(\omega)}{\omega[(k - m\omega^2)^2 + k^2\phi^2]} \tag{7}$$

Objectives

Specifically, this project will study the material properties of silicon, a possible new candidate for the fibers and optics because of its low mechanical dissipation and smaller contribution to the noise floor. The current material, silica has a wide mechanical dissipation peak around 40 K. In comparison, several research groups have shown that intrinsic bulk dissipation of single-crystal silicon cylinders decreases as temperature decreases?studied over a range of 5K to 300K. Thermal dissipation can be as low as $\phi = 3 \times 10^{-8}$ for a 130 μm thick flexure around 10K, corresponding to a surface loss parameter of $\alpha = 0.5$ pm, which is an order of magnitude lower than that of fused silica. These properties make silicon a very promising material for future suspension fibers.

The previous student who worked on this project measured the quality factor Q, a value inversely proportional to the mechanical dissipation. Silicon cantilevers tested at cryogenic temperatures were measured to have quality factors up to 2.84×10^5, with higher Q values corresponding to lower mechanical dissipation. We plan to design and carry out experiments to further investigate Q as a function of temperature, frequency, and surface treatments.

Approach

Our experimental set-up will operate at cryogenic temperatures. To measure the quality factor, we will drive a silicon flexure into oscillatory motion with an electrostatic driving plate (ESD). The ESD produces a non-uniform electrodynamic field, forcing the silicon to oscillate. A signal generator and high-voltage source will be used to control the frequency and amplitude of oscillation. Two stainless

steel blocks will hold the cantilever in place to prevent clamping losses. Beneath the two blocks, will be a layer of PEEK which isolates the system (clamp and oscillator) from the environment, both thermally and electrically. In order to capture the oscillatory signal, we will direct the laser onto the side of the silicon flexure and reflect it onto a split photodiode, which converts the projected shadow into a voltage difference that will be amplified and read on the oscilloscope.
We plan to excite the cantilever to its resonant frequency, and then pause the excitation to observe the resulting under-damped oscillation. The decay is of the amplitude is exponential:

$$a(t) = a_0 e^{-\frac{t}{\tau}} \tag{8}$$

where τ is characteristic ring-down time. We can then relate τ to the Q factor through

$$Q = \pi v_0 \tau \tag{9}$$

with v_0 as the resonant frequency. Because Q is inversely proportional to the mechanical loss, we are looking for a material with high Q. Thus we will study the dependence of Q on temperature, frequency and surface treatments. We plan to collaborate with another group at Caltech working on silicon fabrication to design a fiber with high Q.

Project Schedule

The first two weeks will be devoted to background reading and theoretical predictions. We will also spend time familiarizing with the lab equipment. Starting from the third week, we will be designing and fabricating silicon cantilevers and taking data. Continually throughout the summer, we will be working on improving the lab setup, such as optimizing the temperature control system, automating measurements, adjusting the clamp design, etc. The last week will be used to complete data collection and analysis of our measurements.

References

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