Mirror Thermal Noise in Interferometric Gravitational Wave Detectors

Thesis by

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Abstract

The LIGO (Laser Interferometer Gravitational-wave Observatory) project has begun its search for gravitational waves, and efforts are being made to improve its ability to detect these. The LIGO observatories are long, Fabry-Perot-Michelson interferometers, where the interferometer mirrors are also the gravitational wave test masses. LIGO is designed to detect the ripples in spacetime caused by cataclysmic astrophysical events, with a target gravitational wave minimum strain sensitivity of 4×10^{-22} [7] around 100 Hz. The Advanced LIGO concept [57] calls for an order of magnitude improvement in strain sensitivity, with a better signal to noise ratio to increase the rate of detection of events. Some of Advanced LIGO's major requirements are improvements over the LIGO design for thermal noise in the test mass substrates and reflective coatings [57].

Thermal noise in the interferometer mirrors is a significant challenge in LIGO's development. This thesis reviews the theory of test mass thermal noise and reports on several experiments conducted to understand this theory.

Experiments to measure the thermal expansion of mirror substrates and coatings use the photothermal effect in a cross-polarized Fabry-Perot interferometer, with displacement sensitivity of 10^{-15}m/rHz. Data are presented from 10 Hz to 4kHz on solid aluminum, and on sapphire, BK7, and fused silica, with and without commercial TiO_2/SiO_2 dielectric mirror coatings. The substrate contribution to thermal expansion is compared to theories by Cerdonio *et al.* [32] and Braginsky, Vyatchanin, and Gorodetsky [22]. New theoretical models are presented for estimating the coating contribution to the thermal expansion. These results can also provide insight into how heat flows between coatings and substrates relevant to predicting coating thermoelastic noise [26, 108].

The Thermal Noise Interferometer (TNI) project is a interferometer built specifically to study thermal noise, and this thesis describes its construction and commissioning. Using LIGO-like designs, components, and processes, the TNI has a minimum length noise in each of two arm cavities of 5×10^{-18}m/rHz around 1 kHz.

Contents

Chapter 1

Introduction

Astronomy has a curious position in human society. Once essential for daily commerce, it now figures in the minds of most people as a source of pretty pictures in the newspaper. What then for gravitational radiation? Often hailed as a “new window on the universe,” gravitational waves promise to tell us about massive compact objects in the universe that we might not find by conventional optical astronomy. The state-of-the-art gravitational wave (GW) detectors are long-baseline Michelson interferometers with Fabry-Perot arms (see Fig. 1.1): the LIGO [1, 8], GEO [58], TAMA [119], and VIRGO [44] observatories. Located around the globe, they wait for ripples in spacetime to shake their test mass mirrors, indicating distant cataclysmic events like supernovae [87, 120] and mergers among black holes and neutron stars [11, 47].

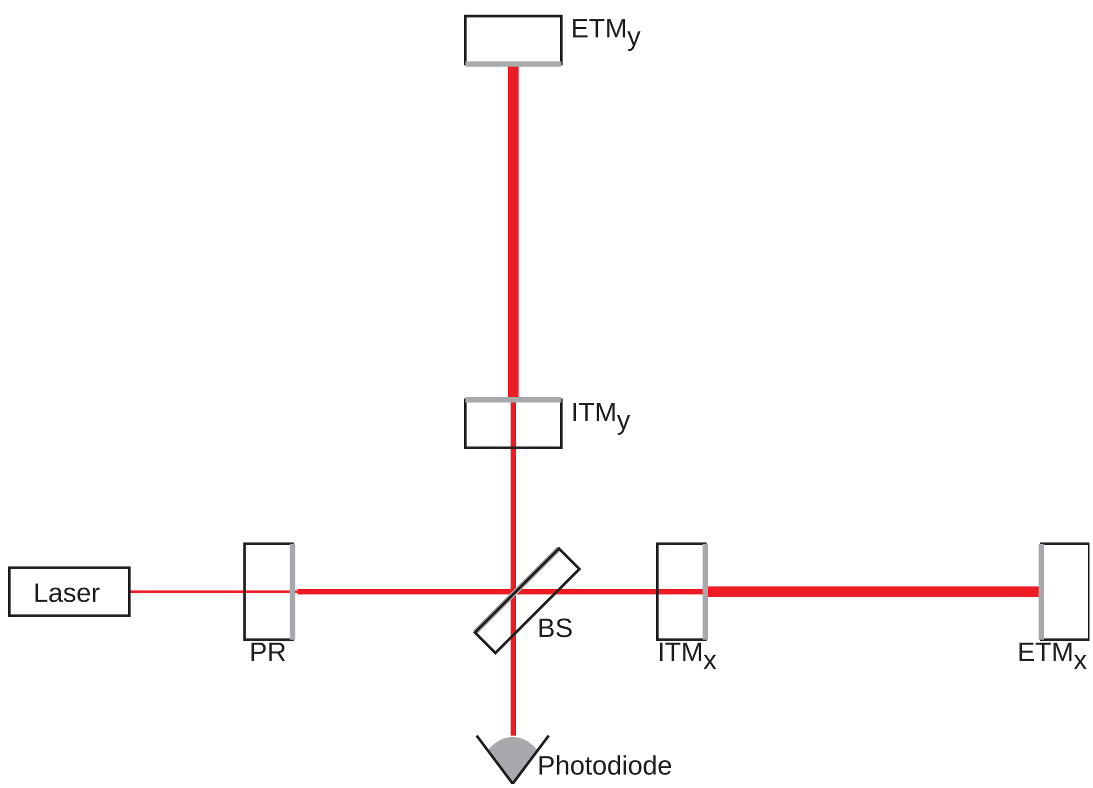
To search for astrophysical events, GW detectors are intended to run continuously, recording what they observe. Events are identified by comparing the data stream from the detectors to matched filter templates based on astrophysical models [21, 98]. Combining data from multiple observatories [37] helps to suppress false positives. Algorithms for searching the data for events improve [4, 100], but advancements in the ability to identify and understand faint GW events still depends on lower-noise instruments [64]. With that goal in mind, can better detectors be built?

GWs appear at earth as a strain in spacetime, and it’s predicted that, every year, a few waves pass through the earth with strength $h \sim 10^{-21}$ to 10^{-22} at around 100 Hz [11, 117], based on estimated abundances of compact binary objects in other galaxies. Detector projects have made great strides in reducing instrument noise: in 1991, the detectable GW strain was $h \sim 4 \times 10^{-19}$ in resonant bars [59], and LIGO reported a noise level of $h \sim 3 \times 10^{-22}$ in 2003 [109]. Note that there is a difference between a detector’s noise level and the detectable GW strain. An interferometer’s noise level is where the signal to noise ratio (S/N) equal to one. With the LIGO observatories combined and the S/N threshold set to 5, the detectable GW strain is 11 times higher than the noise in a single interferometer, when the incoming waves are averaged over all angles and polarizations [57].

As the current generation of GW interferometers advances [109], they draw closer to fundamental limits to detector noise. One of these limits appears to be thermal noise: at non-zero temperature, everything vibrates, which can overwhelm the gravitational signal from a burst event and can impede the ability to observe stochastic background events [64]. The LIGO masses are large transparent cylinders of fused silica, 25 cm diameter by 10 cm thick [14, 71], coated with thin reflective dielectric mirrors[1]. In these test masses, the major ways that intrinsic thermal noise is believed to arise is through thermoelastic damping and internal friction, which have been observed in two-arm interferometers in bulk materials [55, 94]. Thermal noise in the mirror coatings themselves is also

[1] The mirror coatings in LIGO are quarter-wave stacks of $Ta_2O_5/\,SiO_2$. The coating thicknesses are 16 layers or 2.3×10^{-6} m on input test masses, and 40 layers or 5.8×10^{-6} m on end test masses [72].

Figure 1.1: Power-recycled GW detector. The *x* and *y* arms are Fabry-Perot cavities, made from an Input Test Mass (ITM) and an End Test Mass(ETM). With the beam splitter (BS), these form a Michelson interferometer, with the photodiode operating at the dark fringe. A power recycling (PR) mirror is at the bright fringe. In early 2003, the LIGO 4k interferometers operated with this configuration, with 2.3 kW circulating in each arm cavity [72]. Gray lines on the test mass edges represent high-reflectivity dielectric mirror coatings.



a concern, and is being investigated [26, 38, 60, 82, 108]. The GW community has devoted considerable effort to modelling these noise sources, and Chapter 2 reviews several current theories of mirror thermal noise. Special attention is paid to photoelastic noise, for which I present two models for the contribution from mirror coatings. Table 2.2 on page 27 is a convenient summary of many of the current theories.

The test mirrors in the LIGO interferometers invariably absorb a small amount of the light that strikes them, so there are light-induced noise sources in addition to intrinsic thermal noise. As the light itself is subject to photon shot noise and other intensity variations, this absorption process leads to mirror noise. Such absorption could affect an interferometer through fluctuating thermal expansion of the mirror surface [22, 32], known in the literature as the photothermal effect. A similar mechanism is the photorefractive (dn/dT) effect [23], in which optical heating changes the indices of refraction of multi-layer dielectric mirrors, causing variations in the phase shift of the light reflected from a mirror.[2]

The photothermal effect can be measured directly, by optically heating a mirror and measuring its length change in an interferometer. The theory for this effect in homogenous mirrors has been derived by Cerdonio *et al.* [32], and De Rosa *et al.* [106] have measured the bulk expansion in low-absorption (0.5 ppm) dielectric mirrors at low frequencies (10 mHz - 200 Hz). The extension of these measurements up to several kHz would allow the exploration of the LIGO and Advanced LIGO [57] frequency bands, and the examination of what happens in the mirror coatings — thermal expansion coefficients for the dielectric mirrors are expected to be much larger than for substrates [26].

In Chapter 3, I describe an instrument designed to measure the photothermal effect in an interferometer. In experiments with this instrument, I examine samples of sapphire, BK7, and fused silica, with and without high-reflectivity dielectric mirrors. To ensure that they have similar optical absorptivity and reflectivity, all the samples are coated with a thin layer of gold. To measure their photothermal response, two laser beams with orthogonal polarizations resonate in a Fabry-Perot cavity made from a sample and a reference mirror. One laser beam has its intensity modulated to heat the sample, while the second beam measures the length change of the cavity due to thermal expansion of the sample. The modulation frequency is varied from 10 Hz to 4 kHz to map out

[2]The term photothermal is ambiguous. It may refer purely to thermal expansion, or it may refer to a combination of thermal expansion and dn/dT, which is often the case for thin film thermal expansion coefficient measurements found in the literature [118]. In this thesis, "photothermal" refers soley to thermal expansion, with no index of refraction contribution.

the photothermal effect across the LIGO frequency band. From the results, I show that the coating makes a significant contribution to the thermal expansion of the mirror, particularly at high frequencies.

Many types of thermal noise can not be excited directly, and to measure these in low-noise materials requires a low-noise instrument. Chapter 4 describes the construction and the commissioning of LIGO's Thermal Noise Interferometer (TNI) [15] project, built to study thermal noise and evaluate new test mass materials in a small laboratory. The TNI's objective is to measure the differential noise between two suspended arm cavities with mirrors that are smaller than those used in LIGO but of a similar quality. The TNI helps identify the significant engineering challenges to building a fundamental noise limited interferometer by adopting designs, components, and processes from LIGO. While not obviously limited by thermal noise, the TNI's sensitivity is close to the expected level of thermal noise as of this writing.

The LIGO project, its collaborators, and its contemporaries seek continually to improve GW detection technology. The purpose of this work is to provide a measurement of the photothermal effect, information about the role that dielectric mirror coatings may play in mirror thermal noise, and tools with which to learn more about mirror thermal noise in interferometric gravitational wave detectors.