The Effect of Time on Optical Coating Mechanical Loss and Implications for LIGO-India

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Abstract

We report on the change in mechanical loss with time of ion beam deposited dielectric coatings made from alternating layers of Ta_2O_5 and SiO_2 deposited onto fused silica substrates. From this, we predict the coating thermal noise in gravitational wave interferometers, after the coated optics have been stored for years. We measured the modal mechanical quality factor, Q, of two coated fused silica samples in 2015. These samples also had their modal Q's measured in 2002. We conclude that storing the coated silica disks for 13 years does not change their mechanical loss and thus the storage of Advanced LIGO gravitational wave detector optics until their future installation in India will not degrade their achievable thermal noise.

1 Introduction

The experimental efforts to directly measure gravitational waves have been progressing for over 50 years [1], and the recent detections of gravitational waves from inspiralling binary black holes [2] has proven the effectiveness of interferometric gravitational wave detectors [3]. Estimates of the strength and rate of further gravitational wave events are such that the operation of Advanced LIGO [3] along with an international network of similar detectors [4, 5] promises

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a significant detection rate of multiple events per year, or even multiple events per month [6]. The sensitivity of these interferometers is limited by fundamental noise sources, where the thermal noise from the mirrors sets the limit in the middle frequency band where the detectors have the lowest noise [3].

In order to make the test masses of these interferometric detectors reflective, optical coatings are applied to the surface. To obtain high reflectivities with low optical absorption multi-layer, ion-beam deposited, dielectric coatings are used. These coatings consist of alternating layers of materials with different refractive indices whose number and thickness determines the reflectivity. Coatings with Ta_2O_5 and SiO_2 gave the necessary reflectivity while simultaneously satisfying the limits on optical loss required for first generation interferometers operated in the 2000s decade [7].

Thermal noise from these optical coatings [8] is expected to be the limiting noise source for Advanced LIGO in the middle frequency bandwidth between about 30 Hz and 200 Hz [3]. Coating thermal noise is commonly studied indirectly in the laboratory [9, 10, 11, 12, 13, 14], utilizing the fluctuation dissipation theorem [15], which states that thermal noise depends on energy loss in a system. Measurements of coating mechanical loss is more accessible than direct measurements of thermal noise [14]. The mechanical loss has been characterized by the mechanical loss function $\phi(f)$ which also determines the quality factor, Q of the optic's resonant modes. A higher Q predicts lower thermal noise. Recent work [16] has shown that mechanical loss is best expressed as two separate mechanical loss functions in amorphous materials like Ta_2O_5 and SiO_2. We report coating mechanical loss here as a single value to stay consist with the previous work [11]

Long baseline interferometric gravitational wave observation began with the first generation LIGO (Laser Interferometer Gravitational-wave Observatory) detectors in Hanford, Washington and Livingston, Louisiana in the United States [17]. Now, the search continues with the Advanced LIGO detectors at the same sites [3]. There were three initial LIGO detectors, two at Hanford and one at Livingston. A full set of hardware was manufactured for three Advanced LIGO detectors as well. However, only two were installed, one each at Hanford and Livingston, while the parts for the third interferometer are in storage at the California Institute of Technology in Pasadena, California. The government of India has recently given preliminary approval [18] to installing the third Advanced LIGO detector in India during the 2020s [19]. Such geographic separation from the two existing Advanced LIGO detectors, as well as the interferometric gravitational wave detectors under construction near Pisa, Italy [4] and in Japan [5], will improve the angular resolution of the world wide network of detectors to gravitational wave sources [20].

The optics for the third Advanced LIGO detectors are stored in a sealed, stainless steel and aluminum container [21]. The optical surfaces are exposed only to clean 6061-T6 Aluminum and PFA encapsulated viton o-rings. The protective coating of First Contact[1] used during installation of the optics is not

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[1] See www.altechna.com/product_details.php?id=1213

in place during storage. The storage containers are in a temperature controlled room, with temperature 25 ± 5° C at all times. The room is not a clean environment, as the optics containers are sealed. Current experience, covering 15 years, is that LIGO optics emerge from storage with the same performance characteristics, after standard cleaning, as they began with. However, thermal noise performance has never been tested after storage. More broadly, mechanical loss of dielectric coatings has not been tested for any possible degradation over time and concerns have been raised about the effect on thermal noise of storing coated optics for many years. Prior research on long term degradation of dielectric optical coatings has primarily focused on space environments [22, 23]. We investigated the effect of storing the coatings by measuring the mechanical loss of two coated silica disks, first measured in 2002 [11].

2 Experiment

2.1 Method

We measured the mechanical loss of Ta_2O_5/SiO_2 coatings by measuring the quality factor, Q, of normal modes of two fused silica disks. These disks were first measured in 2002 using the same method [11]. Both disks are 76.2 mm in diameter by 2.5 mm thick, made from Corning 7980, Grade 0-A silica. The first sample, #16, was coated by MLD Laboratories [25] with 30 layers of alternating $\lambda/4$ Ta_2O_5 and $\lambda/4$ SiO_2. This coating is referred to as "Type C coated by MLD" in the 2003 paper [11]. The second sample, #1A, was coated by *Laboratoire des Matériaux Avancés* (LMA) of Lyon, France with 60 layers of alternating $\lambda/8$ Ta_2O_5 and $\lambda/8$ SiO_2. This coating is referred to as "Type D Number 1" in the 2003 paper [11].

Each test sample was suspended by a monolithic, fused silica suspension of thin fibers and a single isolation bob. The suspension was held on top by a collet attached to an aluminum stand. The monolithic fiber-bob suspension keeps excess loss from recoil damping or rubbing at interfaces from affecting the Q measurement. The entire setup was contained within a vacuum bell jar which was pumped down to at least 10^{-5} Pa and typically about 7.5×10^{-6} torr to avoid loss from gas damping. This experimental setup is similar to ones used in previous experiments and is more fully described in those papers [9, 10]. This set up is functionally identical to the one initially used in 2002 [11].

Vibrational modes of the samples were excited using a comb capacitor [24] which was placed close to the sample, typically about 1 mm, using a piezoelectric stepper motor. A DC voltage of 500 V was placed on one of the two wires of the comb capacitor while the other was held at ground. This creates a diverging electric field near the exciter which polarizes the dielectric glass of the sample. An AC field with peak amplitude 500 V at the normal mode frequency was then applied to the same high voltage wire. This AC field coupled to the polarization in the glass to produce a force on the sample at the normal mode frequency. The ringdown times, τ_n, of the normal mode was then measured. This allows the calculation of the modes' quality factors, Q_n, characterized by the equation

$$Q_n\left(f_n\right) = \pi f_n \tau_n, \tag{1}$$

where f_n is the frequency of the resonant mode.

The sample's normal mode amplitude was read out versus time using a stress polarimeter. A polarized helium-neon laser was passed through the sample where stress induced birefringence in the sample changes the laser's polarization. After passing through a $\lambda/4$ plate, the beam's polarization was oscillating at the mode frequency with an amplitude proportional to the mode amplitude. This signal was read using a polarizing beamsplitter and two photodiodes, passed through a current-to-voltage amplifier, then heterodyned to about 0.3 Hz by a lock-in amplifier. Finally, the data was passed to an analog-to-digital converter and recorded on a computer.

The weakly damped system undergoes an exponential decay so the data can be fit to

$$x\left(t\right) = Ae^{-t/\tau_n}\sin\left(2\pi f_{\mathrm{demod}}t + \theta\right), \tag{2}$$

where τ_n is the decay time, f_{demod} is the frequency after demodulation, t is time, and θ is an unimportant phase. Fitting code is used to find f_{demod} and θ as slowly varying functions of time t in order to avoid an irreconcilable phase shift from the millihertz variations in f_n caused typically by temperature variations. From this fit, the decay time $\tau_n$was determined.

2.2 Results

We measured the Q of the two samples and compared our 2015 results to the results from 2002. In the interim, the samples were stored primarily on laboratory shelves in air in the plastic containers provided by the coating vendors. They were also moved from the Massachusetts Institute of Technology to American University during summer of 2011. A comparison of the 2002 and 2015 data is shown in Table 2.2.

The Q value of mode 2 for both disks were different than the corresponding values from 2002 and this discrepancy is outside the 2015 uncertainties. This phenomenon was investigated with finite element modeling which is discussed in Section 2.3. However, the results in Table 2.2 for modes other than mode 2 indicate that the mechanical loss of Ta_2O_5/SiO_2 on silica substrates is unaffected by 13 years of storage. Thus the achievable thermal noise in an Advanced LIGO interferometric gravitational wave detector should be the same after the optics are kept in storage for the years necessary before installation in an Indian detector.

2.3 Finite Element Model

To determine how elastic energy is distributed in the oscillations of different modes of the samples we used the finite element analysis package COMSOL Multiphysics. We calculated the elastic energy of vibration in the total sample,

Disk	Mode	Frequency 2002 (Hz)	Frequency 2015 (Hz)	Q 2002 ($\times 10^5$)	Q 2015 ($\times 10^5$)
16	1a	2657	2658	4.89	$5.1 + .3$
16	1b	2676	–	4.44	–
16	2	4022	4014	4.20	$3.95 \pm .05$
16	3a	6054	6053	4.52	$4.5 \pm .1$
16	3b	6059	6055	4.70	$4.7 \pm .2$
1A	1a	2691	2691	4.87	$5.0 \pm .1$
1A	1b	2712	2690	5.48	$5.3 \pm .3$
1A	2	4054	4055	4.39	$4.8 \pm .2$

Table 1: Measured Q's for nodes of Ta_2O_5/SiO_2 coated silica Disks #16 and #1A in 2002 and 2015. A dash indicates that the Q was not measured for that mode. The uncertainty of the 2015 Q values represents the repeatability of the Q measurements in separate trials.

Mode	Frequency (Hz)	$E_{\rm sub}$	$E_{\rm coat}$	$E_{\rm dep}(\times 10^{-4})$	$E_{\rm fiber}(\times 10^{-4})$
1a	2660	.61	.39	3	7
1b	2660	.61	.39	0.6	1×10^{-3}
2	4040	.60	.39	0.9	20
3a	6070	.61	.39	5	3
3b	6070	.61	.39	0.9	4×10^{-2}

Table 2: Finite element model results for elastic energy in different parts of the sample. Energy is presented as a fraction of the total elastic energy in the sample. $E_{\rm sub}$ is the energy in the silica substrate, $E_{\rm coat}$ is the energy in the Ta_2O_5/SiO_2 coating, $E_{\rm dep}$ is the energy in the silica vapor deposition region around the weld between the sample and silica suspension fiber, and $E_{\rm fiber}$ is the energy in the silica suspension fiber welded to the sample.

the coating, the deposition region around the fiber weld point, and the fiber for each mode. The deposition region is the area of the disk around where the silica suspension fiber is welded to the disk. In this deposition region silica vapor gets deposited during the welding process. We analyzed whether excess mechanical loss in this deposition region or the fiber could account for the variable Q in mode 2 for both samples. Excess loss in the weld point between the fiber and the substrate can occur because the welding was done by hand with a hydrogen/oxygen torch. The silica in and around the weld point are left in unreproducible annealing states after each welding, and annealing has a large impact on mechanical loss in fused silica [12].

The values in Table 2 show that the energy in the deposition region for mode 2 is not notably different than other modes but the energy in the fiber for mode 2 is a factor of about 3 or more greater than the other modes examined. This suggests that slightly higher mechanical loss in the suspension fiber, possibly due to a different state of annealing, may be the explanation for why mode 2 has poorer Q for sample 16 in 2015 while all other modes have the same or higher Q. It may also explain why mode 2 of sample 1A has higher Q in 2015 than it did in 2002. The conclusion that mechanical loss of ion beam deposited dielectric coatings is unaffected by storage over 10 years or more is likely still valid despite the change in Q for mode 2 in both samples. Note that test masses in all second generation interferometric gravitational wave detectors are connected to their suspensions by more reproducible techniques than hand welding [25].

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