

# The effects of heating on mechanical loss in tantalum/silica optical coatings

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## Abstract

Second-generation interferometric gravitational-wave detectors will operate at temperatures noticeably above room temperature. Study was done to determine what effect elevated temperatures would have on the  $Q$  and coating thermal noise of the detector mirrors. Results show that increased temperature increases loss angle in a manner that is more significant at higher frequencies. Trends show that the increased temperature will have a negligible effect at the low (100 Hz) frequencies important to second-generation detectors.

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## 1. Introduction

Within the next few years, construction of advanced designs of interferometric gravitational wave detectors will become a reality [1]. These advanced designs promise greatly improved sensitivity, and will make detection of gravitational waves likely [2]. In order to improve sensitivity, research into reducing noise sources of all types continues to this day. One important area of research is in the reduction of thermal noise [3]. Thermal noise is expected to be the limiting noise source for advanced interferometers, especially in the band around 100 Hz, and the optical coatings of the mirrors has been shown to be a major contributor [4]. Coating thermal noise is also the limiting noise source for laser frequency stabilization [5]. Even a minor reduction of coating thermal noise can substantially improve detector sensitivity and lead to an increased rate of detection.

Designs for the advanced Laser Interferometer Gravitational-wave Detector (LIGO) detectors call for increased laser power and more energy stored in the interferometer arms [1]. While these design aspects will increase sensitivity and lower quantum sensing noise, they will raise mirror temperatures as high as 20 °C above room temperature; compared to less than 1° increase in mirror temperatures for initial LIGO interferometers [6]. Using the Fluctuation–Dissipation Theorem, it has been shown that the thermal noise in sensing the position of a coated mirror using a Gaussian-profile laser can be written as [7]

$$S_x(f) = 2k_b T \phi_{\text{eff}} (1 - \sigma^2) / (\pi^{3/2} f w Y), \quad (1)$$

where  $S_x(f)$  is the power spectral density of the position noise,  $k_b$  is the Boltzmann's constant,  $T$  is the temperature,  $\sigma$  is the substrate material's Poisson ratio,  $w$  is the half-width of the Gaussian beam, and  $\phi_{\text{eff}}$  is the effective loss angle of the mirror. From Eq. (1), it is easy to see that the thermal noise depends directly on temperature. However, it is not known how  $\phi_{\text{eff}}$  depends on temperature, if at all. It is important to

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determine experimentally whether the increased mirror temperatures in Advanced LIGO interferometers will substantially effect the mirror thermal noise.

Initial LIGO mirrors are currently made as a fused silica substrate with alternating  $1/4\lambda$  layers of dielectric materials: silicon dioxide ( $\text{SiO}_2$ ) and tantalum pentoxide ( $\text{Ta}_2\text{O}_5$ ). Past experiments have shown that a major source of thermal noise in the mirrors is due to the mechanical loss of the optical coatings, and that the  $\text{Ta}_2\text{O}_5$  is the largest contributor to that loss [8]. In response to these studies, research has taken place into reducing  $\text{Ta}_2\text{O}_5$ 's effect by doping and other methods [9]; however, little is known about the loss mechanisms of  $\text{Ta}_2\text{O}_5$ . Some insight into these mechanisms may possibly be learned by studying its response to varying frequencies and temperatures, which may help the efforts to reduce thermal noise in advanced interferometers.

## 2. Experiment

The method used to study the thermal noise characteristics under varying temperature is similar to that in previous experiments [8]. The sample used for measurement was a coated silica disk, 7.6 cm in diameter and 0.25 cm thick, commercially polished, and coated with 30 layers of alternating  $\text{SiO}_2$  and  $\text{Ta}_2\text{O}_5$  with a total coating thickness  $\sim 4.7 \mu\text{m}$ . The sample was welded to a low-loss silica suspension, which required a small, 1 cm radius semi-circular part of the sample face to go uncoated to prevent coating damage near the weld. The entire suspension was placed in a low- $10^{-6}$  torr vacuum, and the resonant frequencies were excited using an electrostatic comb exciter placed close ( $< 0.5$  cm) to the sample. After removing the excitation signal, the sample's ringdown was measured using a birefringence sensor.

After a record was made of the sample's ringdown, it was fit to determine its characteristic decay time ( $\tau$ ). The decay time is related to the quality factor ( $Q$ ) of the sample by the relation

$$Q_{\text{measured}} = \pi f_n \tau. \quad (2)$$

Assuming that all other loss sources can be ignored, the total loss of the sample,  $\phi_{\text{total}} = 1/Q_{\text{measured}}$ , can be approximated as the sum of the intrinsic loss of the substrate plus the loss associated with the coating [10],

$$\phi_{\text{total}} \approx \phi_s(f_n) + \frac{E_c}{E_s} \phi_c(f_n). \quad (3)$$

Here the subscripts  $s$  and  $c$  represent the substrate and the coating, respectively, and  $E_c/E_s$  represents the ratio between the energy stored in the coating and the substrate. Values for  $E_c/E_s$  were calculated using a finite element model [10], and are given in Table 1. Using Eqs. (2), (3), and the measurements taken from the sample, calculations were made for the values of  $\phi_c$  for each of the measured normal modes and temperatures.

Heating was done using a 25 ohm, 7 cm radius ring heater placed in the vacuum chamber approximately 6 cm from the sample. The heater was powered by a stepping power supply, which was controlled by second power supply. Temperature was measured using a type  $K$  thermocouple mounted  $< 1$  cm

Table 1

Table of  $E_c/E_s$  values used in computing  $\phi_C$ . Values were calculated using values of  $dU/U$  from [9].  $E_c/E_s = DU/U^*t$ ; where  $t$  is the coating thickness ( $t = 4.6 \mu\text{m}$ )

Mode name	Mode ID	$E_c/E_s$
Butterfly	$n = 0, l = 2$	0.0073
Hex	$n = 0, l = 3$	0.0073
Bongo	$n = 1, l = 1$	0.0075

Table 2

Measured frequencies and  $Q$ 's for the four measured modes. The vacuum chamber was heated by a ring heater using a control voltage input into a stepping amplifier. Phi's were calculated using Eq. (3)

Mode	Frequency [Hz]	Temperature [ $^\circ\text{C}$ ]	$Q [\times 10^5]$	Phi [ $\times 10^{-4}$ ]
Bf-low	2683.6	24.8	3.8	3.5
Bf-low	2688.4	32.5	3.7	3.6
Bf-low	2693.0	42.5	3.7	3.6
Bf-low	2696.1	50.3	3.6	3.8
Bf-low	2698.4	56.1	3.4	3.9
Bf-high	2684.2	24.9	3.9	3.4
Bf-high	2688.6	32.6	3.9	3.5
Bf-high	2693.4	42.9	3.8	3.5
Bf-high	2696.7	50.5	3.7	3.6
Bf-high	2699.3	56.9	3.7	3.6
Hex	6111.1	24.9	3.9	3.4
Hex	6122.2	33.2	3.7	3.6
Hex	6133.7	43.0	3.6	3.7
Hex	6141.0	50.6	3.3	4.0
Hex	6147.1	56.0	3.6	3.7
Bongo	9379.3	24.9	3.5	3.6
Bongo	9401.7	32.9	2.5	5.0
Bongo	9422.0	42.8	2.3	5.4
Bongo	9436.7	51.3	2.2	5.5

from the sample face. The thermocouple was calibrated at  $0^\circ$  and  $100^\circ\text{C}$  temperatures, and values were recorded using a LabView<sup>1</sup> program. In order to heat the sample, the control voltages listed in Table 2 were applied to the heater power supply. The sample was heated for no less than four hours to allow the system to reach a steady state before each normal mode was excited and the ringdown was measured.

## 3. Results

Four normal mode frequencies were measured over a  $30^\circ\text{C}$  range: the two degenerate Butterfly ( $n = 0, l = 2$ ) modes ( $\sim 2700$  Hz), one of the degenerate Hex ( $n = 0, l = 3$ ) modes ( $\sim 6100$  Hz), and one of the degenerate Bongo ( $n = 1, l = 1$ ) modes ( $\sim 9400$  Hz). The calculated loss angles for each frequency and temperature can be seen in Table 2 and are shown in Fig. 1. Study of the figure shows that increasing temperature does increase loss. It is also apparent that the temperature effects increase with frequency. This is more clearly seen in Fig. 2 where each frequency line has been normalized to its room temperature loss angle.

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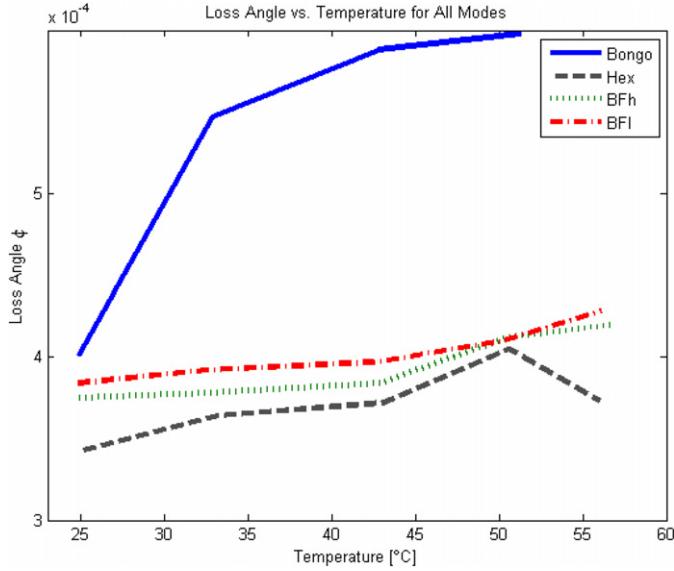


Fig. 1. Loss angle vs. temperature for each of the measured normal modes: Bongo  $\sim$  9400 Hz, Hex  $\sim$  6100 Hz, Bf-high (BFh) and Bf-low (Bfl)  $\sim$  2700 Hz. The effect of temperature is more pronounced at higher frequencies.

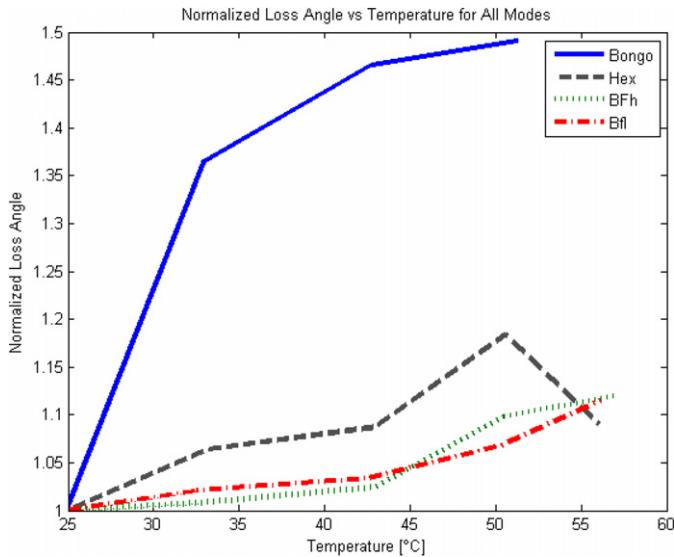


Fig. 2. Loss angles vs. temperature for each measured mode, normalized to its room temperature loss angle. The temperature effect is more obvious than in Fig. 1.

It is important to recognize that the experiment measures the effect of temperature on the coating loss. The loss of the silica substrate at room temperature is so low, that the coating loss completely dominates the loss measurements [8]. For any temperature effects of the substrate to appear in our measurements, the substrate loss would have to change drastically over a short temperature range. This is contrary to the current understanding of the substrate loss mechanisms [11].

When making measurements of mechanical losses, there are many conditions that can increase the measured loss, but few, if any, that can reduce it. For this reason, the values quoted above are those measured with the highest  $Q$ . The uncertainty asso-

ciated with them is the statistical error carried over from the fit to the ringdown. Systematic errors are eliminated in this approach. The statistical errors are small enough to be ignored in the figures.

#### 4. Discussion

Although this is the first heating experiment of its type, there have been measurements made of coating loss at sub-zero temperatures. In one experiment, a sample of similar geometry and coating was cooled to as low as 4 K, and found that temperature had no effect on coating loss [12]. These results agree with the data seen in this experiment. The cooling experiment measured lower (2500 Hz and 1100 Hz) frequency modes than did the heating experiment. The heating experiment showed the effects of temperature becoming much less pronounced at lower frequencies, so much so that the cooling experiment would not have seen any effects at those frequencies.

A more recent paper studied the effects of cooling on thermal noise in Titania-doped Tantala coated Silicon wafers in order to better understand the loss mechanisms involved in the noisier Tantala coating layers, and the effects of Titania doping [13]. This study showed an increase in mechanical loss with decreasing temperatures. Although these results do not directly agree with the findings of this Letter, they do not dispute it, considering the vast differences in temperature ranges. It is of note, however, that the two experiments combined may point to two separate loss peaks, possibly indicating loss mechanisms in the coatings.

A simple linear extrapolation of the trends seen in the data to the temperature and frequency range planned for Advanced LIGO shows a less than 1% change in coating loss, leading to a negligible effect on gravitational wave detection. Of course, until there is more data available, there is no reason to expect a truly linear relation, but these early results appear promising for Advanced LIGO and other second-generation detectors that will not use any cooling mechanisms. Additional experiments are underway to increase understanding of this mechanism, including a study of pure  $Ta_2O_5$  coating samples in order better understand its material properties and design improved mirror coatings.

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