Available online at www.sciencedirect.com
ScienceDirect
Physics Letters A 372 (2008) 87–90
PHYSICS LETTERS A
www.elsevier.com/locate/pla

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

Matthew R. Abernathy [a,*], Gregory M. Harry [a], Flavio Travasso [a], Iain Martin [b], Stuart Reid [b], Sheila Rowan [b], Jim Hough [b], Martin M. Fejer [c], Roger Route [c], Steve Penn [d], Helena Armandula [e], Andri Gretarsson [f]

[a] *LIGO Laboratory, Massachusetts Institute of Technology, NW17-161, Cambridge, MA 02139, USA*
[b] *Department of Physics and Astronomy, The University of Glasgow, Glasgow G12 8QQ, United Kingdom*
[c] *Edward L Ginzton Laboratory, Stanford University, Stanford, CA 94305, USA*
[d] *Physics Department, Hobart and William Smith Colleges, Geneva, NY 14456, USA*
[e] *LIGO Laboratory, California Institute of Technology, Pasadena, CA 91125, USA*
[f] *Embry-Riddle Aeronautical University, Prescott, AZ 86301, USA*

Received 22 June 2007; received in revised form 13 July 2007; accepted 17 July 2007

Available online 1 August 2007

Communicated by P.R. Holland

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.

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]

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

where $S_x(f)$ is the power spectral density of the position noise, k_b is the Boltzmann's constant, T is the temperature, σ is the substrate material's Poisson ration, w is the half-width of the Gaussian beam, and ϕ_{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 ϕ_{eff} depends on temperature, if at all. It is important to

* Corresponding author.
E-mail addresses: mattabe@mit.edu (M.R. Abernathy), gharry@ligo.mit.edu (G.M. Harry), flavio.travasso@pg.infn.it (F. Travasso).

0375-9601/$ – see front matter
doi:10.1016/j.physleta.2007.07.058

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 $1/4$-λ layers of dielectric materials: silicon dioxide (SiO_2) and tantalum pentoxide (Ta_2O_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 Ta_2O_5 is the largest contributor to that loss [8]. In response to these studies, research has taken place into reducing Ta_2O_5's effect by doping and other methods [9]; however, little is know about the loss mechanisms of Ta_2O_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 SiO_2 and Ta_2O_5 with a total coating thickness ~ 4.7 μm. 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 (τ). The decay time is related to the quality factor (Q) of the sample by the relation

$$Q_{\text{measured}} = \pi f_n \tau. \tag{2}$$

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],

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

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 ϕ_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 from the sample face. The thermocouple was calibrated at 0° and 100 °C temperatures, and values were recorded using a LabView[1] 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.

Table 1
Table of E_c/E_s values used in computing ϕ_C. Values were calculated using values of dU/U from [9]. $E_c/E_s = DU/U^*t$; where t is the coating thickness ($t = 4.6$ μm)

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 [°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

3. Results

Four normal mode frequencies were measured over a 30 °C range: the two degenerate Butterfly ($n = 0, l = 2$) modes (~ 2700 Hz), one of the degenerate Hex ($n = 0, l = 3$) modes (~ 6100 Hz), and one of the degenerate Bongo ($n = 1, l = 1$) modes (~ 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.

[1] National Instruments Co., 11500 N Mopac Expwy, Austin, TX 78759, USA.