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Physics Letters A 352 (2006) 3–6
PHYSICS LETTERS A
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Frequency and surface dependence of the mechanical loss in fused silica

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Received 31 October 2005; accepted 18 November 2005

Available online 28 November 2005

Communicated by P.R. Holland

Abstract

We have compiled measurements of the mechanical loss in fused silica from samples spanning a wide range of geometries and resonant frequency in order to model the known variation of the loss with frequency and surface-to-volume ratio. This improved understanding of the mechanical loss has contributed significantly to the design of advanced interferometric gravitational wave detectors, which require ultra-low loss materials for their test mass mirrors.

PACS: 95.55.Ym; 04.80.Nn; 62.40.+i

1. Introduction

As part of the research and development for the LIGO [1] and TAMA [2] gravitational wave detectors, we have conducted investigations into the internal friction of fused silica. Displacement of the interferometer's mirror faces arising from thermal motion of the fused silica test mass mirrors sets a fundamental limit to the detector sensitivity. The frequency distribution of this noise is directly related to the internal friction of the mirror material.

An Advanced LIGO detector has recently been proposed [3] with better sensitivity than Initial LIGO. The Advanced LIGO mirror thermal noise must be as low as possible. Two materials have been under consideration for the mirror substrate: fused silica and single crystal sapphire. To its advantage, sapphire has the higher Young's modulus and a low bulk mechanical loss ($\phi \leqslant 3 \times 10^{-9}$) [4]. However, sapphire also has high thermoelastic noise [5].

In the advanced detectors, thermal noise in the mirror coatings makes a significant contribution to the total noise budget in the central frequency region of 30–500 Hz. Discussion on the mechanical loss in the mirror coatings can be found elsewhere [6–8].

Recent measurements on the mechanical loss in fused silica have revealed a dependence on frequency [9,10] and on surface-to-volume ratio [11–13]. This Letter combines data from several of these research groups in order to model both of these effects. The frequency dependence of the loss agrees well with results from Weidersich et al. [14]. In that work, loss data spanning six decades in frequency is modeled by an asymmetric double-well potential in the bond angle. Together these results provide a more complete picture of the loss in ultrapure glasses and a more physically motivated prediction for the thermal noise in advanced interferometric detectors. It was previously predicted that fused silica's loss dependence would make it suitable for low frequency detectors (10–100 Hz) [15]. Indeed, this

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doi:10.1016/j.physleta.2005.11.046

model's prediction of a very low mechanical loss in the LIGO frequency regime has motivated the recent selection of fused silica as the Advanced LIGO test mass substrate [16].

2. Theory of loss in fused silica

The thermal noise motion of the mirror surface is related to the internal friction of the substrate by the fluctuation–dissipation theorem [17]. The internal friction of very pure fused silica is associated with strained Si–O–Si bonds, where the energy of the bond has minima at two different bond angles, forming an asymmetric double-well potential. Redistribution of the bond angles in response to an applied strain leads to mechanical dissipation, which at audio frequencies has a peak in the cryogenic range 20–60 K. Because fused silica is an amorphous material, there is a distribution of potentials which must be inferred from measurements of the dissipation. It can be shown [14] that the frequency dependence of the loss should exhibit a power law spectrum with exponent $k_B T/V_0$ at low temperatures. Both this power law, with $V_0/k_B = 319$ K, and the distribution of potentials have been measured [14]. The power law exponent of a relaxation process cannot exceed 1, and is expected to saturate near 300 K. At room temperature the exponent is 0.76.

At elevated temperatures there is another loss peak arising from a double-well potential associated with the Si–O–Si bond angles. For this peak the bond angle shift and potential barrier are much larger; the double-wells of the cryogenic loss peak are small features at the minima of the larger potential well. At room temperature, thermal fluctuations allow the bonds to span the cryogenic double-well but not to cross the larger potential barrier, where $V_0/k_B = 3.54 \times 10^4$ K [18]. The calculated internal friction for this loss peak at audio frequencies and room temperature is utterly negligible compared to other loss mechanisms cited herein.

A separate loss mechanism exists in the surface of the glass. The contribution from the surface loss depends on the mode of the sample. The total energy lost per oscillation in an isotropic sample undergoing slowly decaying vibration, can be described by the integral of the local loss angle, $\phi(\vec{r})$ with the energy density $\rho_E(\vec{r})$

$$\Delta E = 2\pi \int_{\mathcal{V}} \rho_E(\vec{r})\phi(\vec{r})\, \mathrm{d}^3 r, \qquad (1)$$

where $\mathcal{V}$ is the sample volume. Assuming that the local loss angle is constant and equal to ϕ_{bulk} everywhere except within a distance h of the surface, and that the energy density in that surface layer is approximately the energy density at the surface, then the loss can be expressed as [10]

$$\phi = \phi_{\text{bulk}} + \mu\alpha_{\text{s}}\frac{S}{V}, \qquad (2)$$

where S is the surface area of the sample and μ is a factor of order unity that depends on the mode shape. The surface loss parameter, α_{s}, is typically several picometers for flame polished or flame drawn fused silica but much higher for abrasively polished surfaces.

3. Experimental method

Three laboratories performed resonant Q experiments to measure the mechanical loss, $\phi = 1/Q$ at resonance. The measurements at Syracuse University (SU) [10–13] were performed on fiber/rod samples with diameters ranging from 0.1–8 mm over resonant frequencies less than 5 kHz. The samples were drawn from and left attached to a massive bob of Suprasil [19], thus forming a cantilever beam. This bob was welded to a vibration isolating suspension formed by similar silica bobs connected by thin silica fibers. In a vacuum of $\approx 10^{-6}$ torr, the samples were made resonant by an electrostatic comb exciter, and their position was measured using a shadow sensor.

The measurements at University of Tokyo [9] were performed on cylindrical samples with optically polished surfaces. The diameters and heights were 70 mm and 60 mm, respectively. The samples were annealed in a vacuum furnace. To exclude the support loss, the samples were supported at nodal points of their vibrational modes during the Q measurements.

The Caltech measurements were performed on a spare input test mass for the Initial LIGO interferometers, a superpolished right cylinder made from Suprasil 312 with a diameter of 25.4 cm and a thickness of 10 cm. It was suspended in a $\approx 10^{-6}$ torr vacuum by a loop of polished stainless steel wire greased with lard. The elastic modes of the mass were excited with an electrostatic actuator and the mode amplitude was monitored using a birefringence sensor. Since friction at the wire could reduce Q, only modes with small motion at the point of wire contact were used in the fit.

4. Modeling method

Resonant Q measurements from each of the labs were submitted for generating this model of the loss. The measurements spanned several types of fused silica, V/S ratios from 0.03 to 28 mm, and frequency up to 10^5 Hz. The data was first separated by silica type since the loss is known to vary significantly between varieties of fused silica [9,11,20]. Only Suprasil 2 and 312 had sufficient data to warrant a fit over both frequency and V/S ratio. Characteristics of these samples are listed in Table 1.

Table 1
Sample characteristics: *Type* lists Heraeus Suprasil variety and shape. Samples are cylinders with diameter (D), height (h), and volume-to-surface ratio (V/S) given in mm. Surface types are superpolished (SP) and flame polished (FP)

Label	Type	D	h	V/S	Surface	Anneal	Lab
P1	312, cyl.	254	100	28	SP	None	Caltech
K12	312, cyl.	70	60	11	SP	980 °C, vac.	Tokyo
SU2	312, rod	3	–	0.75	FP	1025 °C in Ar	SU
SV4	312, rod	8	–	2	FP	950 °C in Ar	SU
AG5	2, rod	3.5	188	0.88	FP	None	SU
AH1	2, rod	0.300	108	0.075	FP	None	SU
AN1	2, rod	0.318	160	0.080	FP	None	SU
AB1	2, rod	0.062	175	0.016	FP	None	SU
AC1	2, rod	0.340	310	0.085	FP	None	SU
AF1	2, rod	0.120	130	0.030	FP	None	SU
K13	2, cyl.	70	60	11	SP	900 °C, vac.	Tokyo