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The mechanical quality factor of a carbon dioxide laser-welded fiber was measured and compared to flame-welded fibers to determine the suitability of laser welding for attaching suspension fibers to test masses in precision experiments. The loss in the fiber was found to be limited primarily by thermoelastic damping and surface loss, rather than loss from the weld. This technique is attractive for the attachment of fused silica suspensions where low thermal noise and precision location of the weld are considered. © *2006 American Institute of Physics.* [DOI: 10.1063/1.2170075]

I. INTRODUCTION

Generation of squeezed states of light will be important for increasing sensitivity in future gravitational wave interferometers.[1] One method of generating squeezed light involves a radiation-pressure controlled oscillator. A design under consideration calls for an interferometer where the end mirrors are light enough to be affected by the radiation pressure of the beams.[2] The sensitivity of this design is such that fluctuations of the thermal energy in the signal band can be a significant source of noise. These fluctuations occur due to coupling of the signal-band degrees of freedom and the thermal bath, which is also the cause of mechanical dissipation. This relationship is quantified by the fluctuation-dissipation theorem,[3,4] which predicts suspension thermal noise above the pendulum mode frequency but below the first violin mode to be[5]

$$S_x(f) = \frac{k_B T g r^2}{16 m L^2 \pi^5 f^5} \sqrt{\frac{Y N \pi}{m g}} \phi, \qquad (1)$$

where $S_x(f)$ is the spectral density of the fluctuations, k_B is Boltzmann's constant, T is the temperature, g is the acceleration due to gravity, m is the mass of the test mass, L is the length of the pendulum, f is the frequency, Y is Young's modulus of the fiber material, N is the number of fibers, r is the radius of the fiber, and ϕ is the loss angle of the fiber material.

Fused silica has been shown to have low mechanical loss, even when drawn into thin fibers.[6] It is strong enough to support mirrors and can be readily worked in a laboratory setting. Attaching silica fibers to mirrors has also been demonstrated, both by flame welding[7] and silicate bonding.[8,9] For the ponderomotive squeezing experiment proposed in Ref. 2, the mirrors are small enough (1.27 cm in diameter and 0.25 cm thick) that a flame could easily damage the dielectric coating necessary for high reflectivity. Silicate bonding the suspension would present challenges both with location precision and with mechanical loss.[10] Welding with a carbon dioxide laser protects the coating and allows for precision location of the attachment point. This is the planned method for attaching fibers to the optics in the proposed Advanced LIGO interferometers and much work has gone into research and development of this technique because of this.[11] If the mechanical loss of the suspension remains low, this would be the preferred method of attachment for such small mirrors in high-precision experiments. However, it had not been known if loss in the weld adds appreciably to the total loss in the suspension. In this article we show that the CO_2 laser welding process does not contribute significantly to the total loss in the suspension.

II. EXPERIMENTAL TECHNIQUE

A. CO_2 laser welding

The silica fibers were hand drawn in air from Hereaus Co. Suprasil 2 brand fused silica rods using a hydrogen flame. The fibers were drawn from the rods as supplied, with no special surface preparation beyond cleaning with ethanol, either before or after drawing. These fibers were initially left attached to the rod from which they were drawn at one end for handling, so the surface of the fibers that will be measured remains pristine and untouched once drawn.

The welding was done with a 10 W CO_2 laser focused by a 12.7 cm focal length lens. The laser together with a translation stage, were controlled by computer in order to achieve the precision weld. The welding setup is shown in Fig. 1. The silica fiber was placed on top of the larger substrate to which it is to be welded (here a silica rod, but in the planned squeezing experiment it would be the side of a silica mirror). The laser was aligned with the help of a guide beam and once in place a weld was made approximately 2 mm in length.

B. Measurement of mechanical loss

To evaluate the suitability of laser welding, measurements were made of the Q of several modes of the welded fiber. These were compared to Q's of freely hanging fibers flame drawn from a silica bob in similar setups.[6,12,13]

The dissipation of the fibers was measured at room temperature using the ringdown method, in the setup shown in

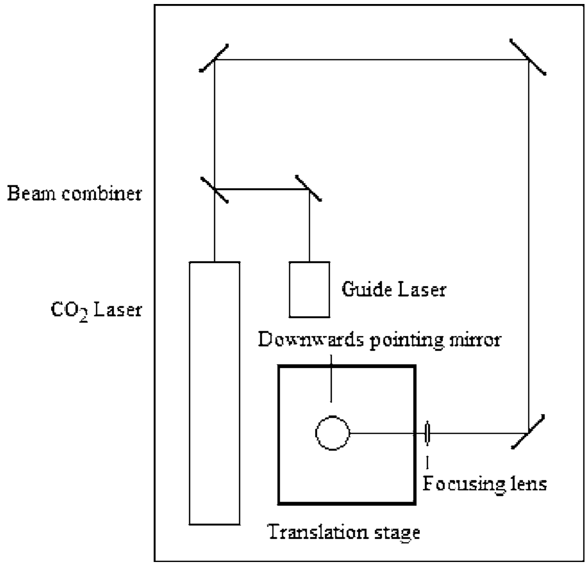

FIG. 1. Schematic of the laser welding setup. Both the laser and the translation stage are computer controlled.

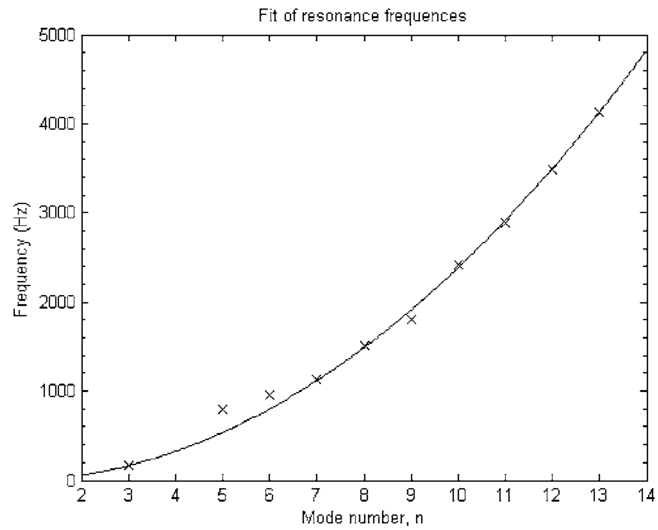

FIG. 3. Fit of measured modal frequency data to the model of resonances of a circular cross-section, fused silica fiber. The fiber was measured to have a length of 80±2 mm and diameter of 65±5 μm. The continuous line is meant to simply guide the eye and has no significance between integers.

Fig. 2. The welded fiber was excited by a comb capacitor creating an oscillating electric field.[14] A force is felt by the freely hanging fibers due to the dielectric constant of fused silica. After a resonant mode was excited, the field was turned off and the capacitor grounded, allowing the fiber to ring freely. The displacement of the fiber was measured with a split photodiode shadow sensor using a laser beam projected through the fiber onto the diode. If the amplitude of oscillation is damped by internal friction in the fiber, the ringdown will have the form

$$x(t) = x_0 e^{-\pi f_n t \phi} \cos(2\pi f_n t) + \xi, \quad (2)$$

where f_n is the resonant frequency of the mode and ξ is amplifier and sensor noise. The quality factor Q of the resonance is related to the loss angle ϕ by $Q=1/\phi(f_n)$ in the case of internal friction.

Measurements were made of the Q's of a number of modes of the welded fiber. The measured frequencies were fit to the approximate formula for a beam of circular cross section clamped at one end,

$$f_n = \frac{\pi}{8}\sqrt{\frac{Yd^2}{\rho L^4}}(0.597)^2 \quad \text{for } n=1, \quad (3)$$

$$f_n = \frac{\pi}{8}\sqrt{\frac{Yd^2}{\rho L^4}}\left(n-\frac{1}{2}\right)^2 \quad \text{for } n \geq 2, \quad (4)$$

where Y is Young's modulus, d is the fiber diameter, L is the fiber length, ρ is the density, and n is the mode number.[15] Figure 3 shows the fit and the measured data. The fit gives a value of the diameter in good agreement with the 65 μm that was found from direct measurement using a microscope. Deviations of the measured frequency from the predicted frequency may be related to the nonuniformity of the fiber, either ellipticity and/or diameter variation along the length.

Extrinsic dissipation was minimized so that the measured Q's would truly reflect the fiber's internal friction. By taking measurements at around 5×10^{-6} Torr, the loss due to residual gas damping was made to be approximately 5×10^{-8} and thus negligible. In order to reduce fiber-clamp rubbing at the interface, the fused silica rod to which the fiber was welded was suspended by another silica fiber from a silica rod clamped in a collet (see Fig. 2). This arrangement also reduces the coupling between the fiber and the higher loss support structure.

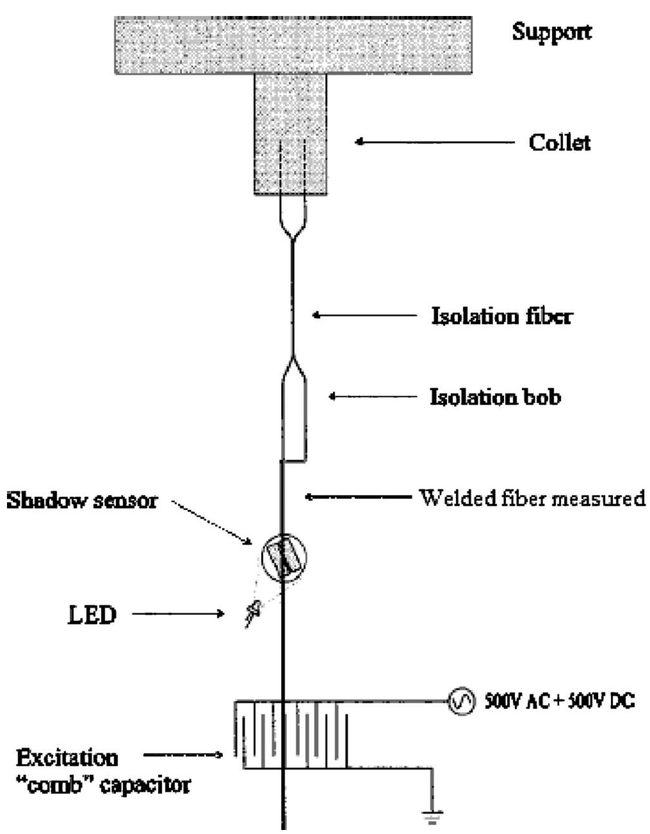

FIG. 2. Schematic of the ringdown experiment. The bob to which the fiber is welded is attached to another silica bob above it by a silica fiber.

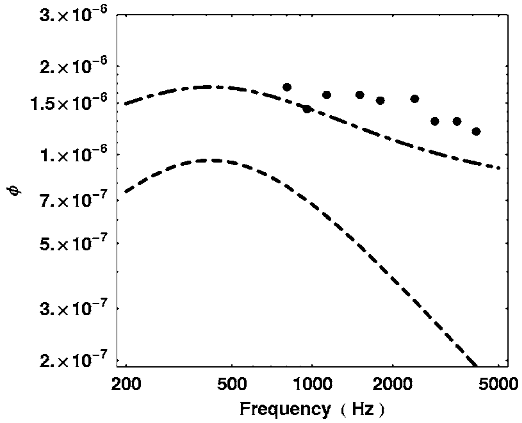

FIG. 4. Measured dissipation against resonance frequency of the welded fiber. The points are the measured loss angles, the dashed line is thermoelastic damping for a 65 μm silica fiber, while the solid line shows the expected loss from thermoelastic damping and structural surface loss for the same diameter. The thermoelastic peak has been reduced by 0.65, in line with results from other measurements.

The loss angles of several modes are plotted in Fig. 4. The data in this figure is shown along with plots of

$$\phi = \phi_{\text{thermoelastic}} + \phi_{\text{internal}}, \tag{5}$$

where ϕ_{internal} is the loss due to internal friction and $\phi_{\text{thermoelastic}}$ is the loss due to thermoelastic damping,[16] which is given by

$$\phi_{\text{thermoelastic}} = \frac{Y\alpha^2 T}{C}\frac{\sigma f}{1+\sigma^2 f^2}, \tag{6}$$

where Y is Young's modulus, α is the thermal expansion coefficient, T is the fiber temperature, C is the heat capacity per unit volume, and f is the frequency. The parameter σ is given by

$$\sigma = \frac{2\pi}{13.55}\frac{Cd^2}{\kappa}, \tag{7}$$

with d the fiber diameter and κ the thermal conductivity.[6] This model assumes a frequency-independent loss. There is a good evidence that silica has bulk loss proportional to $f^{0.8}$ (Refs. 12 and 17) but surface loss is frequency independent.[18] For fibers with diameters below a few millimeters, surface loss is expected to be the dominant loss mechanism over bulk loss.[6]

The top plot in Fig. 4 shows the expected mechanical loss from both thermoelastic damping and surface loss. The surface loss is assume to be at a level,

$$\phi_{\text{surface}} = 7.45 \pm 0.04 \times 10^{-7}, \tag{8}$$

which has been observed in flame-welded fibers.[12] The lower plot is the thermoelastic contribution with the peak height reduced from the value in Eq. (6) by 0.65, using $Y=7\times 10^{10}$ Pa, $\alpha=5.1\times 10^{-7}/\text{K}^{-1}$, $T=293$ K, and $C=772$ J/(kg K). A reduction in the peak height of thermoelastic damping has been observed in silica drawn into fibers[12,18] with 0.65 the reduction found by a fit to Supracil 2 silica data.[12]

The data in Fig. 4 are consistent with only a small addition of loss from sources beyond thermoelastic and surface loss, including the weld. Subtracting the fit from the data gives a residual loss of

$$\phi_{\text{residual}} = 2.8 \pm 1.0 \times 10^{-7}, \tag{9}$$

below the level of surface loss.

III. DISCUSSION

The measurement of loss in a welded free-hanging fiber indicates that the weld contributes less than the fiber surface. Preliminary experiments with constructing whole mirror suspensions using the 1.27 cm mirrors have shown that the welded fibers are fully capable of supporting the mirror. As mechanical losses associated with the weld scale with the ratio of the energy stored in the mass to the energy stored in the bond, the weld loss will be unimportant in the actual experiment as well.

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