THERMAL NOISE FROM OPTICAL COATINGS

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Mechanical loss in dielectric optical coatings of mirrors causes thermal noise. This noise is an important component of the noise budget of the next generation interferometric gravitational wave detectors currently being designed. We discuss the description of this noise, the experimental work being done to characterize it, and plans for coatings with improved noise performance.

1 Theory of coating thermal noise

The special role that coatings play in the thermal noise of interferometric gravitational wave detectors was pointed out by Levin[1]. Working from the Fluctuation-Dissipation Theorem[2], he showed the proximity of the coating to the laser means fluctuations from coating loss can contribute more to the noise than from loss elsewhere on the mirror.

Following Levin, Gretarsson[3] developed a formula for thermal noise in an interferometer with a Gaussian beam. This same formula was found independently by Nakagawa *et al.*[4] using a different approach. Each assumed the mirror to be a half-infinite plane and that the coating's mechanical impedance was isotropic. Gretarsson allowed for anisotropy in the loss angle of the coating.

Following Gretarsson, a formula for coating thermal noise is found without the assumption of isotropy in the impedance:

$$\begin{aligned}\phi_{\rm readout} = \phi_{\rm substrate} + d/\left(\sqrt{\pi} w Y_\perp\right) \\ \left[\left\{Y/\left(1-\sigma_\perp^2\right) - 2\sigma_\perp^2 Y Y_{||}/\left[Y_\perp\left(1-\sigma^2\right)\left(1-\sigma_{||}\right)\right]\right\}\phi_\perp\right. \\ +Y_{||}\sigma_\perp\left(1-2\sigma\right)/\left[\left(1-\sigma_{||}\right)\left(1-\sigma\right)\right]\left(\phi_{||}-\phi_\perp\right) \\ \left.+Y_{||}Y_\perp\left(1+\sigma\right)\left(1-2\sigma\right)^2/\left[Y\left(1-\sigma_{||}^2\right)\left(1-\sigma\right)\right]\phi_{||}\right],\end{aligned} \quad (1)$$

where $\phi_{\rm readout}$ is the loss angle used to calculate thermal noise in the interferometer, $\phi_{\rm substrate}$ is the loss angle of the substrate material, d is the thickness of the coating, w is the field amplitude radius of the laser, Y and σ are the Young's modulus and Poisson's rato of the substrate material, $Y_{||}$ and $\sigma_{||}$ are the Young's modulus and Poisson's ratio for stresses and strains entirely within the plane defined by the planes of isotropic material that make up the coating, $Y_\perp$ and $\sigma_\perp$ are the Young's modulus and Poisson's ratio for stresses perpendicular to the coating plane, $\phi_{||}$ is the loss angle associated with loss in energy from strains parallel to the coating plane, and $\phi_\perp$ is the loss angle associated with loss in energy from strains perpendicular to the coating plane. This formula is to be compared to equation (20) in reference[3].

The limit of Eq. 1 where all the Poisson ratios are small, $\sigma_{||} = \sigma_\perp = \sigma = 0$, gives

$$\phi_{\rm readout} = \phi_{\rm substrate} + d/\left(\sqrt{\pi} w\right)\left(Y/Y_\perp \phi_\perp + Y_{||}/Y \phi_{||}\right). \tag{2}$$

This is to be compared to equation (23) in reference[3].

Thermoelastic damping between the coating and the substrate can also cause thermal noise[5,6]. The magnitude of noise from this source depends on the matching of the thermal expansion coefficients, thermal conductivity, and Young's moduli between the coating and the substrate. These values are often different between bulk samples and thin films, and efforts are underway to measure them for all coatings being considered for Advanced LIGO[7].

2 Experimental Results

A first round of experiments on coated silica disks was done to determine the scale of the loss angle in silica/tantala coatings of the style used in the intial LIGO interferometers[3] as well as in alumina/tantala coatings[8]. It was found that the loss is sufficiently high to make coating thermal noise a limiting noise source in the proposed Advanced LIGO detectors.

A second round of experiments[9] determined that the loss in silica/tantala and alumina/tantala coatings is caused primarily by internal friction in the tantala. It was also found that there is frequency dependence to the loss in the coating materials[10]. The frequency dependence is most evident in silica, but is also found in tantala. In each case the loss is expected to be less at the lower frequency (100 Hz) region where coating thermal noise is expected to be important for Advanced LIGO compared to the higher frequency (10s of kiloHertz) modes where the loss was measured.

There are plans to directly measure coating thermal noise using interferometers at both Caltech, with LIGO's Thermal Noise Interferometer, and in Hongo, Japan[11]. It is planned that these experiments will examine the validity of coating thermal noise theory and measure directly the relevant coating loss angles.

3 Current Plans

Developing coatings that will exhibit low thermal noise while preserving the low optical loss necessary for high finesses Fabry-Perot arms is a high priority in Advanced LIGO research. A plan has been developed to measure the loss in about eight test coatings. This work is being done with two coating vendors.

It has been found that a silica/tantala coating with 2-3 % titanium added as a dopant to the tantala reduces the loss in the tantala from 4.6×10^{-4} to about 2×10^{-4}. Further coatings with doped tantala are planned, either with higher concentrations of titanium, additional dopants, or new dopants.

New materials beyond silica, alumina, and tantala are also planned. Work with niobia has suggested that its loss is slightly worse than tantala. A coating of hafnia/silica is planned to be measured next. A triple alloy of silicon, oxygen, and nitrogen is also being developed. Additional materials may also be considered, depending on results with these.

Finally, different annealing cycles for coated samples after removal from the coating chamber are also planned. Annealing is known to effect the optical loss in coatings, and annealing has been shown to reduce the mechanical loss in bulk silica[12]. Using materials found previously to be promising for Advanced LIGO coatings, experiments changing rise times, peak temperatures, and cool down rates will be tried to determine the optimum values for low thermal noise and low optical absorption coatings.

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