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Three Page Summary

Thermal Noise in Optical Coatings

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Abstract. This paper will discuss the importance of thermal noise in optical coatings for gravitational wave detectors, its definition, merit figure, and approaches towards minimizing it with design, materials selection, and material modification. Experimental and *ab initio* computational materials modeling results will be highlighted.

Introduction.

The Laser Interferometer Gravitational Wave Observatory (LIGO) project objective is to open a new window on the universe – gravity wave astronomy. A gravity wave has never been detected, though they were theoretically predicted in 1916 with the Einstein field equation. When this capability exists, new information concerning the origin of the universe, its present content, and the behavior of gravity when objects are very massive (for example, spinning or inspiraling neutron stars and black holes) becomes available.

The LIGO device is essentially two co-operating Michelson interferometers whose arms are 4 km in length, located in Livingston, LA and Hanford, WA, Figure 1. These detectors are being replaced with a next generation upgrade - a procurement project known as Advanced LIGO. Light in each arm-cavity is bounced between two dielectric-mirror coated substrates hanging freely beneath pendulum suspensions and a signal is registered when a gravity wave changes the length of one arm relative to the other - when this happens, the mirrors themselves do not move, but space contracts while the light wavelength is conserved. The sensitivity of the detector is influenced by many factors, and the absorption & scatter losses of the mirror coatings are paramount. However, the theoretical limit of performance, expressed as a signal-to-noise ratio limiting the masses of bodies that are detectable, or how far away they may be detected, is governed by Coating Thermal Noise. Coating Thermal Noise (CTN) is an active area of research.

Figure 1. Hanford & Livingston LIGO Observatories.

What is Thermal Noise?

In the case of substrates and their coatings, the source of TN is thermally activated atomic motion, or lattice vibrations, that displace the surface of the coated optic. For a detector that needs to be sensitive to changes in length ~ 1/1000 of a proton, this noise is important. In practice, thermal noise is evaluated indirectly with mechanical measurements, that is, through the mechanical quality factor (Q) and the loss angle (φ) when a coated cantilever-like sample is vibrated. The connection between mechanical losses and atomic motion can be made by the very general "fluctuation-dissipation" theorem: thermal fluctuations of a system (atomic motion in this case) results in energy losses for any forced motion *of* the system, or forced motion *through* the system. Turning this around, if there is more mechanical loss (lower Q, higher φ), there must be more statistical fluctuation from the thermally activated motion of atoms, resulting in displacement of the mirror surfaces, and therefore, more *noise*. The Q and φ are measured in film samples, both as multilayers, and layers of the individual materials. These measurements are performed by researchers at U. Glasgow (Rowan, et. al.), Hobart & William Smith College (Penn), and Embry Riddle (Gretarasson). Thermal noise in coatings is also measured directly, interferometrically, at Caltech (Black), and in the actual LIGO detectors.

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How is Thermal Noise Treated in Optical Coatings?

A simple "rule of mixing" for coatings which serves as a figure of merit for coating thermal noise (CTN) is due to Pinto (U. Sannio at Benevento),

$$S = z_{low} + z_{high} \frac{\varphi_{high}}{\varphi_{low}} \frac{n_{low}}{n_{high}} \frac{\dfrac{Y_{high}}{Y_{sub}} + \dfrac{Y_{sub}}{Y_{high}}}{\dfrac{Y_{low}}{Y_{sub}} + \dfrac{Y_{sub}}{Y_{sub}}}, \qquad (1)$$

where, the subscripts refer to the high or low index layer materials in the design or the substrate, Y is the Young's modulus, φ is the loss angle, and z is the total full wave optical thickness for the material in the design.

The fundamental approaches to the reduction of thermal noise in optical coatings are to: 1) By design, limit the amount of high φ material, while also limiting the total thickness, as both materials contribute; 2) Finding or engineering new materials that have lower φ or optimized Y. There are other, more hardware-centric approaches being investigated, including using coating-less mirrors, cavities as mirrors, and non-Gaussian beams.

Current Work.

Design-wise, as an example, consider the Advanced LIGO Input Test Mass (ITM), which is a 35 cm diameter fused silica substrate 7 inches thick, with a dielectric mirror coating requiring, 0.5 – 2% single surface transmittance at 532 nm and 1.3 – 1.5% transmittance 1064 nm. The formula for optimization of such a coating that lowers the CTN and activates the first and second order harmonics is of the form (Pinto, Dannenberg)

$$\text{Substrate}|\ a\cdot H\ |\ (x\cdot L\ y\cdot H)^{m}\ |\ b\cdot L\ |\ \text{Air}, \qquad (2)$$

where L & H are FWOT of the low and high index materials, x ~ 3/8, y ~ 1/8, a ~ 0.25 and b ≤ 0.25. Changing a,b,x,y & and m, for y /x as small as possible, the CTN can be lowered by as much as 14% from a straight x = 3/8 and y = 1/8 design, while minimizing the surface electric field and with manufacturing stability of up to 1% random thickness errors. Other design types and optimization routines are being explored.

For coating materials, as we work in the wavelength range between 532 nm to 1064 nm and are interested in Ion Beam Sputtered coatings due to their low scatter, we are restricted material-wise to SiO_2 with $\varphi_{low} \sim 1\cdot10^{-4}$ rad and $n_{low} \sim 1.45$, and some high index material with $n_{high} \sim 2.2$. A number of high index materials have been investigated for use, including TiO_2, Nb_2O_5, Ta_2O_5, HfO_2, Al_2O_3, ZrO_2, and mixtures of them. They all have higher loss angle than SiO_2, hence the need to minimize the amount of high index material in the design.

Ta_2O_5 and TiO_2-doped-Ta_2O_5 are the ones with acceptable scatter and absorption, with loss angles φ_{high} of $4\cdot10^{-4}$ and $2\cdot10^{-4}$ rad, respectively. The TiO_2:Ta_2O_5 material has half the loss angle of pure Ta_2O_5, *but the reason for this is not well understood.* Nonetheless, it has been proven experimentally, and is the material being used for the Advanced LIGO Test Mass coatings. Materials research to understand the loss angle reduction is underway, the work being referred to as "The Coating Initiative".

So called *ab initio* computational materials codes such as CASTEP are being used to predict material properties from first principles (Cheng, Dannenberg): Young's modulus, bulk modulus, all elastic constants, heat capacity, and index of refraction. Figure 2 shows the Bulk Modulus (B) versus the index of refraction (n) for the SiO_2-doped-TiO_2 mixed system, another system of interest. In Figure 2, a solid blue line connects the experimental B-n points while the rest of the points are the results of *ab initio* calculations, and it can be seen that similarly composed crystals (0%, 25%, 50%, 65%, 100% SiO_2) B-n values fall in the same general regions as the experimental ones. Further, for the SiO_2:TiO_2 system, the B value (therefore *Y*) changes greatly while the index remains at about n = 2.2. Noting the numerator of Equation 1's Y term, for all else fixed, a minimum in the CTN parameter S would result at B ~ 50 GPa, and this is shown in Figure 3. This example shows that material tailoring of elastic constants is valuable, and, computational work can help make useful predictions in selecting materials for experimental evaluation.

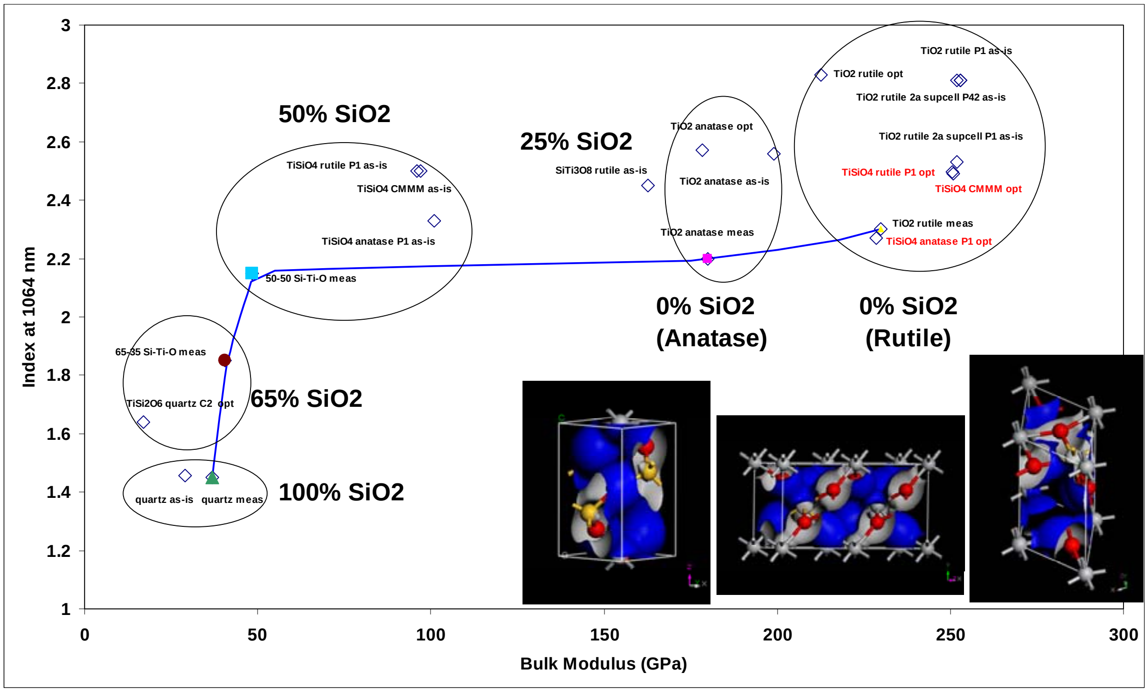

Figure 2. Experimental (blue line through colored points) and *ab initio* B-n values for modeled crystals with compositions close to the experimental one. The inset images are the some of the crystal mixtures under consideration and their electron density computed from density functional theory in CASTEP.

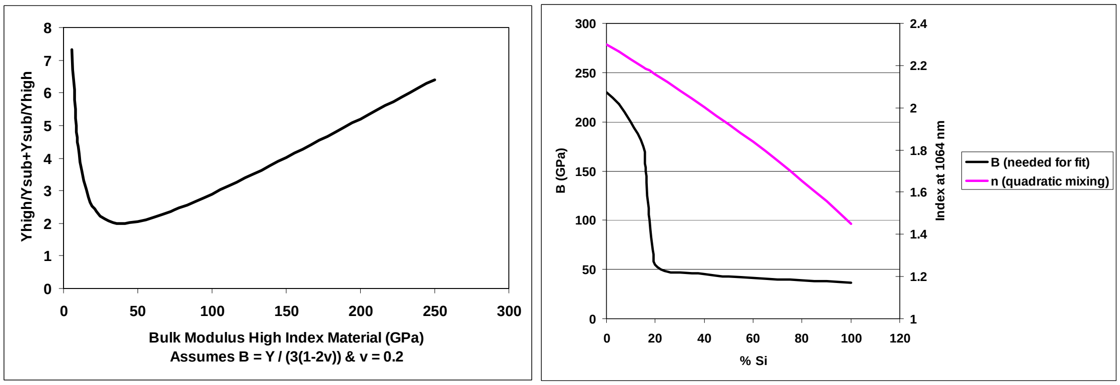

Figure 3. Left: Thermal noise can be minimized in the SiO_2:TiO_2 system by tailoring of the bulk modulus with no cost in the index of refraction, therefore, minimal layer thickness changes for the same design. The vertical axis is the numerator of the Y term of Equation 1, and B ~ 50 GPa would minimize S and the CTN. **Right:** The extracted index of refraction and bulk modulus versus %Si. Plotting the B & n values together produces the blue curve through the experimental data in Figure 2.

Conclusion.

Coating Thermal Noise for LIGO is a critical area of on-going engineering, research, and development, affecting the long term success of the program. Although contracts have been awarded for the Advanced LIGO production program, coating vendors with ideas are sought for discussions on materials choices, design concepts, optimization routines, and characterization for the research Coating Initiative.