Mechanical Loss Measurements of Coated Substrates for Gravitational Wave Interferometry

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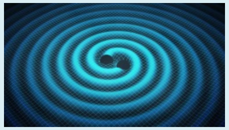
Background

Gravitational Waves – Predicted by Einstein's Theory of Relativity to stretch and compress space-time. Theoretically only astronomical objects produce waves large enough to be detected (changing space by 1 part in 10^{21})



Gravitational wave representation from two black holes merging (above)

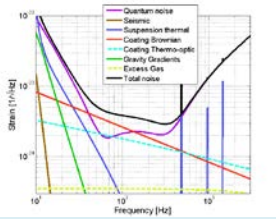
Why We Care – Gravitational waves sources such as black holes, binary neutron stars, and supernovae, are not well observed with electromagnetic telescopes. Detecting such a wave would give us new ways to study these phenomena in addition to further proving General Relativity

LIGO in Hanford, WA (above)

Laser Interferometer Gravitational Wave Observatory (LIGO) – A National Science Foundation funded 4 kilometer long interferometer to detect gravitational waves from space with one observatory in Livingston, LA, and one in Hanford, WA

LIGO Sensitivity

Due to the extremely small effects of gravitational waves on the LIGO mirrors (a relative laser path difference ~$8*10^{-18}$) minimizing noise is crucial. Optical coating thermal noise (dominated by Brownian Noise) may lead to stationary waves in mirror coatings that affect the phase of the reflected laser beam. Thermal noise is the primary limiting noise in Advanced LIGO for the gravitational wave frequencies that we expect to be strongest.



Noise Limitations in Advanced LIGO (above)

Abstract

We measured the mechanical loss of Master Bond EP30-2 epoxy and Aluminum-Gallium-Arsenide Single-Crystal Coating (AlGaAs). The AlGaAs is a possible mirror coating for Advanced LIGO and thus minimizing thermal noise is vital to ensure the sensitivity required in gravitational wave interferometry. The epoxy is of interest as a way of attaching tuned mass dampers to Advanced LIGO test masses to help mitigate parametric instability.

Theory

Thermal noise is defined by the mechanical loss angle Φ of the material where:

$$\Phi_{Total} = \left(\frac{1}{E}\frac{dE}{du}\right)_{Edge}(u\Phi)_{Edge} + \left(\frac{1}{E}\frac{dE}{du}\right)_{Face}(u\Phi)_{Face} + \left(\frac{1}{E}\frac{dE}{du}\right)\Phi_{Bulk}f^{0.77} + \left(\frac{1}{E}\frac{dE}{du}u\right)_{AlGaAs}\Phi_{AlGaAs}$$

Frequency (Hz)	Φ_{AlGaAs} As % of Φ_{Total}
2706	57
4110	58
6167	58
9502	75
10653	53
16096	47
16337	75
17683	69
22431	41
24347	73
27214	22

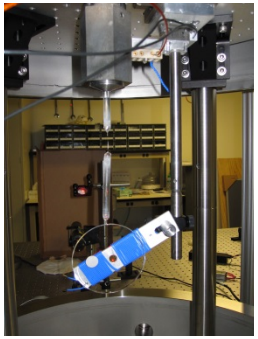
Rough calculations may be done by simplifying the mechanical loss to:

$$\Phi_{AlGaAs,f} = \frac{1}{Q_{total,f}}\frac{U_{total,f}}{U_{AlGaAs,f}}$$

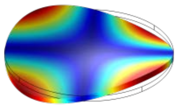
Which comprises 40-70% of $\Phi_{Total,f}$ as shown in the table above right. Results incorporating the other mechanical loss components requires slightly more complex finite element analysis, which is currently underway.

Method

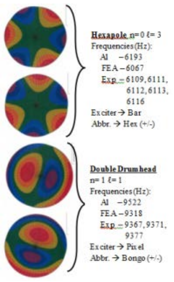
1) Obtain Q values for sample where Q= π $f_n\tau_n$
   - Attach substrate to silica disk and hang in vacuum with electrostatic exciter
   - Resonate sample and measure ringdown time (τ) by observing polarization changes in laser refracting through sample
2) Obtain energy ratios
   - Use Finite Element Analysis models
3) Calculate Φ values

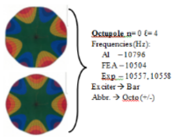


Epoxy sample with exciter, isolation system, and readout laser



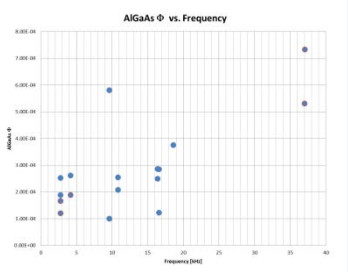
Exaggerated displacement of the butterfly mode at 2672 Hz (above), and higher frequency modes (right)



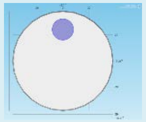


Preliminary Results

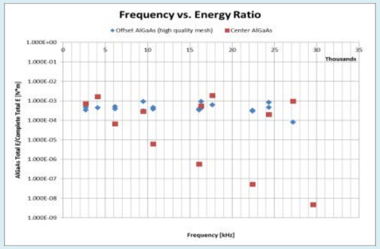
AlGaAs – A promising low-thermal noise alternative coating technology for Advanced LIGO with an apparent low mechanical loss of around 2 * 10^{-4}. However, these models are simplified and more data is needed to make a final conclusion.



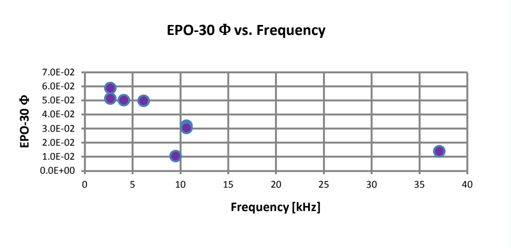
Note: The energy ratio, and therefore Φ, is also dependent upon the geometry of the sample as well as the frequency, as shown in the graph below



The above model shows the offset of the AlGaAs placement



EPO30-2 – RESULTS



Future Plans – Refine our analysis of both AlGaAs and EP30-2 and then study Titaniatantalla as a possible optical mirror coating as well as move on toward EPO-TEK 353ND and EP1730 epoxies