LOSS MEASUREMENTS OF IBS TiO_2:GeO_2 HR COATINGS V.S. EFFECTIVE MEDIUM MODEL

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#1 BACKGROUND

Coating thermal noise is one of the dominant noise sources in the most sensitive detection band of current gravitational wave detectors from 50 Hz – 100 Hz, limiting their sensitivity to signals from weaker and more distant astronomical sources.

Here we present investigations into the promising candidate high-n coating material for future detectors: **TiO_2:GeO_2 – [44% Ti / 56% Ge cation concentration]**.

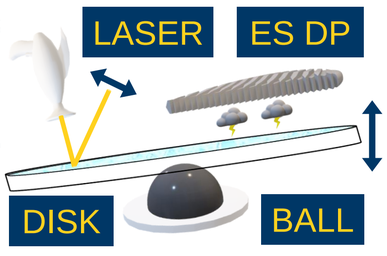
We measured the mechanical losses of uncoated and coated disks at resonance, to infer the loss of the coatings themselves (ϕ_c) through several stages of heat treatment. Furthermore, from the coating losses (ϕ_c) of single layers, we implemented an Effective Medium model (EFF-MED) to predict the coated loss (ϕ) of a disk coated with a 52 QWL HR stack, which we then compared with our real measurements of that HR stack.

#2 METHODS

Single layers & HR stacks of TiO_2:GeO_2 and SiO_2 were deposited on SiO_2 disks via Ion Beam Sputtering at CSU [A].

Losses were measured by exciting coated disk resonances via GeNS [B].

GeNS minimizes external damping. Internal damping is known as the mechanical loss ϕ. $\phi = 1/Q$ [@ resonance]



#3 EFFECTIVE MEDIUM APPROACH

2-material EFF-MED averaging

$$\bar{g} \equiv \langle g \rangle \equiv \frac{d_1}{d_1 + d_2} g_1 + \frac{d_1}{d_1 + d_2} g_2$$

$d_{\#}$ – total thickness of material #
$g_{\#}$ – any quantity **or combination** of quantities in layer #

example: energy stored in stack

$$u = \frac{1}{4}\left[\left\langle \frac{Y}{1-\nu} \right\rangle S^2_{D,s} + \left\langle \frac{Y}{1+\nu} \right\rangle \left(S^2_{\Delta,s} + S^2_{6,s}\right)\right]$$

$$u = \frac{1}{4}\left[\ \bar{g}_A\ S^2_{D,s} + \ \bar{g}_B\ \left(S^2_{\Delta,s} + S^2_{6,s}\right)\right]$$

$S^*_{\#}$ – strain terms

coating stack ϕ_c estimate

$$\phi_c = \frac{1}{2\pi f} \frac{p_{diss}}{u}$$

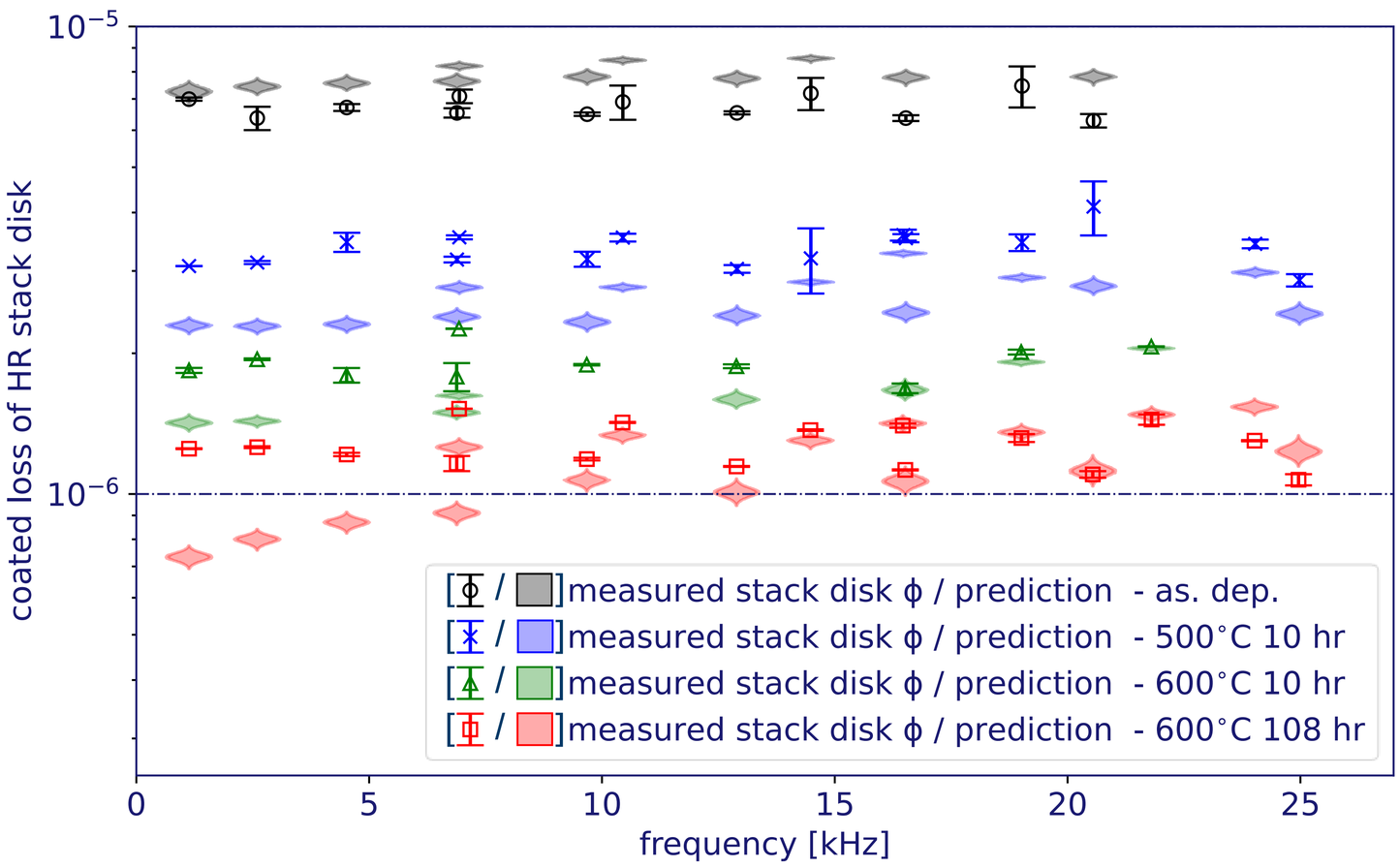
The Coating thermal noise (CTN) PSD is directly proportional to the coating mechanical loss ϕ_c.

After GeNS measurement, one way of inferring ϕ_c for a coating stack comprising of x-materials, is through thickness (d) averaging certain coating material properties (Y, ν, ρ) **individually** to approximate the fractional energy stored in the coating with respect to the whole disk. From this ϕ_c can be extracted from a measured ϕ.

Instead with an **EFF-MED** approach we apply a **local averaging procedure** to compute an **effective stiffness tensor** that accurately approximates response of the multi-layered medium to applied strains and stresses [C].
The essence of this approach is to arrange the components of the constitutive relations in forms that do not contain products of quantities discontinuous at the interface between the layers.

By applying this analysis to material properties (ϕ_c, Y, ν) obtained from single layer coated GeNS measurements we can estimate the loss of a coating stack and hence a sample coated with that stack.

#4 RESULTS & DISCUSSION



With the coating stack ϕ_c now estimated by applying the EFF-MED analysis to single layer data, and knowing the uncoated disk sample ϕ, **we can predict the ϕ of a stack coated disk at each frequency it resonates.**

The graph shows the predicted EFF-MED losses for the HR coated disk, and its real best measured loss though heat treatment.

Only the data for one disk is presented here, but in fact four 52 layer stacks were measured. For all, in the as deposited state, measurements matched (or were *slightly* lower than predictions).

But for all heat-treated samples above 500°C, the measured ϕ values were higher than predictions. I.e. **we see EXCESS MEASURED LOSSES (ϕ) than the EFF-MED predicts** .
It is particularly prevalent at lower frequencies.

As the EFF-MED model aims to better approximate the response of the coating stack to applied stresses, **the witnessed excess losses appearing, after heat treatment, could be potential indicators of undesired material interdiffusion at coating stack layer boundaries (something not possible in a single layer).**

This explanation could somewhat also explain the higher than predicted, directly measured CTN values of some coating stacks - a measurement that takes place at much lower frequencies than these ϕ measurements [D].

A follow-up study is currently underway wherein stacks of different numbers of interfaces, layer thickness, and overall TiO_2:GeO_2 / SiO_2 proportions will be studied, with measured v.s. EFF-MED model loss trends found.

[A] Colorado State University IBS Spector system. C. Menoni & A. Davenport.
[B] E Cesarini, G Cagnoli, et al: Review of Scientific Instruments 80 (5): 053904. (2009).
[C] M. M. Fejer "Effective Medium Description of Multilayer Coatings" LIGO public DCC (2021).
[D] N. Demos & S. Gras "MIT CTN measurements of CSU TiGe" LIGO DCC G2202133 (2022).