Measurements of multi-material coatings using a cryogenic nodal support

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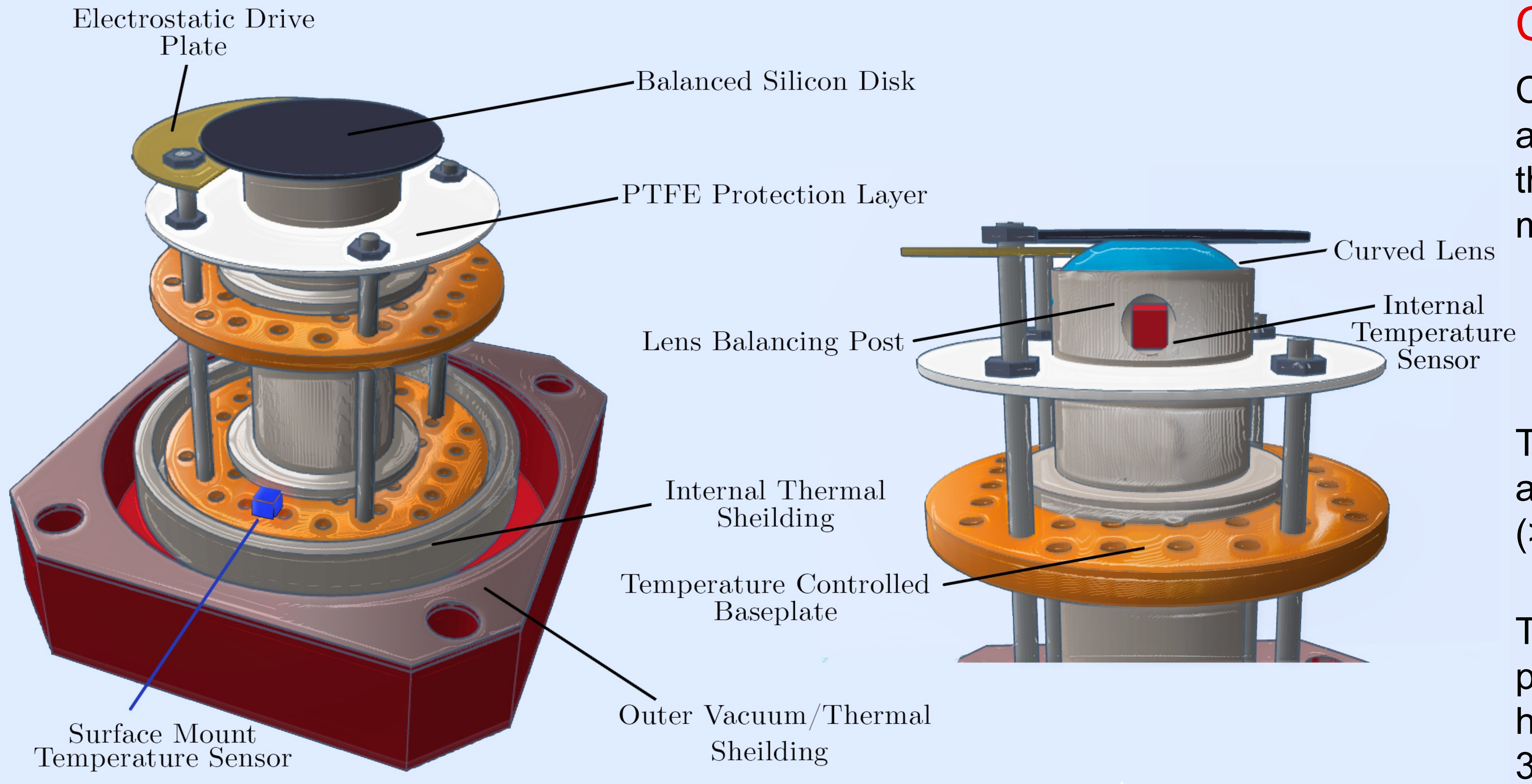
Introduction

Three-material based multilayer coatings comprising of silica, tantala and amorphous silicon, and optimized for use at 1550 nm were first postulated in 2015 [1,2]. This multi-material concept was adapted for a detector operating at cryogenic temperatures and a wavelength of 2000 nm.

To characterize the mechanical loss of these coatings, a series of crystalline silicon discs (2” × 360 µm) were coated, by Tafelmeier [3], with:

- a lower amorphous silicon/silica multi-layer coating comprising of five bi-layers (low mechanical loss, but high optical absorption amorphous silicon)
- an upper tantala/silica multi-layer coating comprising of five bi-layers (to significantly reduce the incident light), and
- a full ten bi-layer amorphous silicon/silica/tantala coating stack.

By using reactive low voltage ion plating, coating materials were deposited at energies comparable to ion beam sputtering, and relatively low absorption amorphous silicon, seen previously, was produced.



Results

Loss measurements between 4K and 300 K were carried out using a cryogenic gentle nodal support [4] which is shown in Fig. 1, with the coating loss calculated from the difference in loss between coated and uncoated disks.

The coating mechanical loss of these coatings has been determined in their ‘as-deposited’ state for a range of resonant modes (1-30 kHz). The coating loss of the first two resonance modes is shown in Fig. 2. As expected, the upper stack has the highest loss (larger tantala component), and the lower stack (uses amorphous silicon instead of tantala) has a lower loss.

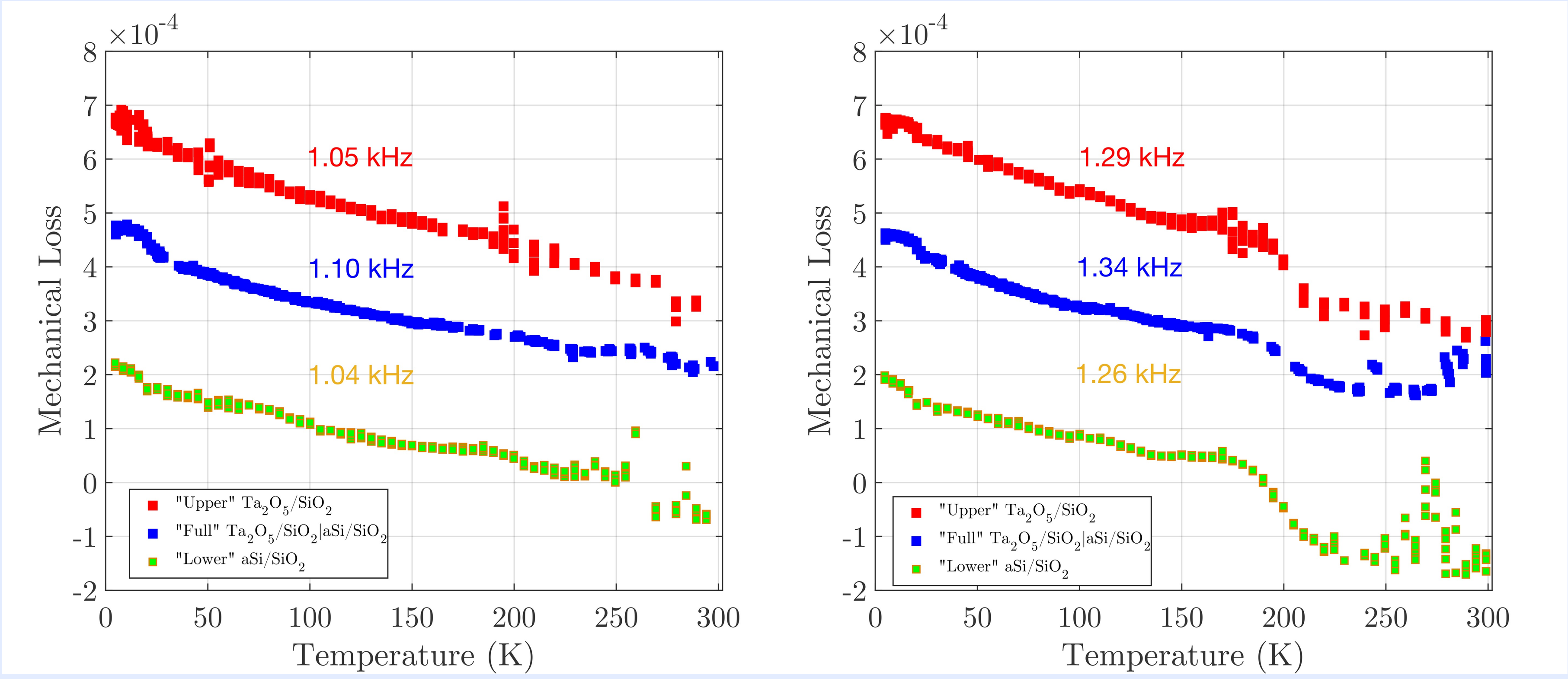


Figure 2: Comparison of coating mechanical losses from the “upper”, “lower” and “full stacks” at similar mechanical mode frequencies as a function of temperature.

Coating mechanical losses from different substrates

Coating loss should be independent of substrate under the same conditions. Measurements of single layer coatings are used to predict the loss of the multimaterial design [5]. By measuring the loss of the full stack using different techniques and substrates some key differences are observed.

- The mechanical loss peak is currently not observed in cSi disk substrates, (possibly due laser heating effects).
- Above 200K, the loss from thinner silicon substrates diverges from single layer predictions.
- The room temperature loss on a thicker silica substrates shows better agreement with single layer predictions.

The differences in loss between substrates is believed to stem from a change in substrate curvature due to the thermal stresses induced by the coating layers.

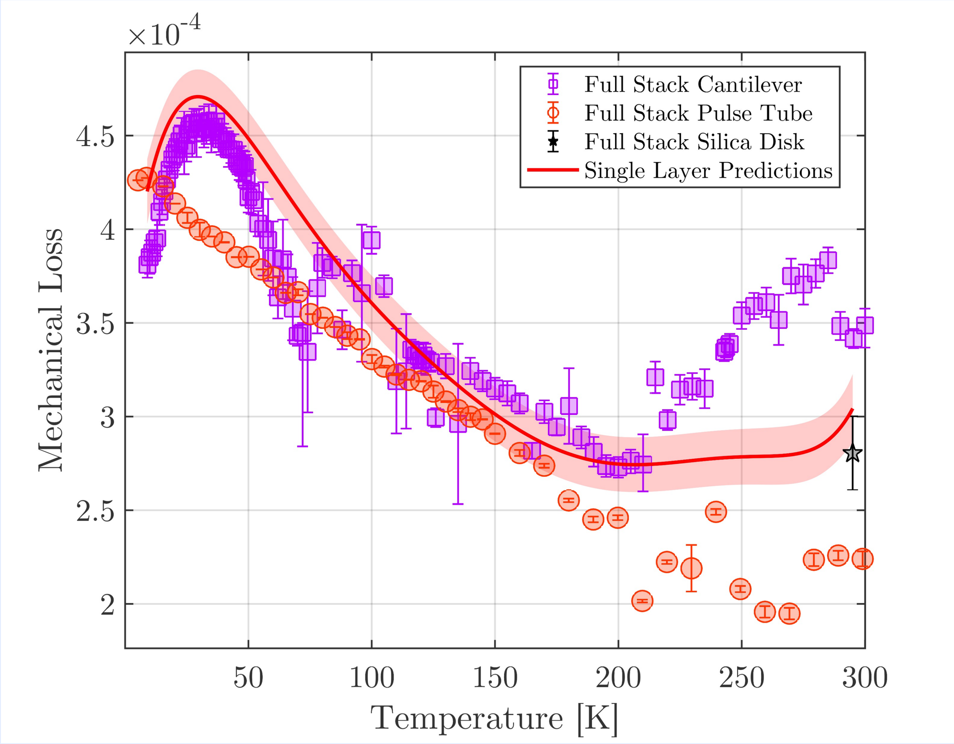


Figure 3: Comparison of the full stack coating losses measured on different substrates (2”×360µm silicon disc, ~70µm thick silicon cantilever and a 3×0.1” silica disc). The predicted coating loss from single layer measurements on cSi cantilevers is also shown.

Coating Thermal Noise

Coating thermal noise is one of the major obstacles to be overcome in the near and longer-term future of gravitational astronomy. The expected Brownian thermal noise is calculated using Eq. 1 using measurements of the multi-material design deposited on cSi cantilevers and a cSi disk.

$$S_z^{\mathrm{Br}} = \frac{4k_{\mathrm{B}}T}{\pi r_G^2 r_0} \frac{1-\sigma_{\mathrm{sub}}-2\sigma_{\mathrm{sub}}^2}{Y_{\mathrm{sub}}} \sum_j b_j d_j \phi_{Mj}, \qquad (1)$$

These are compared to hypothetical coating stacks made of ion plated amorphous silicon/silica and tantala/silica with similar levels of reflectivity (>99.998%) at 2000nm.

The thermal noise levels exhibited the lower amorphous silicon-silica stack out-performs that of the full stack by 59% at 123K as it does not contain any of the higher loss tantala layers. However, after being heat treated at 500˚C for 3.5hrs, the absorption of the full stack is only 8ppm compared to 181ppm for the amorphous silicon/silica stack [6].

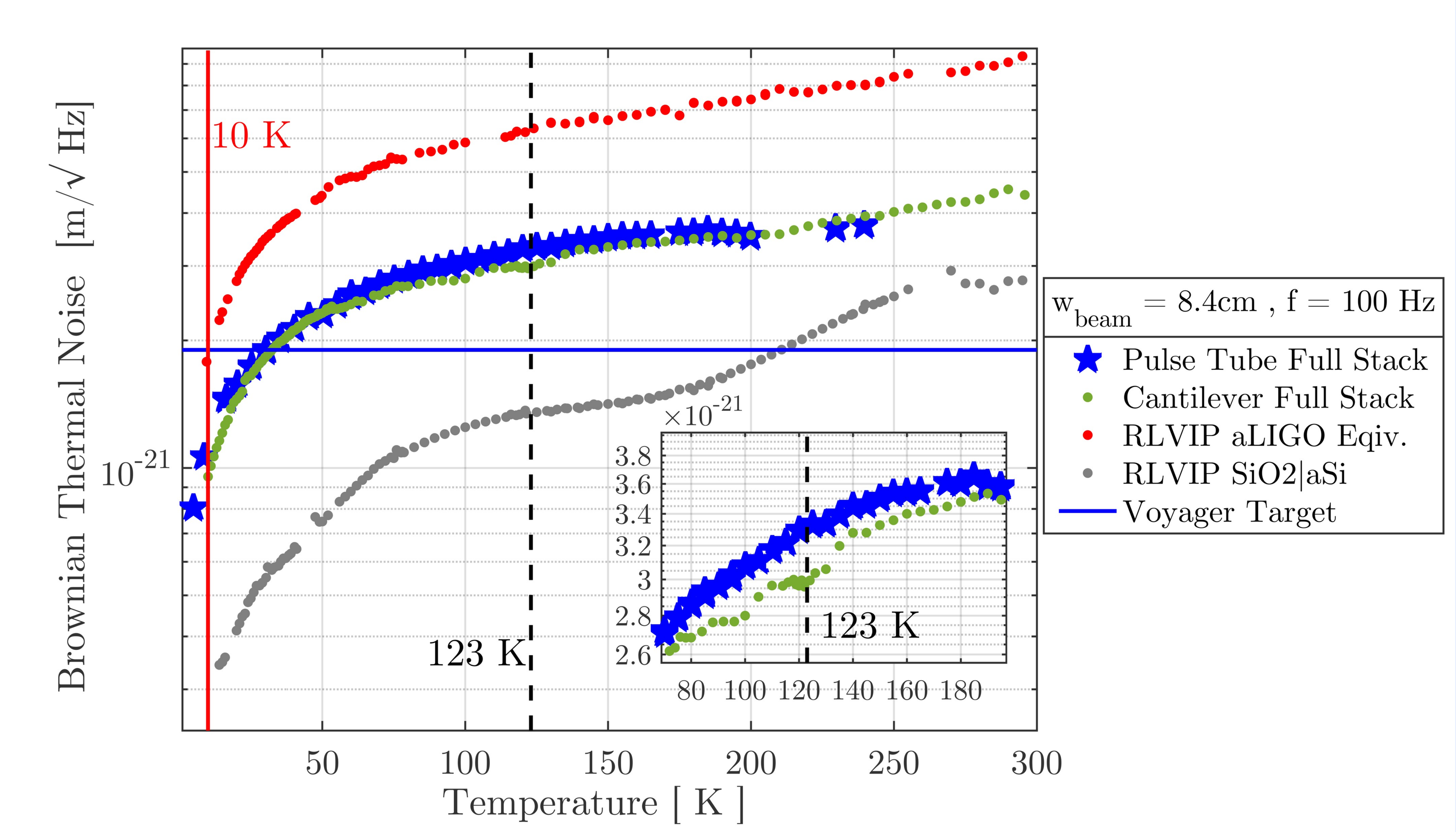


Figure 4: Brownian coating thermal noise for the as-deposited full HR stack calculated from cSi cantilever and disk measurements. This is compared with the LIGO Voyager coating design (blue line), and equivalent ion-plated Voyager and aLIGO coatings.

In the current absence of materials with both sufficiently low mechanical loss and optical absorption, multi-material coating designs are likely to play an important role in the future of the field, allowing thermal noise challenges to be met, and helping the next generations of gravitational wave detectors to reach their full potential.

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Further Reading

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