

Measuring the Effect of Heat Treatment on Mechanical Loss of Optical Coatings for Use in Future Gravitational Wave Detectors

Cassady Smith
University of Glasgow

Abstract

This paper will examine the effect of heat treatment steps on the upper ($\text{Ta}_2\text{O}_5\text{-SiO}_2$), lower (aSi-SiO_2), and full stack mirror coatings for use in future gravitational wave detectors. This includes a full range of measurements at room temperature and establishing the setup for measurements at cryogenic temperatures. We find that each heat treatment step in increments of 100°C does reduce the average lowest mechanical loss of each stack. The maximum reduction in coating mechanical loss for each stack is exhibited at 500°C . The change from the as-deposited upper stack to the optimally heat-treated full stack exhibits a reduction in mechanical loss by approximately 56%. While this does produce a reduction in thermal noise from the coatings currently used, it is not reduced by a factor of two, as required by the aLIGO Plus upgrades. More work must be done to understand the effects of different depositions, treatments, and other methods used to reduce coating thermal noise for use in future gravitational wave detectors.

1. Background

1.1 Mirrors in Gravitational Wave Detectors

In his 1915 General Theory of Relativity, Albert Einstein postulated the existence of gravitational waves. These ripples in the curvature of space-time are created from cataclysmic astronomical events such as coalescing compact binary systems, supernovae, and pulsars. Their detection can provide information about the objects and their lifetime, and even events like the Big Bang. Unless also detected by one or more electromagnetic counterparts, this information would otherwise be invisible to humans. In order to detect these extremely small ripples in space, we utilize large-scale Michelson laser interferometers to measure the motion of two test masses due to their interaction with gravitational waves.

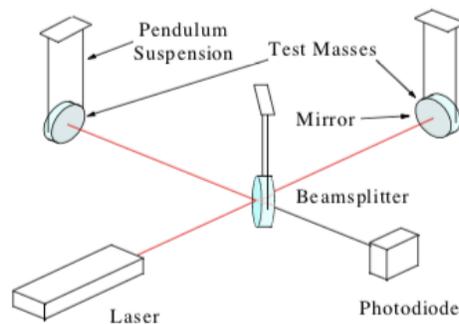


Fig. 1.1: Schematic of basic interferometer

For the laser to measure motion in the test masses, the light must be reflected from the masses to a photodiode. Therefore, the test masses must be mirrors.

1.2 Noise due to Mirrors

Because of the variation in sources of gravitational waves, the possible frequencies for detection range from about 10^{-17} to 10^3 Hz. Such small frequencies require very precise measurements to obtain a signal, so any large sources of noise could make it impossible to isolate a detection. There are three main noise sources for the interferometers in whole: seismic, thermal, and photoelectron shot noise. The first two are dominant in the mirrors that act as test masses.

Seismic noise due to Earth tectonics and even human activity such as passing cars or nearby construction can provide enough motion to change the relative separation of the test masses, and therefore add noise or false signals to the detectors. To eliminate as much of this seismic noise as possible, the two test masses at the end of the two arms are suspended as pendulums. In Initial LIGO, each end consisted of only one mirror/test mass 25 cm in diameter and 11 kg in mass. Each mass was suspended as a pendulum by two steel fibers as a single-segment pendulum. Shock absorbers provide only passive isolation from seismic noise.

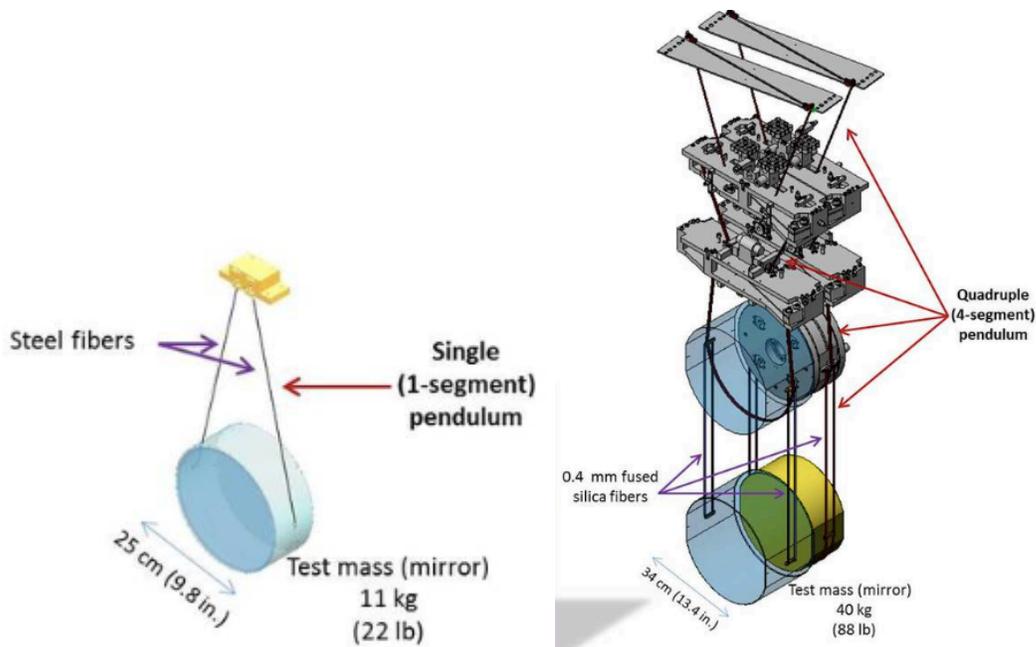


Figure 1.2 (left): iLIGO Mirror Suspension
 Figure 1.3 (right): aLIGO Quadrupole Suspension System

One of the biggest upgrades for Advanced LIGO (now in use) is the quadrupole suspension system, pictured above. Rather than one test mass/mirror, there are now four test masses with only one of them acting as a mirror. This is an additional passive form of seismic isolation, with vibrations at the top of the system reducing by a factor of $1 * 10^8$ by the time it reaches the test mass with the mirror coating. The masses are larger, at 34 cm diameter and 40 kg mass in order to reduce the amount of motion produced from the interaction with the incoming laser. The atoms in metal such as steel are inherently easier to move and can therefore allow easier movement for the test mass. Therefore, the steel fibers used for suspension were replaced with fused silica fibers. Although very easy to break with force perpendicular to the length of the 0.4 mm wide fibers, the glass is capable of holding up to 100 kg and allows for much less motion within the system. Additionally, aLIGO employs active seismic isolation by counteracting motion sensed within the system [1].

1.3 Future LIGO Upgrades

With each upgrade, we aim to increase the sensitivity of the detectors across frequencies and decrease the noise level for different parameters. Figure 1.4 shows the sensitivity level for aLIGO and the planned sensitivity for aLIGO Plus – the next generation of LIGO detectors aimed to operate 2023-2025. Figure 1.5 shows how we aim to achieve these sensitivity levels by reducing the noise curves across different parameters. The main improvements will be the reduction in thermal noise from the mirror coatings and the radiation pressure and shot noise due to laser phase and amplitude squeezing.

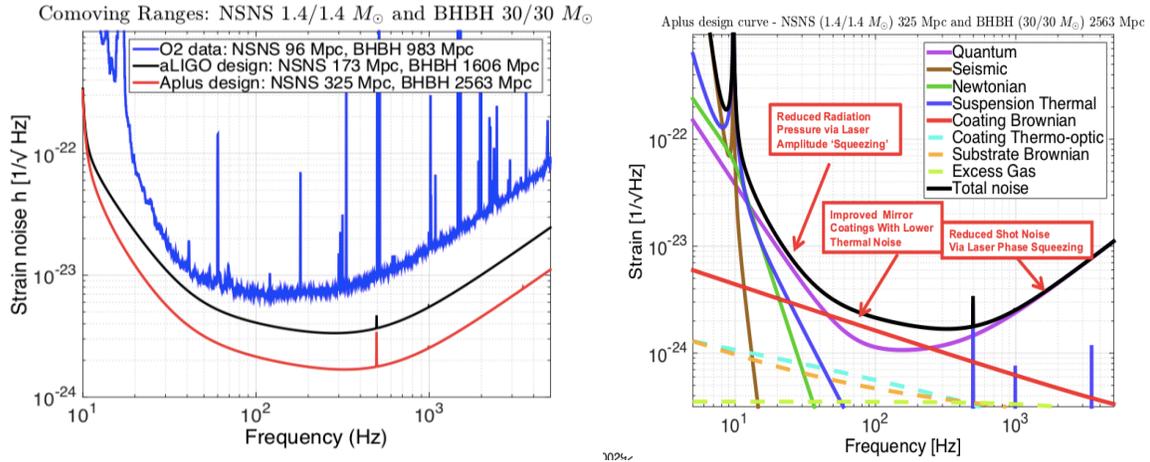


Figure 1.4 (left): Sensitivity Curves for LIGO Detectors

Figure 1.5 (right): Noise Curves for aLIGO+

Future detectors will operate at cryogenic temperatures to further reduce noise curves. This poses new challenges to current infrastructure and materials, as well as those planned for use in the aLIGO+ upgrade. Solutions include changing the laser wavelength, which would also require more infrastructure changes. Because the aLIGO+ upgrade is meant to be low-cost [2], it will operate at room temperature. Cryogenic measurements and implications will be discussed further in later sections.

2. Mirror Coatings

2.1 Noise from Mirror Coatings

Within the quad suspension systems are four masses for seismic isolation, one of them being a substrate with a mirror coating to reflect the laser for the interferometer. Noise from the mirror coatings is in the form of thermal noise due to Brownian motion in the atoms of the coating. Additionally, not all of the laser light is reflected by the coatings, creating trapped heat within the system in the form of optical absorption.

Mechanical Loss

Thermal noise is related to the damping of a system due to intrinsic or external properties [3]. Therefore, in an ideal system that has no damping due to external influences, one can calculate the thermal noise from the system by measuring the damping or mechanical loss of the intrinsic system. This is typically done by finding resonant frequencies of the system and measuring the time it takes for the system to “ring down”. The energy dissipation and therefore mechanical loss can be related to the quality factor.

$$\phi(f_0) = \frac{E_{\text{lost per cycle}}}{2\pi E_{\text{total}}} = \frac{1}{Q}$$

Therefore, the lower the mechanical loss of a system, the higher its quality factor and lower its energy lost per cycle is. Because mechanical loss is frequency dependent, the loss is typically calculated across resonant frequencies and then averaged to find a value for the system to compare to others. Experimental methods calculate mechanical loss from the equation for time-dependent amplitude decay

$$A(t) = A_0 e^{-2\pi\phi(f_0)f_0t/2}$$

where A_0 is the maximum amplitude at the resonant frequency f_0 , $\phi(f_0)$ is the frequency dependent mechanical loss, and t is the time for the amplitude to reach noise levels from the maximum excitation amplitude.

The mechanical loss described above is the loss of the composite system. However, the mirrors consist of mirror coatings deposited onto a mirror substrate. To obtain the mechanical loss of the mirror coatings themselves, the coating loss is calculated by the equation

$$\phi_{coating} = \frac{E_s}{E_c} (\phi_{coated} - \phi_{substrate})$$

where E_s is the elastic strain of the substrate, E_c is the strain of the coating, ϕ_{coated} is the measured mechanical loss of the mirror with the substrate and the deposited coating, and $\phi_{substrate}$ is the measured mechanical loss of an uncoated mirror substrate.

Optical Absorption

Under vacuum pressure in an isolated system, any heat produced within the interferometers has no means of escape. At room temperature, this can be detrimental to the delicate instruments. Warping of the thin film mirror coatings due to absorption also increases the scattering within the optical cavities, further contributing to noise. With future upgrades planned to operate at cryogenic temperatures, continuous high absorption will increase the temperature of the test mass over time and therefore stray from cryogenic temperatures and increase the thermal noise past desired levels.

Although this paper will mainly focus on mechanical loss and include discussion of loss measurements, it is important to note that both low mechanical loss and optical absorption are required for future detector upgrades. Results from other experiments to measure optical absorption will be discussed in tandem with those of mechanical loss.

2.2 Currently in Use: Ta₂O₅-SiO₂

Mirror coatings used in LIGO and current aLIGO consist of alternating stacks of tantala (Ta₂O₅) and silica SiO₂. This combination was chosen because it produces a highly reflective surface at a laser wavelength of 1064 nm and has low absorption and scatter loss [4]. 1064 nm is the industry standard and was chosen because the infrastructure needed was readily available. Use of different wavelengths may be necessary for future upgrades and cryogenic detectors, which will be discussed further in future sections.

Alternating layers of the high index and low index of refraction materials are used to obtain maximum reflection per Fresnel's equations. Although the reflection of this material combination is high, it is found that it has large mechanical loss, dominated by the loss of the tantala [4].

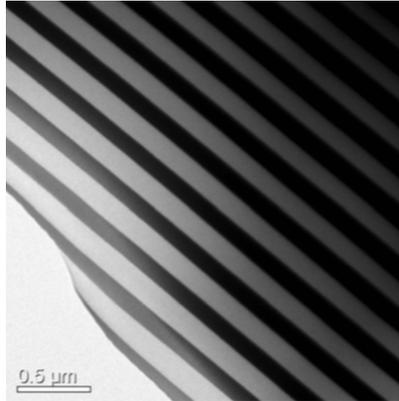


Figure 2.1: Alternating Layers of Silica and Tantala in Mirror Coating

2.3 Incorporating aSi-SiO₂ for Lower Mechanical Loss

One candidate to replace the high mechanical loss tantala is low loss amorphous silicon. With a higher refractive index than tantala, the coating stack of aSi-SiO₂ will require fewer layers. As the thickness of the coating is directly proportional to the loss, fewer layers will also mean lower loss. However, amorphous silicon also has very high optical absorption and therefore cannot solely replace tantala. Instead, a three-material coating seems to be the most likely candidate as of now.

This full stack multi-material coating will consist of an upper stack of Ta₂O₅-SiO₂ and a lower stack of aSi-SiO₂. The low absorption upper stack reduces incident light power for the high absorption lower stack, while the lower stack reduces mechanical loss from the high loss upper stack. Preliminary measurements of as-deposited coatings show that this multi-material approach reduces Brownian thermal noise by 25% and produces an optical absorption of only (5.3 ± 0.4) ppm at 1550 nm [5].

While this is an improvement, the absorption limit for aLIGO+ is 1ppm and the mechanical loss is not yet improved by a factor of four. Moreover, both mechanical loss and optical absorption are temperature dependent, which poses difficulties for cryogenic detectors. Single layers and stacked layers of Ta₂O₅ and SiO₂ have exhibited cryogenic loss peaks. While aSi has low mechanical loss at low temperatures, the stacked layers of aSi-SiO₂ also exhibit loss peaks at cryogenic temperatures [6].

2.4 Heat Treatment

One method to reduce mechanical loss and optical absorption is to heat treat the materials to an optimal temperature, thereby rearranging the molecules to create a more stable structure

[7]. Past this optimal heat treatment, the amorphous films appear to crystallize and the mechanical loss and optical absorption begin to increase. This paper will examine the effect of heat treatment steps on the upper ($\text{Ta}_2\text{O}_5\text{-SiO}_2$), lower (aSi-SiO_2), and full stack mirror coatings for use in future gravitational wave detectors. This includes a full range of measurements at room temperature and establishing the setup for measurements at cryogenic temperatures. Experiments performed measure mechanical loss at room temperature due to heat treatment, but effects on optical absorption will also be discussed.

3. Experimental Method and Results

3.1 Disks and Gentle Nodal Support (GENS)

As stated earlier, typical methods of calculating mechanical loss involve exciting the system to resonant frequencies and measuring the ring-down times. Such systems are typically cantilevers or disks. This experiment uses disks to measure the mechanical loss of the upper stack, lower stack, and full stack at incremental heat treatments.

To ideally take loss measurements, the disk would be free-floating with no points of contact in a vacuum and therefore no means of damping besides the intrinsic loss properties of the material. As this is physically impossible, we aimed to have an experimental setup with one minimal point of contact at the center of the disk where there is minimal motion. The GENS design balances the disk on a small lens, allowing it to be nearly free-floating with only one small point of contact in the center.

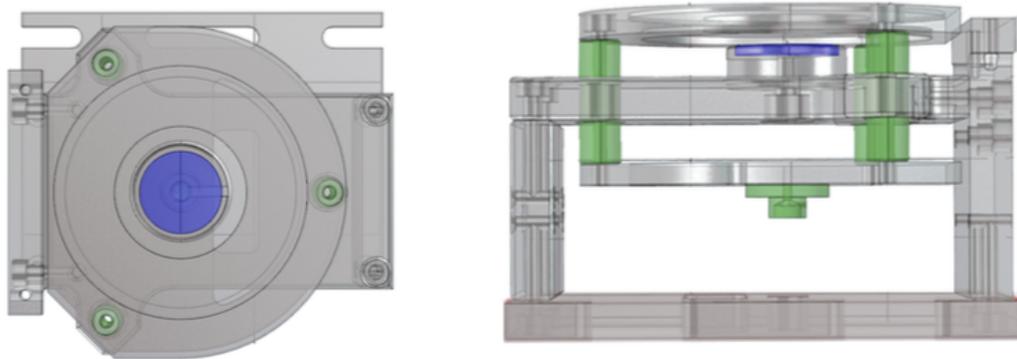


Figure 3.1: Computer Generated Image of GENS System

Held by the green Teflon supports on the right of Figure 3.1, the disk stage consists of two concentric circles, each concentric with the blue silicon lens. This experiment uses the outer circle to hold a 3-inch diameter disk. The stage is first raised so the disk sits concentrically above the lens. The stage is then slowly lowered with a motor so that it balances on the silicon lens at one point in the center.

In addition to the GENS system, there is an exciter plate placed above the disk to sweep through desired frequency ranges, and an interferometer is used to detect relative changes in amplitude of the disk.



Figure 3.2: Full System with Suspended Disk inside Vacuum Tank

To determine the resonant frequencies of each of the three stacks, we use finite element analysis and estimate the coated disk to be a blank, free-floating silica disk. Because the coatings are thin in comparison to the substrate, this estimation provides us with initial resonant frequencies that we then use to find the frequencies of the balanced coated disks.

3.2 Method

For consistency of materials and results, the same disk is used for each heat treatment measurement. Each heat treatment lasts three hours in an atmosphere pressure oven. All measurements have been taken at room temperature in the setup shown above. Disks were treated and measured in increments of 100°C , starting at 300°C and ending at 500°C . Each disk was also initially measured in its as-deposited state. For each heat treatment step, measurements were taken for each disk over a total of three suspensions to ensure repeatability of the experiment. Nine or ten resonant modes calculated by the finite element analysis were detected for each disk.

3.3 Results

The initial analysis of the results takes the lowest measured coating mechanical loss at each resonant frequency. This method produces very frequency dependent results, as shown in the plots below. However, when taking the average of the lowest losses over all resonant frequencies and comparing them over heat treatments, there is a significant reduction in mechanical loss for each disk, with the minimum being at the heat treatment of 500°C . This is shown in Figure 3.6.

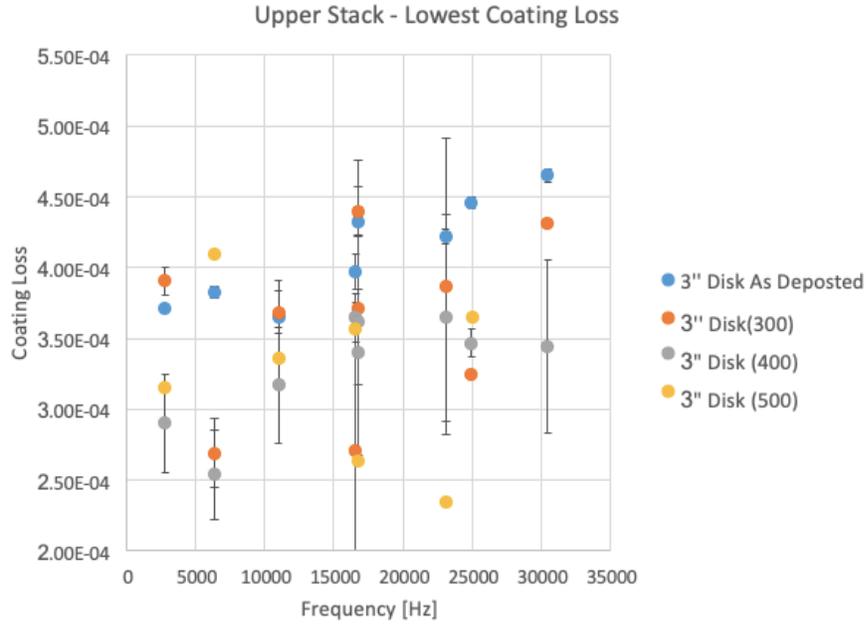


Figure 3.3: Lowest Coating Mechanical Losses for Upper Stack

Here, the lowest coating losses are frequency dependent. For the first resonant mode at 2 kHz, the lowest loss increased after being heat treated to 300°C. When it was heat treated to 400°C, the loss did decrease, however it increased once again when heat treated to 500°C. Expected trends of decreasing loss over heat treatments occurred at 23 kHz, one of the degenerate 16 kHz, and 31 kHz.

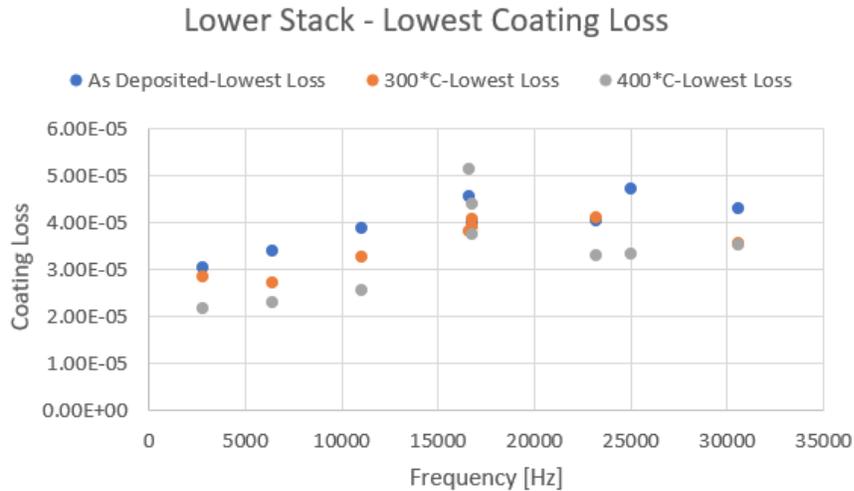


Figure 3.4: Lowest Coating Mechanical Loss for Lower Stack

Full Stack

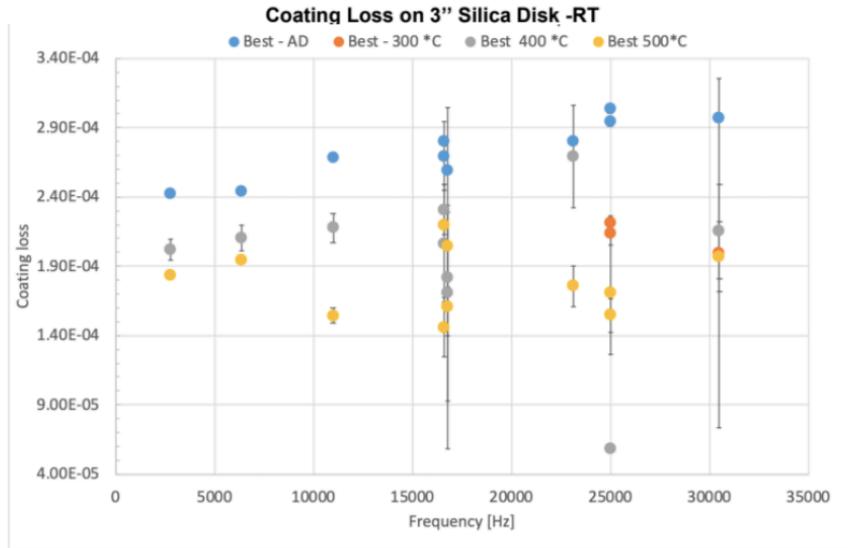


Figure 3.5: Lowest Coating Mechanical Losses for Full Stack

Overall, this disk does follow the expected trend at each frequency.

Disc Coating Loss -Averages

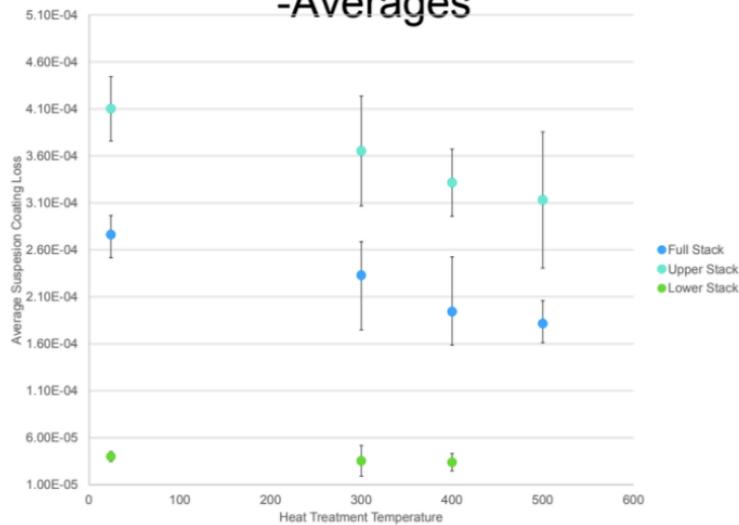


Figure 3.6: Average of Lowest Mechanical Losses Over Heat Treatments

When taking the average of the lowest mechanical losses at each frequency and comparing them over heat treatments, there is a clear reduction in coating mechanical loss. For the upper and full stacks, the minimum occurs at 500°C heat treatment. While measurements are still

being taken for the lower stack, preliminary analysis also shows a significant reduction in coating mechanical loss.

3.4 Comparison to Optical Absorption

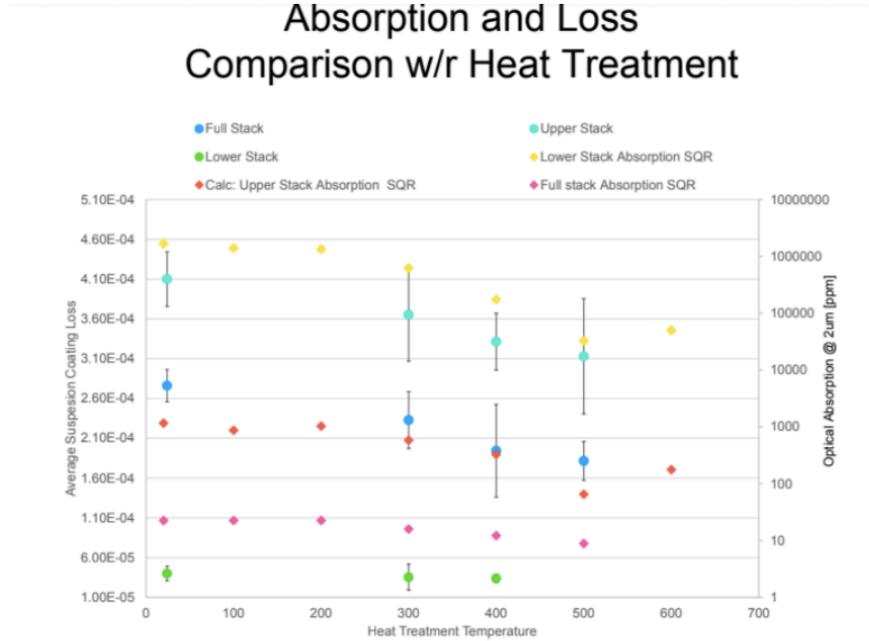


Figure 3.7: Comparison of Optical Absorption and Mechanical Loss with Heat Treatment

Measurements of optical absorption show the same trend of decreasing absorption over heat treatments, with a minimum absorption at 500°C. Additionally, there is a relative increase in absorption at 600°C, which is in accord with the prediction that 500°C is the optimal heat treatment to reduce both mechanical loss and optical absorption. If the matching trends continue, we also expect the experimental results for mechanical loss to increase once heat treated to 600°C.

4. Further Studies

4.1 Cryogenic Mechanical Loss

For future cryogenic detectors like the Einstein Telescope, measurements of mechanical loss must be taken at cryogenic temperatures. While cryogenic measurements of coated cantilevers have been well underway at Glasgow, there have been no cryogenic measurements of disks. The setup for these sets of experiments is still in the process of being established and calibrated. The cryostat, seen in Figure 4.1 below, has an outer nitrogen space, an inner helium space, and an experimental space where one GENS stage will be placed. There is a possibility for installing a second GENS stage in the future for simultaneous measurements. As motors are not operational in cryostats, an electromagnet is used to move the stage and suspend the disk. Besides this replacement, measurements will be taken in the same manner as at room temperature.



Figure 4.1: Cooling Cryostat for Calibration

5. Conclusion

By combining an upper stack of Ta_2O_5 and a lower stack of aSi-SiO_2 for a full stack mirror coating, Brownian thermal noise was reduced by 25% and optical absorption was reduced to (5.3 ± 0.4) ppm at 1550 nm. These reductions are relative to the single stack Ta_2O_5 coating used in iLIGO and aLIGO. While this shows promise for future upgrades, aLIGO+ requires that the thermal noise be reduced by a factor of four and the optical absorption be a maximum of 1 ppm. To further reduce both loss and absorption, we incrementally heat treat disks coated with the upper, lower, and full stacks. We find that the full stack, most suitable for use in detectors, has an average coating mechanical loss of approximately $1.8 * 10^{-4}$. This does not represent a reduction by a factor of four from the as-deposited upper stack, which is used in current detectors. These measurements do not reach the requirements of the aLIGO+ upgrade, so additional research and methods must be used to reduce mechanical loss and optical absorption to the required levels.

6. Acknowledgements

I'd like to thank the National Science Foundation for providing the opportunity to be part of the LIGO collaboration and contribute to their ground-breaking experiments, as well as the University of Florida for organizing this IREU. I'd like to thank my mentors, Ian Martin, Peter Murray, Simon Tait, and Maya Kinley-Hanlon at the University of Glasgow for teaching me and guiding me along the way. I'd also like to thank my professors, Glenn Piner, Seamus Lagan, and Serkan Zorba at Whittier College for preparing me for my research experience.

7. References

- [1] “About aLIGO”, <https://www.ligo.caltech.edu/page/about-aligo>.
- [2] “The A+ Design Curve”, L. Barsotti, L. McCuller, M. Evans, P. Fritschel.
- [3] “Development of Mirror Coatings for Gravitational Wave Detectors”, Stuart Reid, Ian Martin (2016).
- [4] “Mechanical Loss in Tantalum/Silica Dielectric Mirror Coatings”, Steven D. Penn et al. (2018).
- [5] “Thermal Noise Reduction and Absorption Optimization via Multimaterial Coatings”, Jessica Steinlechner et al. (2015).
- [6] “Multimaterial Coatings for 3rd Generation Gravitational Wave Detectors”, Petter Murray.
- [7] “Flying to the Bottom”, Giorgio Parisi, Francesco Sciortino, Nature Materials 12, 94-95 (2013).