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A Multi-Step Approach to Assessing LIGO Test Mass Coatings

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Abstract. Photographs of the LIGO Gravitational Wave detector mirrors illuminated by the standing beam were analyzed with an astronomical software tool designed to identify stars within images, which extracted hundreds of thousands of point-like scatterers uniformly distributed across the mirror surface, likely distributed through the depth of the coating layers. The sheer number of the observed scatterers implies a fundamental, thermodynamic origin during deposition or processing. If identified as crystallites, these scatterers would be a possible source of the mirror dissipation and thermal noise, which limit the sensitivity of observatories to Gravitational Waves. In order to learn more about the composition and location of the detected scatterers, a feasibility study is underway to develop a method that determines the location of the scatterers by producing a complete mapping of scatterers within test samples, including their depth distribution, optical amplitude distribution, and lateral distribution. Also, research is underway to accurately identify future materials and/or coating methods that possess the largest possible mechanical quality factor (Q). Current efforts propose a new experimental approach that will more precisely measure the Q of coatings by depositing them onto 100 nm Silicon Nitride membranes.

1. Introduction

The mirror test masses of the LIGO Gravitational Wave detector [1][2] have been specifically designed and constructed with multi-layered interference coatings [3] deposited via ion-beam deposition to minimize optical absorption, mirror thermal noise [4][5] and light scattering [6]. As precision increases, various noises become more prominent in the detected signal of LIGO. Identifying and eliminating noise sources become vital. At the level of 10^{-18} m, the surfaces of the test mass mirrors move under the effects of thermal excitation. Mitigating thermal noise at this level is crucial for detecting weaker gravitational wave signals from farther away in the Universe. In addition to mirror thermal noise, the scattering of the LIGO stored beam light from the mirror surface also contributes to the noise budget. Light power decreases and the quantum squeezing of the stored beam is affected by the scattering [7]. Scattering is attributed to irregularities in the refractive index of the coating layers, caused by either voids or denser crystallites within the coating layers. A reduction of

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the current levels of scattered light could also potentially increase the current sensitivity of LIGO, by allowing stronger squeezed light in Advanced LIGO [7]. The research efforts at Cal State LA are focused on detecting and identifying scatterers within the LIGO mirror coatings for these purposes.

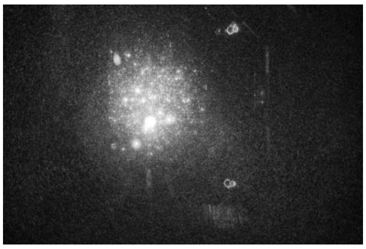

Figure 1: November 2015 Photograph of an End Test Mass at LIGO Hanford with an exposure time of 1.3 seconds. (Note: The rings and faint straight lines that appear in the background on the right side of the image are components of the mirror support structure).

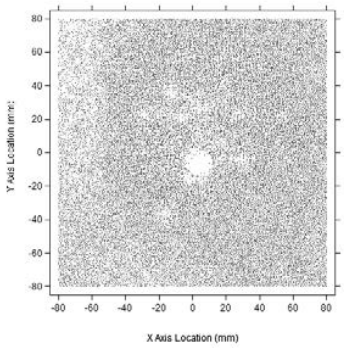

Figure 2: DAOPHOT-detected scatterers with 0.763 second exposure. Smear due to residual surface impurities limits DAOPHOT's detection efficiency in some areas that appear blank.

Until recently, a portion of the observed scattered light was attributed to things such as residual surface impurities deposited on the mirrors during implementation accesses. It was believed that many could be removed with swiping, First Contact and other clean room practices, even if completely clean mirrors could and cannot be achieved. However, using the astronomical image software suite DAOPHOT [8][9] to analyze in-situ photographs of LIGO end test masses, hundreds of thousands of weaker, point-like scatterers have been detected, uniformly distributed across the mirror surface, ignoring the smear of residual surface impurities on the mirror. The amplitude distribution of the observed scatterers implies that they extend through the depth of the coating while their sheer number implies a fundamental, thermodynamic origin pointing towards the presence of crystallites.

Motivated by these observations, the Cal State LA LIGO Research Group developed a scatterer mapping technique [10] capable of sufficient depth resolution not only to identify the layer (high or low-refraction index) hosting the scatterer, but also the distribution within each layer. A density growing towards the top of the layer would signal the presence of crystallites, which are observed to evolve into crystalline columnar growth when layers are thicker. [11] Voids are expected to be more prominent at the coating layer boundaries, near the interface to the previous glass, which has a different atomic spacing and structure (SiO_2 vs. Ti_2O_5 for example). [12] This experiment could potentially distinguish between the two possibilities.

A second effort, in collaboration with Tsing Hua, is working towards the measurement of the quality factor of new coating samples. Further research would follow to determine if there is any correlation between the Q-factor measurements and detected scatterer count and size within the coating samples.

2. Feasibility of mapping scatterers within LIGO coating layers

The detection of hundreds of thousands of sub-wavelength, weak scatterers in the LIGO mirror coatings has served as an impetus for further research. While observing the scatterers with the 100 kW light power of LIGO is informative, it cannot be used to improve the current sensitivity of the device since the mirrors are already installed and cannot be modified or replaced during this stage of LIGO operation. Also, most light is reflected in the first few layers and the scattered light is further attenuated by reflection in the way that the observed scattering effectively explores only the first few layers. To truly learn more about the proliferation of the scatterers throughout the coating layers, in-situ photographs would not be sufficient.

As a follow-up to the previously explained analysis, it is necessary to produce a complete mapping of scatterers in a sample including the amplitude distribution, the lateral distribution (to check for uniformity), and the depth distribution. For best guidance of the coating process, it would be ideal to achieve depth sensitivity sufficient not only to know if the scatterers belong to a high refraction index or low refraction index quarter wavelength layer, but also to determine if they cluster near the bottom or top of the layer, or if they are uniformly distributed.

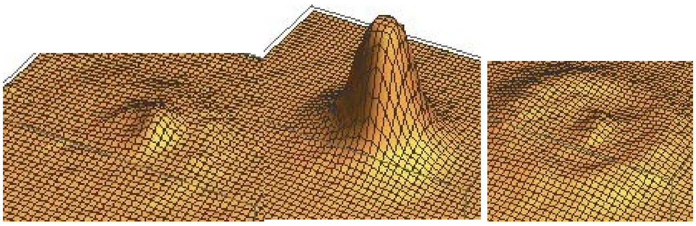

Figure 3: Dark field, 20x 3D images of ROI containing a scatterer moving from out of focus, to in focus, to out of focus as the scan progresses. Note the Airy function rings present when out of focus. In the center the image is fully focused and the Airy function rings have collapsed into the central peak, which does not significantly change width. The pictures were taken at roughly 15 steps apart.

As an initial feasibility study, a microscope with both bright and dark field was used for observations on a 25 mm diameter commercial dielectric mirror and images of diffraction-limited scatterers were found in the mirror. When properly focused, scatterers appear as bright dots on dark field or dark dots with bright field in microscope observation.

Out-of-focus scatterers are not visible or appear as blurred dots. As the focal plane is scanned through the coating layers, scatterers first appear as fuzzy blotches, then they show as an Airy function with rings. When in complete focus, the rings coalesce into the central peak that becomes sharp and bright. As the scan progresses, the sequence inverts, until each and all scatterers disappear. Three points of a sequence is illustrated in figure 3.

We take advantage of this sequence to measure the depth of each scatterer in CCD microscope images, by fitting the shape and amplitude of the Airy function images as the position of the focal plane goes through a micrometrical scan through the coating's thickness.

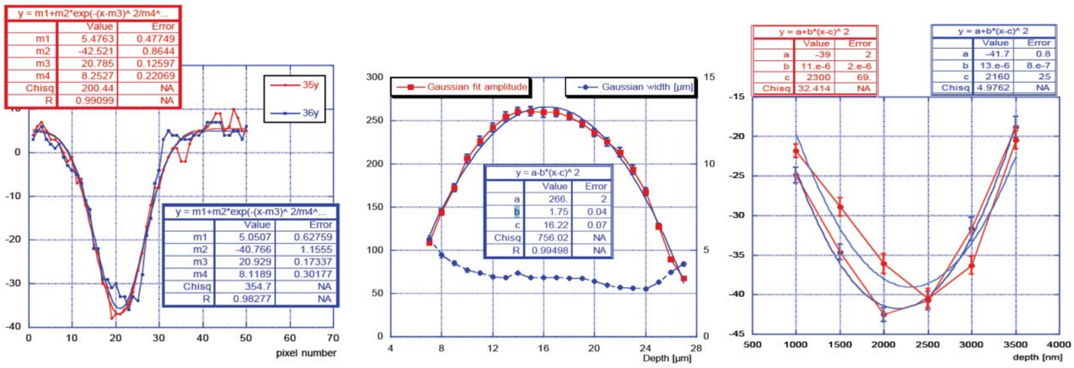

Figure 4: Left: Gaussian fit to two dark field Airy function slices, whose amplitude (m1) is used to find the scatterer depth. Center: amplitude vs. depth fitting with dark field (20x magnification) used to determine the depth (C). Right: Two bright field (50x magnification) amplitude vs. depth fittings, a slightly better depth resolution is achieved.

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Dielectric mirrors reflect only under specific conditions, i.e. at very specific wavelengths and angles so that the light returning from each layer is in phase. With the cone of illumination light in the microscope, with both bright or dark field, light comes in at all angles. In addition, the white light used contains all wavelengths of visible light. The multiple angles and wavelengths ensure that, unlike the case of the stored beam illuminated LIGO mirrors, the light can reach all layers and scatterers can be detected at all depths.

Before proceeding, it is useful to note that, due to the refraction index within the coating, the focusing beams are compressed in depth by Snell's law. Each movement of the microscope in air corresponds to lower distance within the sample. The best depth resolution obtained, 30 nm, corresponding to 3% of the 1064 nm LIGO light wavelength, should be divided by the local refraction index, thus yielding even higher accuracy inside the glass if measured in nm, but always 3% of the wavelength. This resolution allows for identification of not only the layer in which the scatterer is located, but even whether it is located near the top, middle, or bottom of each layer: crucial information in understanding the physics at play.

The worse resolution obtained is ~100nm, while the best has been ~30 nm. When considering calculations that account for the refraction indexes of the coating layers, the achieved resolution of ~ 50 nm allows clear identification of the host layer.

As the current system evolves, there should be complete automation in the Z-axis as well as a X-Y axes raster scan, allowing for better resolution and comprehensive analysis of coating samples in order to detect scatterers with greater detail.

3. Feasibility of measuring coating Q-factors with low dilution factors using SiN membranes

While this microscopic search technique could prove to be useful in detecting and locating scatterers in greater detail, in order to determine if there is a correlation between scatterers and thermal noise, it is necessary to also measure the quality factor of different coatings. This, followed by microscopic analysis of these same coatings, would provide information on the quantity and distribution of scatterers within these samples and determine if there is a correlation between scatterers and coating q-factors. Currently, there are efforts being made by the Cal State LA LIGO Research Group, in collaboration with Tsing Hua, moving towards just that.

A common method of q-factor assessment involves coating a ~50 μm thick cantilever beam and clamping it at one end. The substrate, in this method, is ~100 times thicker than the coating which yields D on the order of 10^{4}. The cantilever system has an additional problem due to the clamping mechanism. It has been observed [13] that losses from clamping are significant and can lead to unpredictable measurements. Just unclamping and re-clamping the cantilever introduces perturbations sufficient to severely affect the measurements of Q.

A different method has been devised to avoid clamping the system altogether. This is the GeNS (Gentle Nodal Suspension) and involves balancing a thin (~1 mm) fused silica disk on a small diameter sapphire bead. The center of the disk is a nodal point of the even modes that, therefore, can oscillate with virtually no losses [14]. There are very limited holding losses but in this case the substrate is now ~10,000 times thicker than the coating [15] and a value for D on the order of 10^{-8} contributes to an uncertainty of the coating's Q.

Silicon nitride membranes are a new material used to fabricate windows for electron microscopes. In some ways, it is ideal as a substrate for the coatings. They are grown over a silicon wafer substrate, where a window then is etched at the center to free up the membrane with a strong silicon frame. They have been shown to possess quality factors on the order of 10^{7}, and are strong enough to hold

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atmospheric pressure even at thicknesses of 100 nm. Due to their minimal thickness and to their strength, a ~1:1 coating to substrate thickness ratio can be achieved.

The basic experimental idea is to coat the front and back of the membranes with the material to be tested, hold the frame with as little clamping losses as possible, electro-statically excite the individual modes and monitor the oscillation ring-down with an optical lever system to make precise measurements of the Q of the coatings.

The main drawback of using SiN windows as substrates is that the loss angle of the coating materials should be measured within the sensitivity range of the gravitational wave detectors, ~1 to 1000 Hz, because the material Q factor is not necessarily constant across all frequencies. The resonant frequency of typical SiN windows is between ten and hundreds of kHz, well outside the frequency region of interest. Depositing the coatings adds mass linearly with thickness, which reduces the resonant frequency but also increases the moment of inertia with the cube of the thickness. Thus, neglecting the tensioning contribution, the resonant frequency can be expected to grow (more or less) linearly with thickness, moving even further from the region of interest.

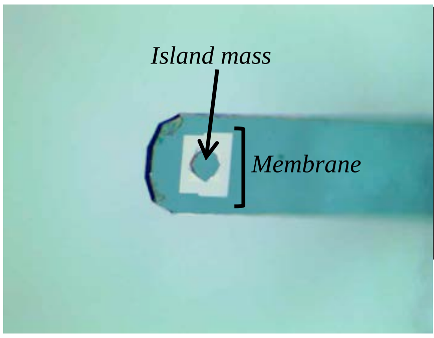

Figure 5: Pictured is an actual sample in our possession that was manufactured by Chao Shiuh's group at National Tsing Hua University. The membrane and island mass are at the end of a long stem to prevent damage during shipping. The island mass has a diameter ~380 microns. The exposed membrane area is ~890 microns, with a thickness of ~100nm. We will glue the entire stem to our fused silica stage using the UV activated epoxy, with minimal losses.

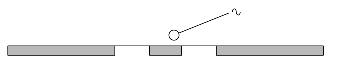

Figure 6: An electrode excites the coated membrane at the desired frequency. We place it off-center from the axis to provide the torque required for higher order modes.

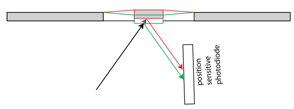

Figure 7: First mode of resonance, and we see how the motion is measured by a laser reflected onto a position sensing photodiode.

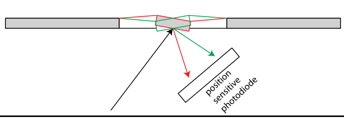

Figure 8: The second resonant (tilt) mode

To reduce the resonant frequency of the membrane, we can have it manufactured where an island of silicon is left in the center. The island's mass will affect the frequency with the usual formula

$$\omega = \sqrt{\frac{k}{m}} \qquad \text{Eq 1}$$

while the width of the membrane around the island determines the effective restoring force constant k.

Considering that the silicon is typically 10,000 times thicker than the SiN membranes, resonant frequency reductions on the order of 100 may be achievable, thus bringing the measurement much closer to the frequency region of interest.

To mitigate the clamping problem the frame will be bonded to a fused silica substrate, which in turn will be clamped in the UHV apparatus, possibly suspended from a vibration isolation stage.

4. Conclusion

The ongoing aspects of research that are underway all complement one another. With the detection of scatterers from in-situ images of LIGO, the Cal State LA LIGO Research Group was motivated to take a more in-depth look at detecting scatterers within samples by means of microscopic imaging. Also, determining if there is a correlation between the number of scatterers within a sample and its determined Q factor has the potential to make a big impact on how we understand the coating materials used on the test mass mirrors. There is the possibility that all these different avenues of complementary research could paint an intricate mosaic, giving us a better understanding of the coating materials that are being utilized. This could potentially help increase the sensitivity and detection rate of GW events, making better astrophysics.

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