Loss Measurements of Waveguide Grating Cantilevers

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Abstract

High mechanical loss coatings make the surface of mirrors a main contributing factor to thermal noise in earth based gravitational wave detectors, limiting their sensitivity. This study investigates the possibility of replacing current coatings with a surface grating to produce similar reflectivity with a lower loss. The first sample was etched to have a reflective grating, the second was etched flat, and the third was created flat without etching. Initial investigations show the losses between the grated and ungrated samples to be comparable, suggesting that the loss associated with these gratings is significantly lower than that of current coatings. Loss measurements for three silicon samples were taken from 11K to 300K. The losses of the etched samples are at least as low as the losses of the control sample in the high temperature ranges, and their losses are comparable at lower temperatures.

INTRODUCTION

Ground-based interferometric gravitational wave detectors are currently one of the leading methods used to search for gravitational waves [1]. They are comprised of two long arms, through which lasers are passed. The lasers are bounced off of suspended mirrors to measure the length of the two arms to extreme degrees of precision. Theoretically, when a gravitational wave passes through the detector, it will stretch space-time in one direction and compress it in the other. Because the gravitational wave would only stretch and compress space-time a very small amount, these detectors need to be extraordinarily sensitive. One of the largest limiting factors for the precision of these detectors is background noise [2].

Ground-based gravitational wave detectors are mainly limited by three types of noise, seismic, thermal, and shot noise [2]. Seismic noise is from movements of the earth and other mechanical noise. Thermal noise is from the internal motion of the test masses, or mirrors, and their suspensions. Shot noise is from the photocurrent and photodiode, which detect the interference pattern at the output. All of these sources of noise are described in more detail in [3]. The three kinds of noise are each prevalent in different parts of the frequency range, as seen in Fig. 1. In the most sensitive frequency range, from a few hundred hertz to approximately ten thousand hertz, thermal noise is the largest problem.

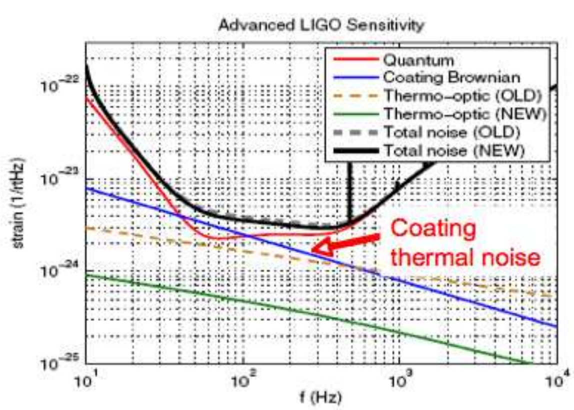

FIG. 1. The graph of the sensitivity of the Advanced LIGO detector due to different types of noise. [4]

There are a number of sources of thermal noise, but one of the most limiting is the high mechanical loss, or internal friction, from the coatings on the mirrors at the ends of the arms of the interferometers. In order to make the mirror material, the bulk of which is usually silica, silicon or sapphire, reflective enough, a reflective coating needs to be added to the front of the mirror. This becomes a problem, because the coatings, which are made of alternating layers of materials with high and low reflective indexes, have an incredibly high mechanical loss. Studies have been done to reduce the loss of these coatings, namely through doping of the coating material [5]. Generally tantala, the coating material, has been doped with titania to produce a coating material with a lower mechanical loss [6]. However, even these doped materials still have fairly high mechanical losses.

A new area of study is being developed to investigate the possibility of replacing the coatings with a waveguide grating pattern etched into the mirror. Bruckner et al.[7] developed samples of triangular grooves etched into tantala on a silicon substrate. These initial grating samples produced a reflectivity of 99.08 percent. While this method does reduce the amount of high loss material, tantala, from approximately $3\mu m$ thick to $0.2\mu m$ thick, it does not eliminate the tantala entirely. Theoretically, these gratings could be etched straight into the bulk material, eliminating the need for a different, high loss material for a coating. Currently, etched gratings have produced a reflectivity that is slightly lower than the coatings currently used in ground-based gravitational wave detectors. However these gratings are just beginning to be developed, and future gratings have a good chance of having a higher reflectivity [8].

One possible method for increasing reflectivity is to create a t-shaped groove in the samples. This idea is being pursued by colleges at the Institute of Applied Physics in Jena but has not yet been satisfactorily manufactured [4]. The t-shaped grooves would allow for total internal reflection, which would possibly lead to a reflectivity as high as those caused by the coatings.

MATERIALS AND METHODS

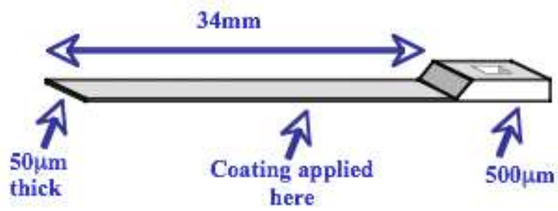

FIG. 2. A of a cantilever that would either have a coating applied or a grating etched into [4].

We investigated the loss of the surface of the mirrors using cantilevers, which are thin strips of the bulk material, as shown in Fig. 2. Because we were using silicon cantilevers and many of the properties of silicon are temperature dependent, we measured the losses from 11K to 300K. We used a cryostat as detailed in Fig. 3 in order to reach the cryogenic temperatures. A laser was mounted at the top of the cryostat and reflected down into the cryostat and off of the cantilever by a mirror held at 45 degrees. The reflected beam was directed towards a photodiode, as shown in Fig. 4.

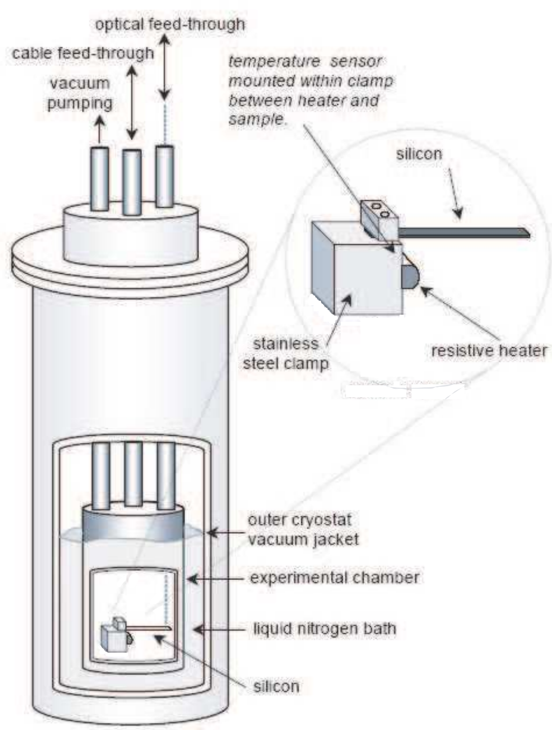

FIG. 3. The schematic of the cryostat setup [9]

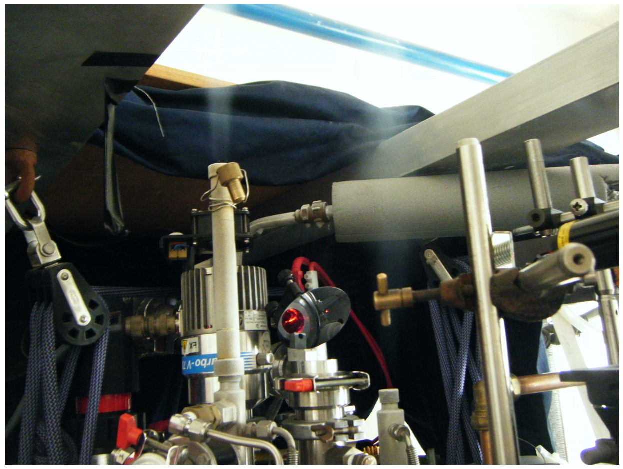

FIG. 4. An image of the laser, mirror, exhaust pipe, and vacuum pump on top of the cryostat setup.

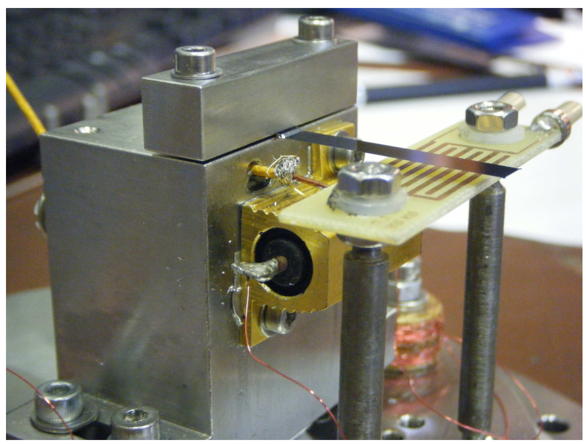

FIG. 5. An image of the silicon cantilever held in the clamp over the excitor plate.

The cantilever was held inside the cryostat by a clamping block, seen in Fig. 5, and was mounted over an excitor plate. When the voltage to the excitor plate was turned on, the function generator could be tuned to resonant modes at different frequencies. A photodiode that was partially covered, as in Fig. 6, collected the reflected laser beam. The exposed area of the photodiode recorded how much light was being reflected onto it. As the cantilever oscillated in each mode, the reflected beam would be moved up and down, allowing more or less of the laser spot to be on the exposed piece of the photodiode. The signal from the photodiode was sent through a spectrum analyzer.

In order to measure the mechanical loss of different modes, we would excite each mode and then let it ring down. When the mode was excited, we would turn off the voltage to the

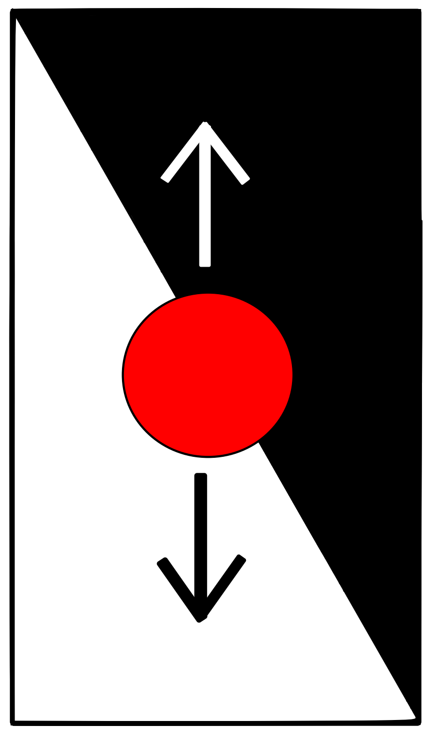

FIG. 6. A schematic of photodiode, showing the partially covered sensor and moving laser beam.

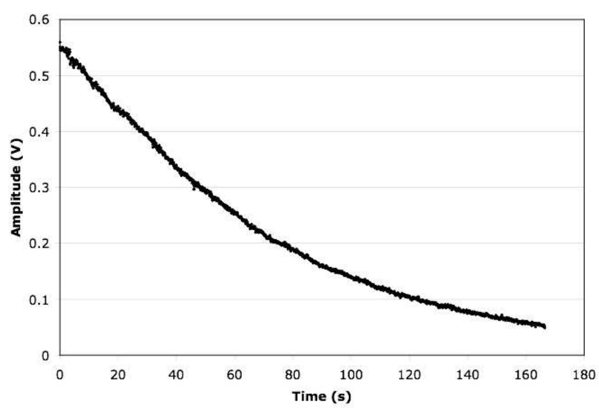

FIG. 7. A representative ringdown pattern. An exponential decay is fit to this pattern in order to determine τ, the characteristic time.

excitor plate. The amplitude of the movement of the cantilever would decrease naturally. A representative ringdown pattern in Fig. 7 shows the characteristic exponential decay pattern. By fitting an exponential decay, as in Eq. 1:

$$A(t) = A_0 e^{\frac{-t}{\tau}} \tag{1}$$

to the ringdown pattern, we were able to find the characteristic time, τ. The characteristic time is related to the mechanical loss of the cantilever as described by the equation:

$$\o = \frac{1}{\pi f \tau} \tag{2}$$

where ø is the mechanical loss, f is the frequency of the mode, and τ is the characteristic time.

Using this method, we examined several samples. First, we took mechanical loss measurements of a grating sample. The first sample was wet etched in order to create rows of grooves perpendicularly across the cantilever. The grating had about a $700nm$ period, and the grooves were about $160nm$ deep. Each groove was about $455nm$ wide with about $235nm$ between them. Figure 8 shows side and top views of the gratings, as imaged with a scanning electron microscope.

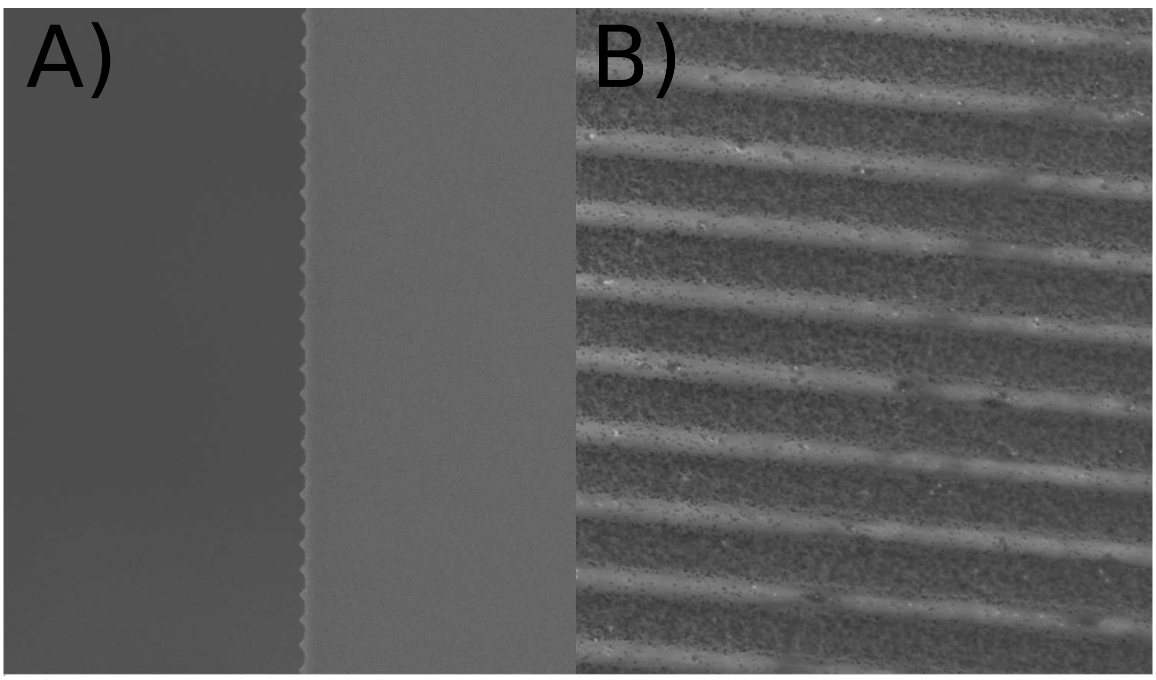

FIG. 8. Images of the grating cantilever taken with a scanning electron microscope. A) A side view of the grating with a depth of approximately $159nm$. B) A top view of the grating showing the period of about $700nm$.

The second sample measured was created through the same process, only the surface was etched to be smooth instead of grated. The third sample was not etched, leaving it in its original state, without a grating. Figure 9 shows the surfaces of the three samples and their surface features.

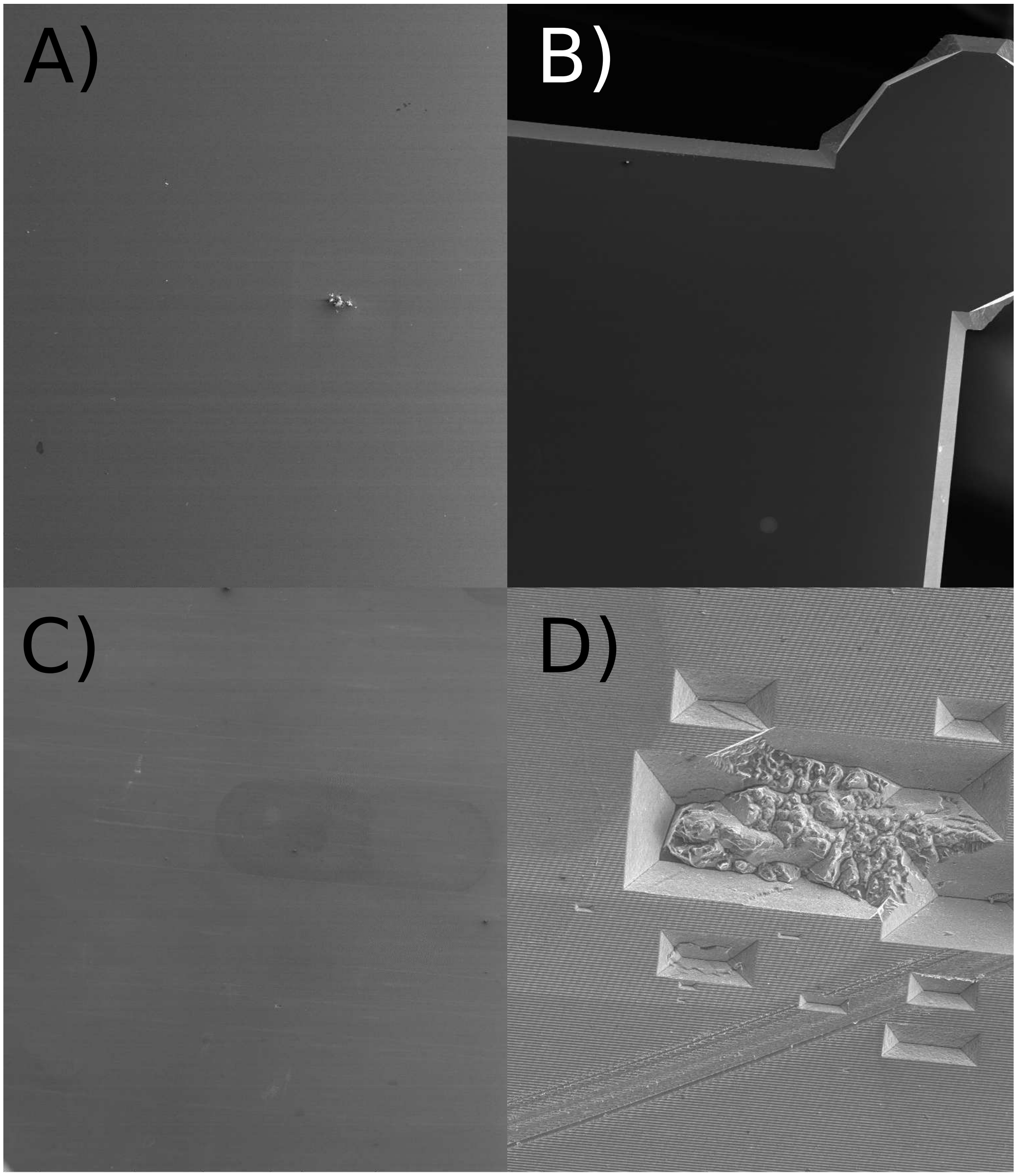

FIG. 9. Scanning Electron Microscope images of the three cantilevers. A) The surface of the second sample, which was the blank, etched cantilever. This sample had very few defects. Note the visible piece of dust as the only apparent defect. B) The surface in the corner of the third sample, which was the control cantilever, also showed few defects. C) The surface of the first sample with the etched grating with oval shaped visible defects. D) A close-up of a defect on the surface of the grating cantilever. This type of defect was not present on the blank or control samples.

It is very apparent that the first sample, with the grating etched into it, had many more defects than either of the other two samples. Figure 10 was taken with an optical microscope in order to get a better image of the defects on the surface of the grating sample. Defects on the surface of the grating sample may be due to the etching process, and hopefully will be reduced with future samples.

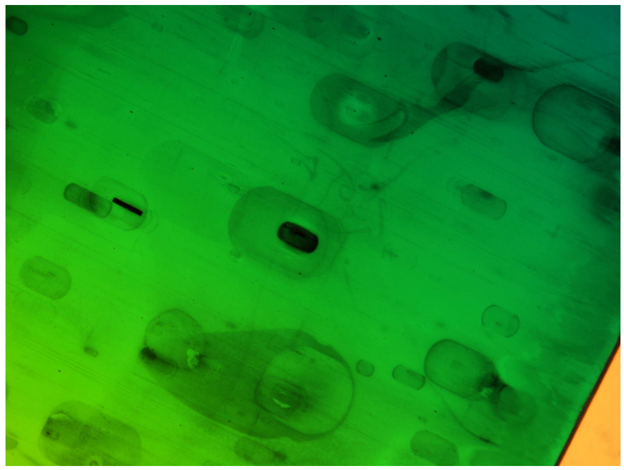

FIG. 10. An image of the first (grating) cantilever surface taken with an optical microscope.

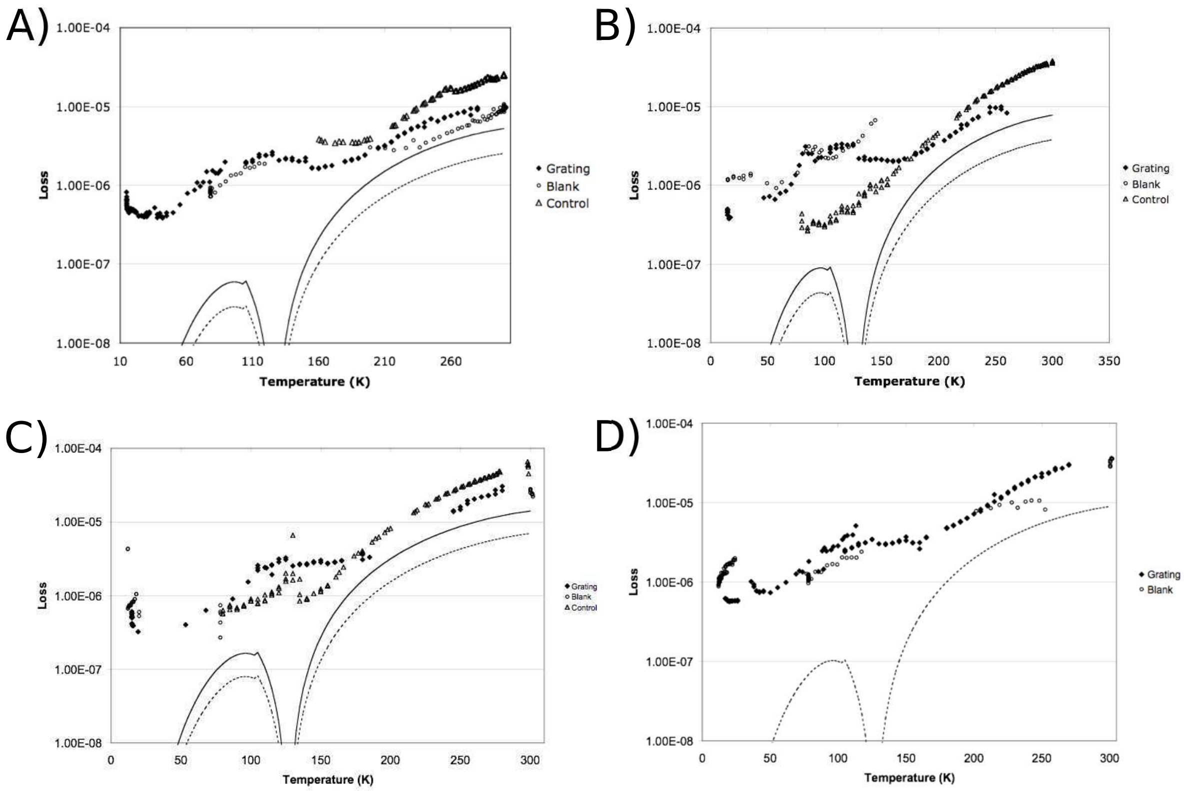

FIG. 11. The losses of the three cantilevers vs temperature. The solid line is the calculated thermoelastic loss for the control sample, and the dotted line is the calculated thermoelastic loss for the two etched samples. A) Mode 4; B) Mode 5; C) Mode 7; D) Mode 8, blank and grating cantilevers and grating thermoelastic loss only.

RESULTS AND DISCUSSION

Although coated samples have higher losses than their uncoated counterparts, etching a waveguide grating into the sample did not increase the loss. Initial mechanical loss measurements of the three samples show an interesting pattern; the grating sample (first sample) has a similar loss to the blank (second) sample. These two samples were also compared to a traditional silicon cantilever, created without any etching. The losses of the two etched samples, blank and with grating, were both lower than that of the unetched sample.

Figure 11 shows the mechanical losses for the three samples across the full temperature range of 11-300K. Four modes are shown with the calculated thermoelastic losses for both the etched and control samples shown. For each sample, the modes appeared at slightly different frequencies, and the frequency of each mode changes with temperature. However, as a point of reference, on the grating sample at room temperature, the fourth, fifth, seventh, and eighth modes, which are shown in Fig. 11, were found at 3218Hz, 4806Hz, 8934Hz, and 11472Hz respectively. For the grating sample at 14K, the modes were found to be at 3234Hz, 4830Hz, 8979Hz, and 11528Hz for the same modes.

While the lower loss of the etched cantilevers may be due in part to the etching process, another factor that may affect their losses is their thicknesses. The unetched cantilever is slightly thicker than the etched cantilevers (blank and grating cantilevers = 50mm, unetched cantilever = 64mm). The thickness of the cantilever is correlated to the thermoelastic loss, which means that as thickness increases the thermoelastic loss increases. This can be seen in Fig. 11, which shows the losses for the three samples as well as their calculated thermoelastic losses.

The equation for calculating the thickness of the cantilever is:

$$t = \frac{\omega_n}{(k_n L)^2}(2\sqrt(3)l^2)(\frac{\rho}{Y})^{\frac{1}{2}} \tag{3}$$

where t is the thickness of the sample, ω_n is the frequency of the nth mode, $k_n L$ depends on n and l is the length of the cantilever. ρ is the density and Y is the Youngs modulus of silicon.

Using that calculated thickness, the thermoelastic loss was calculated using the equation:

$$\o_t(\omega) = \frac{Y\alpha^2 T}{\rho C}\frac{\omega_n \tau_t}{1+\omega^2\tau_t^2} \tag{4}$$

where $\o_t(\omega)$ is the thermoelastic loss, α is the thermal expansion coefficient, T is the temperature in Kelvin, C is the specific heat capacity and the other variables are as defined above. τ_t is defined as follows:

$$\tau_t = \frac{\rho C t^2}{\pi^2 \kappa} \tag{5}$$

where κ is the thermal conductivity of the material and the other variables are again as defined above. Thermoelastic loss dominates the thermal noise at the higher temperature ranges, as can be seen in Fig. 11 by the dramatic increase in the calculated thermoelastic losses above approximately 130K. Because thermoelastic loss is the largest introduction of noise at higher temperatures, it is helpful to look at lower temperatures when investigating surface noise.

Nawrodt et. al. [10] describe how below 50K, the losses are relatively constant. Below 50K, the thermal loss is dominated by the loss of the surface material, which has previously

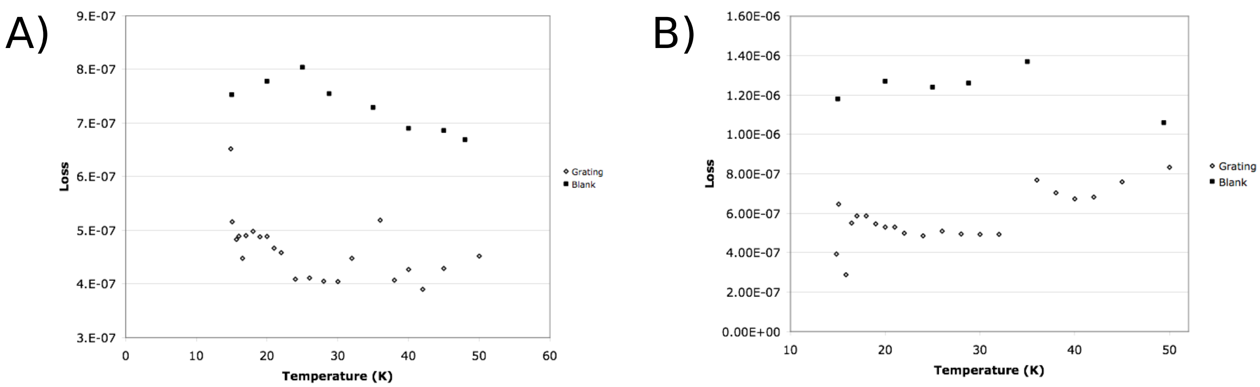

FIG. 12. Low temperature loss measurements for A) mode 4 and B) mode 5 for both the grating and blank etched samples.

been made up of high loss coatings. By investigating this temperature range closely, we believed we would have be best chance of seeing any effect of the waveguide grating on the loss. Figure 12 shows the losses for the fourth and fifth bending modes at temperatures below 50K. As Fig. 12 shows, our losses for the grating sample were consistently lower than those of the blank samples. This difference may need to be investigated further since it may be within our uncertainty range. Mode 4 of the grating sample at low temperatures gave a loss of less than 5×10^{-7} whereas the blank sample gave a loss of over 7×10^{-7}. Mode 5 had slightly higher losses, but still the loss of the grating sample was lower than that of the blank sample. For this mode, the grating gave a loss of about 6×10^{-7} while the loss of the blank sample was around 1.2×10^{-6}.

We were able to measure the losses of the control sample down to 80K, and temperatures below that are still being measured. However, in the full temperature range graphs in Fig. 11, we see that the control sample has significantly higher losses than the other two cantilevers at high temperatures and has similar losses at the middle of the temperature range.

One factor that may affect loss is the surface area. Previously in coating research, there was no need to take this into account, as the coating would cover the same surface area as the original sample. However, with etching these gratings into the cantilever, the surface area is increased. Using the measurements of the cantilever and information about the structure of the grating collected from the scanning electron microscope images, we were able to calculate the difference in surface area from the blank sample to the grating sample. The surface area of the blank sample is $175mm^2$. The surface area of the grating sample, with measurements as described previously, is $175.081 mm^2$. The original design for the gratings would have increased the surface area to $175.75 mm^2$. However, there was a problem with the fabrication of the grating, and the result was a shallower grating pattern than intended.

Because there was not a large increase in surface area, the difference in losses between the grating and blank etched samples is not thought to be affected by the surface area. However, the surface area was only increased by a very small portion. Because the increase was so small, it is possible that any effect of the increased surface area could be masked by the uncertainty in the measurements in this study.

CONCLUSION

The mechanical loss of the grating sample is close to that of the blank etched sample and similar to or possibly lower than that of the unetched sample. Because the reflective coating usually increases the loss by quite a noticeable amount, this research suggests that waveguide gratings are a promising new development in reducing the thermal noise of gravitational wave detectors.

FUTURE WORK

Further research should be done to investigate the effect of a significantly increased surface area on the reflective surface through the decrease of the period of the grating and an increase in the depth of the grating. This will require research into improved etching techniques. An important step in surface loss research will be determining if there is an effect from the surface area increase that was hidden in our research. Future research should also concentrate on temperatures below 50K, where the thermal noise is dominated by the surface loss.

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