LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

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Coating Research Whitepaper

Gregory Harry, Ed.

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California Institute of Technology
LIGO Project - MS 18-34
1200 E. California Blvd.
Pasadena, CA 91125
Phone (626) 395-2129
Fax (626) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Project - NW17-161
175 Albany St
Cambridge, MA 02139
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

LIGO Hanford Observatory
P.O. Box 1970
Mail Stop S9-02
Richland WA 99352
Phone 509-372-8106
Fax 509-372-8137

LIGO Livingston Observatory
P.O. Box 940
Livingston, LA 70754
Phone 225-686-3100
Fax 225-686-7189

http://www.ligo.caltech.edu/

The optical coatings on the core optics are a crucial component of the advanced LIGO design. The thermal noise from the coatings will likely be the limiting noise source in the most sensitive frequency band, and the optical absorption will be the dominant heating mechanism for the thermal compensation system. Beyond this, the scatter and reflectivity must meet strict specifications while the engineering challenge of coating mirrors 40 kg in mass and nearly 35 cm in diameter is taxing. The LIGO Science Collaboration is involved in an ongoing research effort to develop coatings suitable for advanced LIGO and future interferometers.

I. Current Status

Ia. Silica/Tantala Coatings

The first goal has been to understand the silica/tantala coatings that are being used in initial LIGO; to determine if they would be suitable for advanced LIGO, and if not, what parameters would need to be improved. It was found that the mechanical loss and hence the thermal noise of these coatings would be unacceptable, that the loss comes from internal friction in the coating materials as opposed to friction between layers or between the coating and the substrate, and that the internal friction of the tantala was the dominant contributor to this loss. Evidence for frequency dependence of the loss angle of both the silica and the tantala was also found. This frequency dependence is in LIGO's favor, with the loss angle and hence thermal noise better at 100 Hz than the kilohertz band where laboratory measurements of mechanical loss are typically made. There is some evidence of the internal friction depending on which vendor supplied the coating, but the range of observed loss angles is not large, from 2.7 10^{-4} to 4.1 10^{-4}, with an outlier at 5.2 10^{-4}. The thermal noise from silica/tantala coatings has been directly observed, and the scale of the loss angle confirmed, by direct measurements at the Thermal Noise Interferometer at Caltech and by a similar instrument in Japan. The Caltech measurement showed results consistent with a coating loss angle ϕ of 4 10^{-4}. The Young's modulus, which is also important for thermal noise calculations, has been measured with an acoustic reflection technique. A value of 8.6 10^{10} Pa was found for the silica/tantala coating.

The dependence of the silica/tantala loss angle on a variety of sample and deposition parameters has been tested. Some samples were coated with a secondary beam of oxygen ions directed at the sample in addition to the usual argon beam aimed at the coating material targets. This was done with two separate masks; one which concentrated the ions the other spread them out more. The additional oxygen ions increased the ratio of oxygen in the coating, improving the stoichiometry. The ϕ was better for the second mask, but both masks gave coating coating ϕ's higher than usual, about 4.1 10^{-4} and 3.2 10^{-4}. A coating with intentionally reduced oxygen in the tantala has also been measured, for comparison. The ϕ was measured before annealing, for fear annealing would introduce additional oxygen ions, and found to be very poor, about 5.2 10^{-4}. It is currently being annealed in a non-oxidizing environment and will be remeasured. Changes in silica/tantala ϕ with the polish level of the substrate have also been explored. The coating ϕ on a commercially polished silica substrate was very similar to that on a superpolished substrate, 3.3 10^{-4} compared to 3.4 10^{-4}. The effect of the ion used to release coating material from its target has also been studied. Most coatings use argon ions, so a coating was produced using the heavier xenon. The xenon-bombarded coating showed slightly worse ϕ than the argon coatings, about 4.0 10^{-4}.

The optical absorption and scatter of silica/tantala coatings has been studied in detail, both on laboratory test samples and on the initial LIGO optics. Laboratory samples show absorption starting around 1.7 ppm for samples annealed at 250 C and decreasing in absorption with increasing annealing temperature down to 0.4 ppm at a temperature of 500 C. Initial LIGO optics *in situ* have typically been seen to have absorptions of a few ppm, with two outliers as high as 30 ppm. In laboratory measurements, 2 ppm or less is typical for initial LIGO witness optics with a low value of 0.5 ppm. The outliers may be due more to cleanliness and handling, rather than intrinsic properties of the coatings. Similar results are seen with scatter, with *in situ* numbers typically around 70 ppm, but laboratory results more like 20-40 ppm.

Coating	Vendor	Loss Angle ϕ
SiO_2/Ta_2O_5	LMA/Virgo	2.7 10^{-4}
SiO_2/Ta_2O_5	CSIRO	3.4 10^{-4}
SiO_2/Ta_2O_5	REO	5.2 10^{-4}
SiO_2/Ta_2O_5 – O_2 SIBB 1	CSIRO	4.1 10^{-4}
SiO_2/Ta_2O_5 – O_2 SIBB 2	CSIRO	3.2 10^{-4}
SiO_2/Ta_2O_5 - Comm. Polish	CSIRO	3.3 10^{-4}
SiO_2/Ta_2O_5 – Xenon ions	CSIRO	4.0 10^{-4}
SiO_2/TiO_2 doped Ta_2O_5	LMA/Virgo	1.5 10^{-4}
Al_2O_3	MLD	2.3 10^{-4}
SiO_2	LMA/Virgo	0.9 10^{-4}
Ta_2O_5	LMA/Virgo	4.3 10^{-4}
Nb_2O_5	MLD	6.0 10^{-4}

Table 1. Mechanical loss angles of coatings and materials found from modal Q measurements. SIBB – Secondary Ion Beam Bombardment.

Ib. Silica/Titania-doped Tantala Coatings

The most successful modification of the basic silica/tantala coating to date has been the addition of titania ions as a dopant to the tantala. Any amount of titania reduces the mechanical loss in the coating by almost of factor of 2, from 2.7 10^{-4} to about 1.5 10^{-4}. The exact concentrations of titania are still be measured, but rough estimates indicate similar ϕ's from a few percent up to about fifty percent. The titania-doped coatings done at the large coater at LMA/Virgo show a slight trend for higher ϕ's than those done in the small coater. It is not clear if this is significant, or what the cause might be. There is evidence of frequency dependence in the ϕ similar to what is seen in the undoped coatings, with improving ϕ towards lower frequencies.

Optical absorption of titania-doped tantala coatings is higher than without the dopant, between about one and two ppm with the dopant. There is some disagreement between absorption measurements made at Stanford and LMA/Virgo, but in all cases it is above 0.5 ppm. It is possible that this could be brought down with further optimization of the coating process.

Coating	Annealing Temperature	Optical Absorption
SiO_2/Ta_2O_5	250 C	1.65 ppm
	300 C	1.15 ppm
	350 C	0.70 ppm
	400 C	0.65 ppm
	450 C	0.43 ppm
	500 C	0.40 ppm
Al_2O_5/Ta_2O_5	300 C	2.67 ppm
	350 C	1.41 ppm
	400 C	1.13 ppm
Nb_2O_5/SiO_2	300 C	1.17 ppm
	350 C	0.76 ppm
	400 C	0.40 ppm
ZrO_2/SiO_2	300 C	21.7 ppm
	350 C	19.2 ppm
	400 C	11.6 ppm

Table 2. Optical absorption of various coatings annealed to different peak temperatures. All coatings were produced by MLD.

Ic. Coatings with other materials

Some materials other than tantala, silica, and titania-doped tantala have been explored. Alumina has been measured as an alternate low index material. It has been found to have higher mechanical loss than silica, about 2.3 10^{-4} for alumina compared to 0.9 10^{-4} for silica, and 4.3 10^{-4} for tantala. Optical absorption for alumina/tantala coatings has been seen to higher than for silica/tantala. The absorption also improves with higher annealing temperature, from above 3 ppm at 300 C down to about 1.1 ppm at 400 C. Niobia was explored as an alternate high index material. It was found to have a ϕ of 6 10^{-4}, but with a slightly higher index of refraction which would require fewer, thinner layers for the same reflectivity. The net thermal noise effect would still be worse than using tantala. The optical absorption of niobia/silica coatings was found to be good, from 1.2 ppm at an annealing temperature of 300 C down to 0.4 ppm at 400 C. Zirconia was also measured for optical absorption as an alternate high index material, but it was found to be unacceptably high, between 11 ppm and 22 ppm depending on annealing temperature. Hafnia has begun to be explored as a high index material, but initial attempts to coat substrates were unsuccessful. Cobalt has also been tried as an alternate dopant into tantala, but the resulting material proved to be unstable so no ϕ or optical absorption results were obtained.

Id. Other issues

An analytical model of thermal noise has been developed for mirrors infinite in extent. There is also an analytical correction for finite mirrors if the mechanical loss is homogeneous throughout. Current thermal noise projects are made with a combination of these two models. These models show that thermal noise depends on the match in Young's modulus between the coating and the substrate and the laser spot size in addition to the coating material loss angle, ϕ. There are also finite-element models that give numerical estimates of thermal noise that show good agreement with the analytical expression, especially for small spot sizes compared to the radius of the mirror. An argument has been presented that shows the effect of Mexican hat mirrors on coating thermal noise should be similar in size to Mexican hat mirrors on substrate thermoelastic noise.

Thermoelastic damping between the coating and substrate has also been understood theoretically. For most combinations of coating and substrate, this is a small but noticeable addition to the material ϕ. The effect of this thermoelastic damping has been subtracted off from ϕ's inferred from modal Q measurements. For silica substrates, most coatings using silica as the low index material should avoid problematic levels of thermoelastic damping, but candidates for the advanced LIGO coating will have to be carefully examined to make sure thermoelastic damping is not troublesome.

Organizationally, the coating research is currently done with two coating vendors; LMA/Virgo in Lyon, France and CSIRO in Australia. Prior coating research has also been done with coating vendors REO in Boulder, Colorado and MLD in Oregon. There has been some collaboration on coating research between the LSC and outside groups, notably with LMA/Virgo (acting in a different role than coating vendor) and groups in Italy and Japan.

II. Future Plans

IIa. Modifications of tantala

Since tantala is acceptable from an optical absorption perspective, is the dominant source of mechanical loss in tantala/silica coatings, and has shown improvements in loss from modifications (titania doping), further modifications to tantala will be a focus for future work. Annealing is known to effect mechanical loss in bulk silica, so attempts to improve loss in tantala through annealing will be pursued. We are already in possession of three pure tantala coatings; one annealed at 270 C from an initial stress of 70 MPa compressive to 60 Mpa tensile, one annealed at 400 C to 220 MPa tensile, and one unannealed. If results with these samples prove promising, a more systematic test of annealing could be pursued. Annealing in an ozone environment, with the goal of increasing the oxygen content, would also be a possibility, although the results of the bombardment with a secondary ion beam of oxygen are not encouraging that this will result in improvements in mechanical loss. The sample with low oxygen content will be measured once it is annealed in a low oxygen environment. Annealing in a helium environment is known to increase strength in silica fibers; it may provide some benefit for mechanical loss as well. Using helium ions rather than argon as the target bombardment ion may be pursued as well, since the mechanical loss was seen to get worse when using the more massive xenon; a lighter ion could show benefits.

Additional dopants, beyond the titania and the failed cobalt will also be pursued. Lutetium has been suggested as having the correct ionic size to fit in the tantala amorphous structure. Other rare earths may also be promising. It may be possible to experiment with these exotic materials without obtaining coating targets, simply by having samples of the material placed above the tantala target. Having multiple dopants, with or without titania, simultaneously in the tantala is another idea that will be explored. It is possible that cobalt doped tantala could be stabilized by the addition of another dopant, so it may be revisited.

Since the thermal noise from the coating scales with the amount of tantala, coating designs that obtain the desired reflectivity with less tantala will also be explored. Using known optical techniques or other algorithms (including genetic ones), the thickness of tantala can be reduced. It has already been shown that a reduction of about 20 percent is feasible, and more may be possible. These reduction techniques will almost certainly be used in addition to any material improvements that are made.

IIb. Other materials

Materials beyond those already measured will be explored for possible improvements in thermal noise performance. Titania is known to be unstable when pure, but with the addition of a dopant, possibly silica, it may be suitable for measurements. Hafnia may also be able to be stabilized with dopants, possibly rare earth elements. Nitrides, as opposed to the usual oxides, have also been suggested. These materials will be evaluated for optical and thermal properties, in addition to the mechanical one important for thermal noise performance.

IIc. Optical measurements

Coating research has focused on mechanical loss as one of the most important and least understood of coating properties. As thermal noise behavior is improved, research emphasis will shift to verifying and (as necessary) improving the optical parameters of the coatings. A cross-over project will be to look for any correlations between optical absorption and/or index of refraction with mechanical loss. Whatever materials end up being used for the coating, but especially if the titania-doped tantala remains the preferred high index material, effort will likely have to go into reducing the optical absorption. Whether this can be done without increasing the mechanical loss is unknown and may lead to some difficult trade studies and decisions. Determining how close to 50/50 the beamsplitter needs to be and can be made may also be an important project.

Scatter is a known problem in initial LIGO optics. Understanding the reason for this and for the anomalously high optical absorption in two installed optics at Hanford is important so the same problems are kept from arising in advanced LIGO. If it turns out to be a materials problem, research will have to be initiated to find a solution. Once a coating with acceptable thermal noise and optical absorption properties for advanced LIGO is found, its scatter will have to be measured and evaluated. Further research could be necessary to solve any problems.

Handling the high cavity power planned in advanced LIGO could prove a challenge for coatings. One possible reason for absorption problems with installed initial LIGO optics is some material changes due to lengthy exposure to laser light. If this is found to be the case, research will be needed to avoid this problem in advanced LIGO. Silica/tantala coatings are known to break down at about 5 MW/cm^2. This is well above the expected 10 kW/cm^2 in the advanced LIGO Fabry-Perot cavities. However, titania-doped tantala/silica coatings have been observed to be more sensitive to power density than non-doped tantala/silica ones. Plans are in place to test coatings at the Gingin high power test facility. In addition to *in situ* measurements, smaller scale benchtop measurements are needed to more accurately characterize the damage threshold and long term surface physical and chemical effects of high laser powers and intensities in controlled environments. These experiments are particularly relevant to the mode cleaner, which will see the highest powers and intensities in Advanced LIGO.

Meeting the challenges of the advanced LIGO thermal compensation system will be an important objective for coating research. The 0.5 ppm goal for optical absorption should be sufficient for normal operation of a similar thermal compensation system as used in initial LIGO. The thermal compensation system in use on initial LIGO has had success with similar levels of absorbed power as expected in advanced LIGO. It may be desirable, however, to use ring heater rather than CO_2 lasers because amplitude noise in the lasers could contribute significant noise through radiation pressure. If there is high inhomogeneity in the absorption across the face of the coating, it could necessitate using a scanning CO_2 laser system. Developing a reasonable specification for inhomogeneous absorption then researching a coating to meet it will be a major goal for the coating program. There may be merit in developing a coating, likely for use on the AR side of ITMs, which has absorption with a radial dependence, with higher absorption in the center. This would even out the absorbed power and reduce the amount of laser power needed for compensation. This would impose a centering requirement on the beam and might require complete redesign of the ring heater compensation system. Modeling will be the first step to see if this approach is feasible. It may also be desirable to have an on-axis sensing beam to monitor the thermal lens. This beam should be of a different wavelength than the main sensing, which would require the coating on the compensated optic to be reflective at more than one wavelength.

IId. Other issues

Direct verification of thermal noise from the Thermal Noise Interferometer is an important component of the coating program. Preliminary measurements of thermal noise from titania-doped tantala/silica mirrors have already begun. It will be very valuable to test any coating chosen as a candidate for advanced LIGO first in the TNI to verify it has the thermal noise expected. It should also be possible to fit existing and future TNI data with a frequency dependant model for the coating ϕ, both as a test of results from Q measuring and to determine if any significant difference in thermal noise is to be expected in the frequency band around 100 Hz. Further modeling of the expected thermal noise from coatings will also be pursued. A full theory that incorporates coating loss with finite-sized mirrors is needed. A full model of coating thermal noise from Mexican hat mirrors is also lacking, which needs to be developed.

Greater understanding and insight into the microscopic causes of coating mechanical loss needs to be gained. There is a theory that explains loss in bulk silica that has successfully been applied to the LIGO case. It is unknown if this mechanism, or a similar one, can be used for other amorphous materials. Measuring the mechanical loss as a function of temperature can be an important tool for understanding loss mechanisms. There are data from TAMA that shows the ϕ of tantala/silica coatings remains the same for temperatures below room temperature, down to near 77 K. Preliminary work has begun to measure tantala/silica mechanical loss at elevated temperature, up to about 30 K above room temperature. This is a practical measurement, as well, since optical absorption in advanced LIGO will cause the equilibrium temperature of the mirrors to be elevated by about this amount. Direct measurements of coating composition and structure will also be pursued. This has begun by measuring more accurately the titania concentration in the doped tantala coatings and will be followed up by impurity and structural studies.

There are some decisions that need to be made of an organizational nature about the coating research. Foremost among these is how many coating vendors are needed to continue this research. Both LMA/Virgo and CSIRO have contributed coatings and results to the research effort. Financial considerations may force a rethinking of whether this remains the best model after the current contracts expire in a few months. It is also possible that the nature of our relationship with the coaters could change, from the current vendor model to a more collaborative one. This will also be a financial decision, but also dependant on larger issues of the relationships between LIGO, Virgo, and ACIGA. Finally, there may be opportunities to increase the amount of person power available to the coating research effort, both within the LSC and by working more closely with others outside.