



LIGO Laboratory / LIGO Scientific Collaboration

LIGO-T030233-00-D

9/29/2003

Requirements and Testing of Advanced LIGO Coated Optics

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Distribution of this document:
LIGO Science Collaboration

This is an internal working note
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1. Introduction

LIGO is a basic physics experiment designed to detect gravitational radiation from astronomical sources as predicted in Einstein's theory of general relativity. The effect of these gravitational waves on Earth is extremely small (changes of length of 1 part in 10^{21}), so reducing noise in the detector is the primary design concern. The detector consists of an "L" shaped interferometer, where an IR laser is split into two beams at a beamsplitter, then sent into a 4 km long Fabry-Perot cavity in each arm. Thermally excited vibrations in the optics, and most importantly in the dielectric coatings on the optics, are a limiting noise source. Coating absorption is also a particular concern in the optics of Advanced LIGO because of thermal distortion on the mirror's surface from the high stored power.

The optics referred to as Core Optic Components and which comprise the LIGO interferometer are: one recycling mirror (RM), one beamsplitter (BS), two input test masses (ITM's) and two end masses (ETM's). The Test Masses, ETM's and ITM's, have the most stringent coating requirements as seen on Table 1 below. Two different substrate materials are under consideration for the test masses, fused silica and sapphire.

2. Coating Parameters

Table 1: Test Mass Coating Parameters, Goals and Requirements

Parameter	Sapphire goal	Sapphire requirement	Fused Silica goal	Fused Silica requirement
Mechanical loss	2×10^{-5}	6×10^{-5}	1×10^{-5}	3×10^{-5}
Thermal expansion	$5 \times 10^{-6}/K$	$< 2 \times 10^{-5}/K$ $> 1 \times 10^{-6}/K$	$5 \times 10^{-7}/K$	$< 2 \times 10^{-6}/K$ $> 1 \times 10^{-7}/K$
Birefringence	1×10^{-4} rad	2×10^{-4} rad	-	-
Thickness uniformity ⁵	10^{-3} (over 21.5 cm diameter) 10^{-2} (over 33.0 cm diameter)	10^{-3} (over 21.5 cm diameter) 10^{-2} (over 30.0 cm diameter)	10^{-3} (over 21.5 cm diameter) 10^{-2} (over 33.0 cm diameter)	10^{-3} (over 21.5 cm diameter) 10^{-2} (over 30.0 cm diameter)
Optical Absorption	0.5 ppm	1 ppm	0.2 ppm	0.5 ppm
Scatter	1 ppm	2 ppm	1 ppm	2 ppm
ITM HR transmission	-	5×10^{-3} $\pm 2.5 \times 10^{-4}$	-	5×10^{-3} $\pm 2.5 \times 10^{-4}$
ETM HR transmission	5 ppm	10 ppm	5 ppm	10 ppm
Test Mass HR matching $2(T_1 - T_2)/(T_1 + T_2)$	5×10^{-3}	1×10^{-2}	5×10^{-3}	1×10^{-2}
AR reflectivity	-	200 ± 20 ppm	-	200 ± 20 ppm

3. Coating properties to be addressed during the Coating Development Program

- **Mechanical loss**

Coating thermal noise comes from a relatively complex interaction of coating mechanical loss, thickness, Young's modulus, thermal expansion, and thermal diffusivity, as well as substrate Young's modulus, thermal expansion, and thermal diffusivity.

Coatings exhibiting low thermal noise for advanced LIGO optics are to be achieved during the Coating Development Program. After the coating materials, coating processes, and coating designs are identified and deemed appropriate for LIGO Core Optics, they will become part of the Coating Specifications.

The mechanical loss of the coating will be inferred from Q measurements and finite element modeling. We will measure the mechanical quality factors of small coated samples of two different thicknesses, 2.5 cm and 0.25 cm. In each case, the sample is suspended beneath a rigid structure by a pendulum. Internal modes of the sample are excited using an electrostatic comb capacitor. The ringdown of these modes is monitored by either interferometry or ellipsometry. The longer the exponential decay time, the lower the mechanical loss. There are Q measuring setups for coating work at MIT, Hobart and William Smith, Stanford, and Glasgow. Modeling will tell us how much of the mechanical loss is due to the coating, as opposed to the substrate.

- **Young's modulus**

Predicting thermal noise also requires knowledge of the Young's modulus of the coating. This will be measured using an acoustic reflection technique being developed at Stanford. The coated sample is immersed in water. The amplitude of acoustic waves reflected off the sample are monitored. This gives the impedance of the sample, which is a function of density and Young's modulus.

- **Thermal expansion and diffusivity**

Knowing the mechanical loss and Young's modulus of the coating allows the Brownian thermal noise to be predicted from a straightforward formula. Knowing thermoelastic noise from the coating requires knowledge of the thermal expansion and diffusivity coefficients for the coating. Thermal expansion will be measured at Caltech by using an optic heater around one mirror of an interferometer. As the optic is heated, the expansion is measured by the interferometer and allows the thermal expansion to be inferred.

In a separate experiment at Caltech, the thermal expansion and thermal diffusivity coefficients will be measured using photothermal displacement spectroscopy. In this technique, two laser beams are directed on a sample: one to periodically heat, or "pump" the sample, the other to interferometrically measure, or "probe" the resulting thermal expansion. The thermal waves driven by the pump beam have a characteristic penetration depth that depends on frequency (falling off as $1/\sqrt{f}$), so at different frequencies structures at different depths in the sample are probed. At low frequencies the thermal properties of the substrate are probed, and at higher frequencies the coating properties are measured. The thermal expansion coefficient is determined by the amplitude of the

photothermal (for the substrate at low frequencies, for the coating at high frequencies), and the positions of two characteristic "knees" in the frequency dependence determine the thermal conductivities of the substrate and coating.

- **Absorption**

Coating absorption will be measured by photothermal common-path interferometry. The system is under development at Caltech while a working setup is in use at Stanford.

The apparatus consists of a 1.06 micrometer pump laser used to heat the sample under test. A chopper wheel modulates the laser intensity. A probe laser of spot size ~2 mm is directed through the sample, crossing the pump laser beam at an angle of ~10 degree. The sample heating causes a distortion to appear in the optical path of the probe. The distortion is projected to a photo detector. The intensity of the photo detector's signal is converted to a dc signal by a lock-in amplifier, which is proportional to the sample absorption. This technique is capable of measuring absorption below 0.5 ppm.

Table 2 shows the organizations and people involved in the characterization of coating properties during the Coating Development Program.

Table 2: Coating Development Program – Involved Organizations and Personnel

<i>Measurement</i>	<i>Location/Lead</i>	<i>Milestones</i>
Q	MIT - Harry (thin) HWS – Penn (thin) Glasgow – Rowan (thick)	pick candidate coating 9/04 final choice of coating 6/05 TMs coated 11/05
Young's modulus	Stanford - ?	?
Thermal expansion	Caltech - Billingsley - Black MSU - Braginsky	First measurements at Caltech 8/03 Single layer measurements 12/03 MSU results sub to Phys. Lett. A, gr-qc/0304100
Thermal conductivity	Caltech - Black	Single layer measurements 12/03
Absorption	Stanford – Route Caltech - ?	finish second round of R&D 9/04
Scatter	Caltech - Billingsley	?
Transmission/ Reflectivity	Caltech - Billingsley	?

4. Coating characterization to be performed on all Advanced LIGO Core Optic Components (COC's)

A. Optical Absorption

Coating absorption needs to be minimized in LIGO core optics because of the high stored power in the advanced LIGO interferometer. Absorption, as heat source, will create a thermal distortion on the mirror's surface profile compromising the beam integrity that is transmitted through the ITM's. Thermal compensation is also being investigated to control thermal distortion in the ITM's

Coating absorption on COC's will be measured by the same technique as used during the development program. The system can scan the entire optic's surface. Initially, measurements will be taken this way until we gain enough confidence to decide that spot checking the surface is sufficient.

B. Transmission

The transmission of the ITM's is currently specified at 0.5% (+/- 0.05%). The ITM pairs are to be matched at 1%.

Transmission of HR surfaces on COC's will be tested with the existing equipment at Caltech. In this set-up, the light from an NPRO laser is chopped and sent to a beamsplitter. One beam segment is directed to a power meter to monitor the laser stability; the other beam goes through the mirror being tested and to a photo detector. Both signals go to a lock-in amplifier. An initial measurement is taken of the laser beam intensity with out the mirror intercepting the beam. The mirror transmission is the result of these two beams' intensities difference.

The system has scanning capabilities. If spot checks on the surface show a uniform transmission no scanning will be required. This test will also serve to assess coating uniformity.

C. AR Reflectivity

For pick-off beams, the AR reflectivity on some core optics is an important parameter. AR reflectivity will be checked with the same set-up used to check transmission, reading the intensity of the reflected beam instead of the transmitted beam. If spot checks across the surface deliver uniform readings no scanning should be required.

D. Scatter

There are two components for large angle scatter from an optic's surface. One comes from the microroughness of the polished surface and the other comes from coating defects.

The set-up presently available at Caltech gives a measure of estimated scatter. Modifications to the existing system or a new set-up will be required if bidirectional reflectance distribution function measurements are required. On the present system a

NPRO laser beam is chopped and brought normally incident to the mirror under test. Six scatter detectors collect the reflected beam spot at 45 degrees. The summed detector output is measured with a lock-in amplifier.

Scatter will also be characterized visually under a dark field microscope. The optic's surface will be mapped to correlate visual observations with scatterometer measurements.