LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

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COC Subsystem
Development Plan

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1 Overview

The purpose of this document is to outline the design and fabrication approach that will produce Core Optics Components (COC) that support the design goals of the Advanced LIGO interferometer.

1.1 Applicable Documents

LIGO-T000127 Core Optics Components Design Requirements Document

LIGO-T000098 Core Optics Components Reference Design Document

LIGO-E000487 Advanced LIGO Coating Program and Specification

2 Research and Development

The purpose of the research and development phase is to investigate the possibility of reasonably producing optics that will not limit the performance of an Advanced LIGO interferometer. We must have results from the research and development phase in time to impact the selection of test mass material and final design in the second quarter of 2002. The two areas of interferometer performance which can be most affected by the test mass optics are thermal noise and shot noise.

Sapphire has been chosen as a baseline test mass material in order to reduce thermal noise of the system. The remaining COC are to be made of fused silica. The primary concerns, which must be addressed in this scenario, are the absorption, birefringence and homogeneity of the sapphire. To this end, there will be a development program aimed at bringing sapphire growth and processing to the point where this material can be used to increase the sensitivity of the LIGO interferometers. This program will continue until the choice test mass material is finalized in the second quarter of 2002. Fused silica is the fall back choice in the event that sapphire is not selected as the test mass material.

2.1 Modeling

The predictions of advanced LIGO sensitivity are based on analytical models. These models are the best tools we have for understanding the optical properties that are required to obtain maximum detector sensitivity. The models use a description of the properties of the COC that we believe are attainable using reasonable production methods. The research outlined here will be used iteratively with the models to provide the best possible final optical design.

2.2 Material Properties

The test mass material development effort will be lead by Caltech and supported by work at Stanford and Southern. These efforts are also coordinated with the mechanical characterization efforts of the suspension group.

2.2.1 Absorption

The LIGO group is working with two potential sapphire vendors to reduce absorption as well as provide a material with good optical properties. The two avenues to be explored are; contamination by trace elements, and subtleties of growth processing. The absorption measurements will be performed by the Stanford and Southern groups.

Absorption in fused silica is also being investigated since fused silica may be used as the test mass material. An alternate vendor of fused silica has been identified; absorption in this new material will be characterized.

2.2.2 Bulk Absorption

It is accepted that there must be compensation for bulk absorption in the LIGO II design. It is currently assumed that absorption is mostly uniform within bulk materials. The absorption at 1064 nm in sapphire and fused silica must be mapped to verify this assumption. The tests should provide a sufficient statistical sample of the absorption properties of these materials that the data can be used to support the design of a thermal compensation system by the AOS group.

2.2.3 Coating and polishing Effect on Q Tests

There is concern that processing of blank substrates may significantly reduce the Q of optical materials. Should this be true, there are not many avenues immediately open to remedy the situation. However, for modeling and performance purposes, we must know the ultimate Q of our test masses, as well as the processes that effect the Q of any given material. The Q measurements will be performed by the Stanford group.

2.2.4 Birefringence

At the inception of this program, the only 30-40 kg sapphire blanks obtainable have their optical axis along the m-axis. That is, blanks that do not have symmetric material or optical properties in each direction when viewed along the optical axis. Initial calculations indicate that this is acceptable as long as LIGO continues to use linearly polarized light. These calculations will be verified by experiment.

2.3 Optical Properties

The test mass optical development effort will be lead by Caltech.

2.3.1 Polishing and optical homogeneity

A significant part of this research program will be to investigate the possibility of applying a corrective polish to m-axis sapphire, in order to compensate for material inhomogeneity. M-axis sapphire shows considerable inhomogeneity of index of refraction. This inhomogeneity is of a characteristic high spatial frequency, with changes occurring on the order of a few millimeters. The ability of the polishing vendors to compensate for these inhomogeneities may be the deciding factor in the test mass material selection.

In the first LIGO interferometers, the inhomogeneity of the input test masses was corrected by applying a corrective surface to the second surface of the optic. This correction compensated for power only and did not address astigmatism or any higher order terms.

2.3.2 Coating development

A coating development program will be initiated using small samples to test for coating absorption, and large plates or arrays of microscope slides to test for coating uniformity. Initially, the coating development effort will concentrate on lowering the coating absorption. The process will then be expanded to develop the capability of producing uniform coatings over large diameters. Coating uniformity will be measured using spectrographic or elipsometric techniques. Ideally, to optimize arm matching, the coating chamber used will be able to fit two test masses in each coating run.

The pathfinder program will verify that coatings of the same quality and uniformity can be produced on COC scale surfaces.

2.3.3 Coating and Birefringence

The asymmetric properties of m-axis sapphire material may induce stress birefringence in optical coatings. This effect will be measured on small samples to verify the birefringence level. These results will be used to model the effect on the interferometer and to set an acceptable level.

2.3.4 Gravitational loading strain

The suspension places a highly asymmetric stress on the COC. The elastic strain induced will be studied by finite element analysis. This may be used to set or change surface figure requirements.

3 Design

Designs for both sapphire and fused silica test masses will be carried in parallel until the final selection of test mass material in the second quarter of 2002. Designs for 30 and 40 kilogram test masses will be carried in parallel until the first quarter of 2001.

3.1 Pathfinder

The pathfinder process forms a bridge between the development and the design phases of this program. Early in the program, the purpose of the pathfinder demonstration is to determine manufacturing capabilities of various polishing vendors. Pathfinder also provides a scaled back first article opportunity so that the manufacturing system can be exercised without undue schedule pressure. Pathfinder will take place in two phases; phase 1 consists of polishing and coating half size pieces and phase two will do the same with full size pieces.

Who in the heck knows how many half-size pieces of sapphire will be procured for a competitive demonstration of polishing, coating and testing to the levels required by the advanced LIGO program. After the test mass material final selection, two full size blanks will be procured. These optics will serve to ensure that processes developed for half size sapphire can be extrapolated to full size optics. In the event that fused silica is chosen, the optics will serve to demonstrate that LIGO 1 quality polishing can be applied to larger optics. This second phase also provides the necessary optics for use by LASTI.

3.1.1 Polishing of pathfinder substrates

At least two vendors will be asked to polish the half size pieces of sapphire during phase one. Ideally, they will demonstrate that sapphire can be polished with a tight tolerance on radius of curvature as well as good surface figure and microroughness over a large area. The polishing vendors will be asked to attempt a corrective coating on size two of the sapphire optics. Independent metrology of these pieces will aid in determining the polishing vendor for Advanced LIGO optics.

3.1.2 Coating of pathfinder mirrors

Pathfinder substrate faces will be coated with HR stacks tuned for maximum reflectivity at 1064 nm. The remaining faces should be representative AR coatings.

3.1.3 Metrology

3.1.4 Surface Figure, Metrology I and II.

Full aperture wave front distortions of the phase one pathfinder optics will be mapped by reflected and transmitted phase front interferometry at Caltech. This will be performed in two phases:

3.1.4.1 Metrology I

The polished pathfinder test substrates will be mapped by reflection interferometry before coating. Transmission OPD maps will similarly be made through the bulk substrates at normal incidence.

3.1.4.2 Metrology II

The coated pathfinder optics will be mapped using the same reference flat as was used to measure the uncoated substrates. This will provide a clear indication of the change in surface figure of the sapphire due to coating stress.

3.1.5 Scalar tests

Measurements needed to confirm performance of the pathfinder optics other than those mentioned above will be performed by a combination of in house (LIGO facilities) tests and contracted measurements. The scope of these measurements remains TBD. The infrastructure and methodology of these tests are to provide the basis for the final fabrication effort. The essential areas of testing to be performed are:

3.1.5.1 Micro-roughness/diffuse scatter

The microroughness of the pathfinder final polished surfaces must be measured. This needs to be done directly or correlated to a scale that provides a measure of the diffuse surface scatter loss to be expected from such surfaces in the LIGO IFO. A comparison of uncoated surface profile with subsequently coated surface TIS will be undertaken, using standard test samples. These standards can then be used to categorize the diffuse scatter of coated pathfinder faces (1064 nm).

3.1.5.2 Blemishes

Individual scatter centers on both coated and uncoated faces will be identified statistically. Methodology will be appropriate to reveal their origin. This will become the basis for process control in COC production.

3.1.6 LASTI

LASTI will serve as an intermediate step between pathfinder and full production. The full size pathfinder optics will be fabricated after the final test mass material is selected. These optics will serve as a first production article to demonstrate that the polishing and coating technologies transfer as expected from half size to full size mirrors.

3.2 Support Equipment Design

3.2.1 Metrology Design

The beam footprint on the optics is likely to be twice the size it is in the current LIGO. This raises the question of defining the appropriate aperture and resolution for future LIGO metrology. We will examine the role of surface metrology in modeling the interferometer performance. The outcome of these discussions will dictate whether we pursue a low noise approach, as we had been planning, or a large aperture approach. It could be that the right answer is a combination of low noise and large aperture.

The low noise approach would require noise reduction upgrades to the current system, the most significant is the replacement of the current camera. Other improvements address the reduction of thermal gradients and vibration on the measurement platform and the reduction of the effects of vibration on the measurement.

3.2.2 Cleaning Process Design

Cleaning will be based on immersion in warm water with detergent. A large optics cleaning and drying machine has been identified for potential use for LIGO optics. This system has been demonstrated at REO and been found appropriate for LIGO use.

3.2.3 Fixture/Handling Design

The next generation of optics will weigh up to 40 kg. It is imperative that we design fixtures to accommodate mechanical lifting and positioning of the optics, for the safety of personnel and for the protection of the optics. The initial concept is to use fixtures that interface with a small, mobile crane.

The carrier for the optic plays a pivotal support role; all handling fixtures will interface with the carrier.

3.3 Core Optics Design

The basic requirements for the COC come from the systems group. These requirements include mass, Q, aspect ratio, radius of curvature and coating reflectivity. The requirements also include a performance budget, which can be allocated by the COC group amongst various tolerances and error sources.

The specific design of the core optics will most likely require some compromise between the characteristics that are desired for these optics, and those characteristics that are reasonably attainable given cost and schedule restrictions. In cases where a compromise is necessary, the impact on interferometer performance will be understood using the available modeling tools.

3.3.1 Modeling

Allocation of the performance budget will be accomplished by use of the various LIGO models. The FFT code will be used specifically to determine tolerance on radii of curvature and surface figure.

3.3.2 Blank Design

Homogeneity and absorption are the major concerns in blank design. These will be specified along with standard optical characteristics. The blanks will be procured slightly larger than the final optic to allow enough material for final shaping.

3.3.3 Polishing Design

3.3.3.1 Radius of curvature

Indications are that the tolerance on radius of curvature may be tight for the Advanced LIGO interferometers. The radius of curvature changes in several ways after the final polish. The coating applies a compressive stress, which tends to flatten a concave optic. The anti reflective coating on the opposite side will tend to reverse the stress, though not completely since there are fewer layers. Typically, optics are annealed after coating, this will reduce some of the stress applied by the coating. The coating uniformity may also change the apparent radius of curvature since changes in uniformity may be axially symmetric; this can increase or decrease the radius of curvature.

Absorption in the bulk material and the coating will also change the radius of curvature, once the optic is exposed to the full laser power. Compensation for this may be accomplished under the Auxiliary Optics Support task. This compensation may provide good enough control to allow us to relax the radius of curvature requirements on the core optics and significantly reduce the cost.

There are two approaches to controlling the radius of curvature during manufacturing. The first, which is the one we followed in the initial LIGO program, is to tightly control each step. The second is to understand the trend that each step adds to the curvature and then work backward to arrive at the proper starting point, the polished radius of curvature. This approach is less costly in manufacturing, but may require significant up front investigation. These two approaches will be weighed when finalizing the COC design.

3.3.3.2 Surface Figure

Surface figure is usually specified as the rms of the surface phase map after removal of the Zernike coefficients that describe piston, tilt, power and astigmatism. The surface figure is specified in two zones, a central zone on which most of the beam impinges, and an outer zone which will extend out to ~ the 1ppm contour.

The surface figure is also broken into frequency ranges, with the low spatial frequency errors being called surface figure and the high spatial frequency errors called microroughness. The microroughness specification may also be divided into the same inner and outer zones as the surface figure.

3.3.3.3 Scratches and Point defects

The amount of scratches and point defects allowed on the optics is determined by a simple ratio of total defect area to beam waist area. This will be on the order of a few parts per million and will be included in the performance budget for COC.

3.3.4 Coating Design

The specific dielectric coating stack will be designed by the vendor to meet the LIGO specification. There will however, be a requirement that the coating design be tuned for zero or minimal electric field at the surface of the optic.

Reflectivity and absorption will be specified in the system design. Uniformity may be addressed partly in terms of radius of curvature. Higher frequency uniformity variations will not be acceptable if they degrade the surface figure of the optics. Blemish or defect specifications will be allocated from the performance budget, or allowable losses. They may be specified in terms of their overall cross section similar to the manner in which defects are specified in polishing.

3.3.5 Interface Design

3.3.5.1 Support Optics Subsystem

The COC wedge angles and side 2 coating reflectivity will be determined by the Support Optics Subsystem group (SOS).

3.3.5.2 Suspensions Subsystem

3.3.5.2.1 Coatings

The suspensions may call for a metallic coating on side two that would be used for alignment control. The material and pattern for this coating is specified by the suspension group.

3.3.5.2.2 Ear Mounts

Mounting flats will be polished onto the sides of each optic. The position, parallelism and surface quality for these flats will be specified by the suspension group.

4 Fabrication

4.1 Support Equipment fabrication

The support equipment will be designed and tested during the Pathfinder process and will be fabricated in quantity and in time to support the COC fabrication. Support equipment consists of the following:

- Metrology Fixtures

- Cleaning Process Equipment and Fixtures
- Carriers and Shipping Cases

4.2 Core Optics Fabrication

Forty-four mirrors will be procured as COC. There are six different types of mirrors, and seven configurations. Input Test Masses for the third interferometer have different wedges than those used in the first and second interferometers. There is very little overlap in sizes, so each type of mirror will require different fabrication tooling.

All of the COC fabrication will be subcontracted. These subcontracts will be competitive to the extent that there are multiple vendors who are qualified to perform the various operations.

Due to the long delay between the first and second interferometer installation, the mirrors will be procured on a "per interferometer" basis as follows:

	First interferometer		Second interferometer		Third interferometer		
Optic Type	Required	Spares	Required	Spares	Required	Spares	Total 44
PRM	1	2	1	1	1	1	7
SRM	1	2	1	1	1	1	7
BS	1	2	1	0	1	0	5
FM	0	0	0	0	2	1	3
1st 2 ITM	2	4	2	0	0	0	8
3rd ITM	0	0	0	0	2	2	4
ETM	2	4	2	0	2	0	10

Table 1: Mirrors will be procured in three separate groups, since the IFO installations are spread in time

4.2.1 Blank Fabrication

There are three different types of material specified for the COC. Standard fused silica will be used for both Recycling Mirrors and for the Folding Mirrors. Low absorption fused silica will be used for the Beamsplitters and sapphire will be used for the Test Masses. These blanks will be fabricated by up to three vendors. After fabrication, the blanks will go to Caltech for inspection. They will be examined for inclusions, homogeneity, and in the case of sapphire, absorption. Test Masses will then be designated for use as Input Test Masses or End Test Masses based on absorption and homogeneity.

There may be an intermediate machining step before the blanks are sent for final polish. This would mean providing optics which already have a commercial polish on all surfaces, leaving only final polishing of the faces. This may save both time and money, as some precision polishing houses are not set up to machine large substrates. The vendor who performs this task will be asked to certify all mechanical dimensions.

4.2.2 Polishing Fabrication

Ideally, there will be more than one polishing vendor in the Advanced LIGO procurement. Due to the tight tolerances expected on radii of curvature, these vendors will each need an internal capability to perform high precision metrology.

The polishing vendors will apply a compensating polish to side two of Input Test Masses and Beamsplitters. This polish may need to compensate for high spatial frequency inhomogeneities.

The polishing vendor will certify surface defects, radius of curvature, surface figure and microroughness. They will also certify transmitted wave front for the Input Test Masses and Beamsplitters. Phase maps will be a required part of the data set.

The uncoated optics will be measured at Caltech before being shipped for coating.

4.2.3 Coating Fabrication

Test Masses will ideally be coated two per run. This will allow for optimum matching. The masses chosen for pairing will have comparable radius of curvature and measured absorption.

A witness sample will be required along with a spectrophotometer trace for each coating run.

4.2.3.1 Final Metrology

Final metrology will consist of a surface map, a scatter map, ringdown, and transmission measurements. Measurements, which will have been performed up to this point, are:

- Absorption will have been measured while blank
- Bulk homogeneity will have been measured while blank
- Microroughness will have been measured at polishing vendor
- Coating birefringence and Q will have been measured in pathfinder