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Core Optics Components
Reference Design Document

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1 Overview

This document is to accompany the COC Design Requirements document. This document specifies a design approach and fabrication and testing strategy which will produce COC whose performance satisfies the COC DRD requirements. The same conventions, acronyms, and assumptions stipulated in the DRD document are used here.

1.1 Ligo references

COC Scalar Test Program LIGO-T960016-00-D0

1.1.1 Non-LIGO references

C. Evans ,et. al., MS AO10260 and 9646 to be published in Applied Optics: Optical Technology (1996).

P. Hariharan, Opt. Eng. 35, 1 (1996).

Coating technology....

H. J. Kimball, ate al, Opt. Let., 17, 364, and 17, 640 (1992).

Z. L. Wu, Overview of photomurals..... (1995). Also: V. Loretta and C. N. Man (VIRGO), 8th Into. Topical MT. on Photoelectric and Photomurals Phenomena (1994).

V. Loretta, ate al, J. de Physique IV, C7-631 (1994).

2 Conceptual Design Description

Table 1 summarizes the reference design for the advanced LIGO cores optics components. The design for realizing the final COC will be discussed under the following headings.

- Substrate materials
- Substrate processing (including polishing and figuring).
- Coatings
- Pathfinder
- Mounting, interfacing and stay clear considerations.
- Metrology
- Spares.
- Cleaning, handling and contamination.

2.1 Substrate material

Sapphire is the baseline material for all COC Test Masses. This includes input test masses (ITM) and end test masses (ETM). Fused silica is the baseline material for all remaining COC.

The different physical type substrates are specified in table 1.

Fine ground blanks of high grade material are to be procured from suppliers according to the following considerations

2.1.1 Material types

2.1.1.1 ITM, ETM

Sapphire is the required material for both test masses. The ITM bulk material must have low inhomogeneity, and scatter, for normal incidence beams. Absorption must also be low, though matching of absorption in ITMs is most important. The material properties for the ETM are not as critical. There can be higher absorption and poorer homogeneity. The material may be ordered then tested and sorted for absorption and homogeneity. The blanks with the best homogeneity will be used for ITMs and will be sorted according to absorption in the hopes of making well matched pairs for eventual use in the interferometers.

2.1.1.2 BS type

The Beamsplitter material is low absorption and high homogeneity fused silica intended for beams at a 45 degree angle of incidence.

2.1.1.3 RM, FM type

The RM and FM material is fused silica. The transmission properties are less important for these pieces. High bulk homogeneity material with no special absorption specification is adequate. The Recycling mirror should have no inclusions which would scatter the input beam. The folding mirror specification may allow more inclusions and lower homogeneity, since this is not a transmissive optic. Cost may be the most significant driver for this material.

2.1.2 Blank sizes and selection

Material must be available in blank sizes which can be finished to the dimensions of table 1. Common practice is to procure the glass blanks oversize by 2mm in diameter and 4mm in thickness.

Sapphire blanks will be delivered already machined to their final form and with an inspection polish in place on both surfaces, on the outside cylinder and on the bevels. Machining of sapphire is a difficult process, it has been decided to leave the breakage risk in the hands of the material supplier.

2.1.3 Bulk homogeneity

Each procured blank will require measurement certification by the vendor to a certain columnar homogeneity (specific to size and type material).

2.1.4 2.1.4. Bulk scatter

For the high quality FS LIGO considers, bulk scatter is anticipated to be near the Rayleigh limit (~ 2 ppm/cm, at 1064 nm). This is will be inconsequential as a power loss, and will be > 100 times less than the anticipated TIS from the adjacent TM ER coatings.

2.1.5 2.1.5. Inclusions

For each material type an inclusion specification will be imposed on the vendor. To keep this specification manageable it will be stated as a limit on the total geometrical cross section of those inclusions within the central Gaussian diameter. These inclusions would have two effects:

- TIS of energy out of the TEM_{00} beam in an amount approximately equal to sum of their geometrical cross sections weighted by the local beam intensity.
- The [far field] distortion to the TEM_{00} wave front due to absences of small (~geometrical cross section) patches of wave front.

However it can be shown that for the LIGO geometry, the CD due to the latter mechanism is given as an upper limit by the former.

2.2 Substrate processing

In this category we consider all other fabrication to the COC exclusive of the coatings (2.3) and all suspension attachments (2.5). Two stages may be distinguished:

2.2.1 Shaping to final size and rough polishing

After all appropriate inspections, tests and selection steps, the blanks will be shaped to final substrate form by grinding and rough polishing over 100% of surface area. This polishing stage will be final for all surfaces except the surface #1 and #2 faces. At this stage the substrates will be brought to the form described in figure 1.

2.2.1.1 Shapes.

The basic shape of all COC elements is taken to be the right circular cylinder. The exact right circular cylindrical shape will be modified in four ways:

- xM secondary surface wedge, < 4°. The exact wedge angle will be determined by analysis of the entire IFO configuration and beams layout. Preliminary results of this analysis indicate that each COC will likely require a different specific wedge angle. Transmissive optics (RM, BS, ITM) will be wedged symmetrically such that there are no 90 degree internal reflections. This minimizes the possibility of scatter back into the IFO resonant cavities.
- BS secondary surface wedge, <1°. This angle is constrained to be smaller due to the thinness of the substrate. For mechanical integrity the plate should not be less than 10% thinner at one edge. Asymmetric thermal (from laser beam absorption) distortion (potato chip) could also result.
- Standard optic edge bevel, 45°, 2 mm width.
- All primary face surfaces except for BS and FM will have spherical form, given by the values in Table 1
- All COCs will have flats polished on the OD parallel to the direction of the wedge. These flats are used for attachment of the suspension ears. The flat size, position and polish are specified by SUS.

2.2.2 Final precision polishing/figuring

All COC faces will be polished to a figure whose deviation from the exact values of table 1 is determined by the requirements of the COC Design Requirements Document (DRD), as well as the final results of the PF process. In particular a final balance between specification of surface microroughness and figure errors awaits evaluation of actual process results.

2.3 Coatings.

All COC front surface optical coatings are to be of the hard oxide dielectric type. The coating technique is to be sputter ion beam technology. It is known that this technique yields the highest uniformity and lowest loss coatings. The optical coatings will be of two types, Enhance Reflectance and Anti Reflectance.

2.3.1 Enhanced Reflectance coatings.

These coatings will provide front surface mirrors for the IFO cavities and the 50/50 beam splitter. They will be of multi quarter wave thickness stack design of up to 40 layers deep (in the FM case). The design will be of alternating SiO_2 and Ta_2O_5 layers. The bottom layers of the coating are to be tuned in thickness such that there is zero electric field at the surface of the coating. A remaining parameter for this coating is the desirability of a low index (SiO_2) cap layer (standard practice has been a half wave layer for protection).

2.3.1.1 ERETM and ERFM

At 1064 nm a 40 layer stack coating would ideally give T= 10.6 ppm. It remains to be seen what practical transmissivities can be achieved. At 180 watts of input power there will be sufficient leakage through the ERETM to ensure good sensing signals, so these coatings should be made as highly reflective as the technology will allow.

2.3.1.2 ERITM and ERRM

In this case the number of quarter wave layers is dictated by the desired reflectivity. The bottom layers of the coating are to be tuned in thickness such that there is zero electric field at the surface of the coating. A remaining parameter for this coating is the desirability of a low index (SiO2) cap layer (standard practice has been a half wave layer for protection).

2.3.2 Anti Reflectance coatings

These coatings will be on all secondary (wedged) surfaces. They serve to limit the beam power diverted to ghost reflections. The design will be two layers, of SiO_2 and Ta_2O_5, with appropriate thickness to meet the specifications of the COC DRD.

2.3.3 Suspension coatings

Suspension coatings are low optical quality metallic coatings. The thickness and pattern are determined by SUS. These coatings are applied to the second surface of all optics which are under high frequency alignment control. Table 1 explicitly states which optics are to be coated.

2.4 Pathfinder

The COC design concept assumes that the requisite optics can be fabricated by existing techniques using industry fabrication facilities. A pathfinder (PF) process, whose purpose is to have full scale optics (illustrated in figure 1) fabricated, polished, coated and tested by existing techniques, will serve to verify whether this premise can be realized within the requirements, and under stipulated schedule and budget constraints. PF will be made up of:

2.4.1 FFT data

A closely related purpose of the pathfinder process is to provide reliable, absolute metrological data of all the optical imperfections of typical candidate COC. These data will accurately represent the actual optic’s performance in FFT code modeling.

2.4.2 Independent metrology (I and II)

The full optical aperture wave front distortions of the PF optics will be mapped by reflected and transmitted phase front interferometry at a designated independent metrology contractor. The design and development of this metrology is to provide the basis for eventual similar testing of production (2.6) COC. This will be performed in two phases:

2.4.2.1 Metrology I

The final polished PF test substrates will be absolutely surface mapped by reflection interferometry before any coating. Transmission OPD maps will similarly be made through the bulk substrates at normal incidence (to surface 1).

2.4.2.2 Metrology II

The measurements of 2.4.2.1 will be repeated on the same final coated PF substrates.

2.4.3 Polishing selection

One or two PF substrates will be finished polished and figured (to stage of 2.2.2) by prospective vendors. At least one flat and one radiused surface will be produced. The vendors will be encouraged, but not required to apply their best metrological capability to describe their finished surfaces. The final arbiter of all the polished PF surfaces will be 2.4.2. and 2.4.5.1.

2.4.4 Coating development

The coating of PF and eventually of the COC will be performed by one or two coating vendors. A contracted coating development program will be performed using small samples to test for coating absorption, and large plates or arrays of microscope slides to test for coating uniformity. The PF program will verify that coatings of the same quality and uniformity can be produced on COC scale surfaces. It is anticipated that the exact specification of the COC coating designs (e.g. numbers of layers, cap layer desirability, AR design, BS design) will be arrived at during this phase.

2.4.4.1 Coating of PF substrates

Most PF substrate faces (including all radiused faces) are to be coated with 34 layer ER stacks tuned for Rmax at 1064 nm. The remaining faces should be representative AR coatings.

2.4.5 Scalar tests

Measurements needed to confirm performance of the PF optics other than those in 2.4.2 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 2.6.2. The essential areas of testing to be performed are:

2.4.5.1 Micro-roughness/diffuse scatter

The micro-quality of the PF 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 un-coated 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 PF faces (1064 nm).

2.4.5.2 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 1064nm 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 may be used to support the design of a thermal compensation system.

2.4.5.3 Surface (coating) properties

Here, measurements will be performed on 1064 nm coatings exactly duplicating the anticipated COC designs (where necessary on specially coated samples). Coating absorption and loss will be measured using the Resonant Frequency Spacing, and Ring Down techniques. Coating uniformity will be measured using spectrographic or elipsometric techniques.

2.4.5.4 Blemishes

Individual scatter centers on both coated and uncoated faces will be identified (at least statistically). Methodology will be appropriate to reveal their origin (e.g. poor substrate surface micro-quality, coating run problem, etc.) and become the basis for process control in COC production.

2.4.5.5 Q measurements

These are to be adequate to assure that Q's of PF substrate internal mechanical modes are maintained sufficiently high through the various stages of COC processing so that the thermal noise requirements of the COC-DRD can be satisfied.

2.5 Mounting and Stay-clear

COC will finally be used in the mounted configuration illustrated in figure 3. Strictly the components shown, other than the coated COC substrate itself are excluded from this design. however crucial account of this mounting must be taken in the following respects:

2.5.1 Effect of appendages on Q.

The expected degradation of substrate mechanical Q must be carefully monitored. The PF optics will be used for this purpose after all optical tests have been performed.

2.5.2 Stay-clear

For all COC the suspension components must be designed to stay adequately clear of the beam envelopes so as not to occlude the $^{\mathbf{TBD}}$ppm beam envelope.

2.5.2.1 ETM

This element presents no problem, since only the primary surface is of critical concern. Electrostatic or photon drives and close proximity support structure can be arranged to be at the secondary (AR) face side.

2.5.2.2 ITM

This element requires critical stay clear on both faces.

2.5.2.3 BS

This element requires critical stay clear on both faces, the situation is complicated by the 45^{o} incident beams.

2.5.3 Gravitational loading strain

The suspension laces a highly asymmetric stress on the COC. The elastic strain induced will be studied by finite element analysis.

2.6 Verification metrology

Technical development through the PF mechanism should allow all production COC to be specified and measured to a level satisfying the optical performance requirements of the DRD. Several measurements will be developed beyond the PF level to be better suited to volume measurement of the final COC.

2.6.1 Automated mirror parameter measurement

It will be desirable to fully characterize COC by automated scan measurements of their (coated) faces. This would include blemish mapping, reflectivity, transmission and surface scatter. This program will be fully developed for 1064 nm.

2.6.2 1064 nm phase front interferometry.

Surface maps will be generated for each COC. These maps will cover the central 147 mm diameter. The maps will include surface frequencies up to ~180 cm^{-1}. There is no plan to test for higher spatial frequencies on production optics. The high spatial frequency characteristics of optical surfaces will be measured using a LIGO approved process at the polishing vendor.

2.6.3 Homogeneity

Homogeneity of all sapphire blanks will be measured using phase shifting interferometry.

2.6.4 Absorption

The absorption of all sapphire ITMs will be measured in an effort to match them for use in interferometers. Beamsplitter absorption may be measured on boule witness samples.

2.6.5 Inclusions

Incoming blank material will be inspected for bulk inclusions.

2.6.6 Dimensions

Mechanical dimensions will be certified by the responsible vendor. In the case of sapphire, this is the material supplier, for fused silica it is the polishing vendor. There is no plan to verify these within the LIGO project.

2.7 Spares

The spares requirements are detailed in Table 1. In general, the spares policy is based upon one spare per type of optic.

Test masses require more spares because the radii of curvature must be matched more closely in the interferometer than even exceptional manufacturing tolerances allow.

Recycling mirror spares are based on one spare per type, plus one replacement should the final configuration require a different recycling mirror transmission.

Beamsplitters have additional spares due to the complexity of the coating.

2.8 Storage and handling

Optics should be stored in protective containers. These containers should protect the optical surfaces during conditions of standard commercial shipping. The containers should also prevent the optics from coming into physical or vapor contact with any non-vacuum qualified material. The containers should support the optic without contacting any surface within the clear aperture, as defined in each optic specification. Generally, the area that can be contacted is the OD and the outer 1cm.

Table 1 Summary of COC requirements

	PRM	SRM	BS	FM	1&2 ITM	IFO 3 ITM	ETM
Sapphire size (mm)	254 x 100	254 x 100	350 x 60	285? x 118	285 x 118	285 x 118	285 x 118
Fused Silica option size (mm)	254 x 100	254 x 100	350 x 60	350 x 140	350 x 140	350 x 140	350 x 140
No.Required 1st 2 IFOs	2	2	2	0	4	0	4
Spares 1st 2 IFOs	3	3	2	0	4	0	4
No. Required 3rd IFO	1	1	1	2	0	2	2
Spares 3rd IFO	1	1	0	1	0	2	0
Total Number 44	7	7	5	3	8	4	10
Material	Low Inclusion FS	Low Inclusion FS	Low Absorption FS	FS	Sapphire	Sapphire	Sapphire
SUS coating	Yes	Yes	No	No	Yes	Yes	Yes
Clear Aperture (Dia-2cm)	224	224	330	265	265	265	265
Sagitta over central 215 mm dia (2*w_o dia)	240 ±; TBD	240 ±TBD	Flat ±TBD	Flat ±TBD	165 nm ±10 nm	165 nm ± 10 nm	165 nm ± 10 nm
Surface error -TPA (nm rms) over 215 mm diamter	< 0.16	< 0.16	< 0.16	< 0.16	< 0.8	< 0.8	< 0.8
Microroughness over 215 mm dia (rms)	< .4 nm	< .4 nm	< .4 nm	< .4 nm	< .2 nm	< .2 nm	< .2 nm
Microroughness goal over central 215 mm dia (rms)						< .1 nm	< .1 nm
Absorption ppm/cm	< 20	< 20	< 1	< 20	< 80	< 80	
Coating (ppm) Absorption	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Coating (ppm) Absorption goal					<0.5	<0.5	<0.5
Homogeneity Peak to Valley (nm)	<500	<500	<500		<40	<40	