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Core Optics Components
Conceptual Design Document

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1 Overview

This document is to accompany the Core Optics Components (COC) Design Requirements document and COC development plan. This document specifies a design, fabrication and testing strategy to produce COC whose performance satisfies the COC DRD requirements. The conventions, acronyms, and assumptions used in the DRD document are also used here.

1.1 LIGO references

Advanced LIGO Systems Design LIGO-T010075

Optical Layout for Advanced LIGO LIGO-T010076

COC Design Requirements Document LIGO-T000127

COC Development Plan LIGO-T000128

Test Mass Material Downselect Plan LIGO-T020103

1.1.1 Non-LIGO references

2 Conceptual Design Description

Table 1 summarizes the reference design for the Advanced LIGO cores optics components. The design will be discussed in general under the following headings:

- Substrate materials
- Substrate processing (including polishing and figuring).
- Coatings
- Mounting, interface and stay clear considerations.
- Spares.

Section 3 Supporting Design

- Metrology
- Storage, cleaning and contamination.

2.1 Substrate material

Sapphire is the baseline material for all COC input test masses (ITM) and end test masses (ETM). Fused silica is the baseline material for all remaining COC. Fused silica may be used for the test masses in the event that sapphire is found to be undesirable. LIGO-T020103, the Test Mass Material Downselect Plan covers this question in great detail.

The different physical type substrates are specified in tables 1 and 2.

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 Input Test Mass, End Test Mass

Sapphire is the required material for both test masses. The ITM bulk material must have low inhomogeneity and scatter for polarized, normal incidence beams. Absorption must also be low. The material properties for the ETM are not as critical. These can have higher absorption and poorer homogeneity. The material may be ordered then tested and sorted at Caltech for appropriate use as ITM or ETM blanks. The ITM blanks will be processed in groups of similar absorption in the hopes of making similar pairs for use in the interferometers.

When viewed in transmission, sapphire is known to have reasonably high inhomogeneity. Goodrich has demonstrated, under contract to LIGO, compensating polish of side 2 which leaves a residual inhomogeneity of 10nm rms single pass. It is assumed that sapphire ITMs will require compensating polish to correct the inherent material defect.

2.1.1.2 Beamsplitter

The Beamsplitter material is low absorption and high homogeneity fused silica intended for beams incident at a 45 degree angle. An example of this type material is Heraeus 311 or 311SV. In initial LIGO the 311 material was seen to have a typical homogeneity of 5 nm rms over a 200 mm diameter area. Absorption testing of this material showed all 13 samples as absorbing less than 5 ppm/cm at 1064 nm.

2.1.1.3 Power Recycling Mirror, Signal Recycling Mirror, Folding Mirror

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 that might scatter the input beam. The folding mirror specification may allow inclusions and inhomogeneity, since this is not a transmissive optic. Cost may be the most significant driver for this material.

2.1.1.4 Compensation Plates

The recycling cavity contains two compensation plates, suspended near the ITMs. The exact design of these plates comes from Auxiliary Optics Systems (AOS). Nominally it is understood that the compensation plates will be a high homogeneity, low absorption fused silica, similar to the Beamsplitter.

2.1.2 Blank sizes and selection

Material must be available in blank sizes that 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, we may decide to leave the breakage risk in the hands of the material supplier.

2.1.3 Bulk homogeneity

Each PRM, SRM, CP and BS blank will require measurement certification by the vendor to a certain homogeneity (specific to size and type material). In the event fused silica is chosen as the test mass material the vendor will also certify homogeneity. The sapphire vendor will not certify homogeneity, due to both the difficulty of the measurement and the de facto requirement to compensate inhomogeneity by applying a compensating polish to the AR coated side 2 of the ITM.

2.1.4 Bulk scatter

For the high quality fused silica considered here, bulk scatter is anticipated to be near the Rayleigh limit (~ 2 ppm/cm, at 1064 nm). This is inconsequential as a power loss, and will be > 100 times less than the anticipated total integrated scatter from the adjacent TM coatings. Rayleigh scattering for sapphire is understood to be roughly 10 times lower than that of fused silica.

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 lead to loss in the recycling cavity only and should be limited by the recycling cavity loss budget.

2.2 Substrate processing

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

2.2.1 Shaping to final size and rough polishing

After 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.

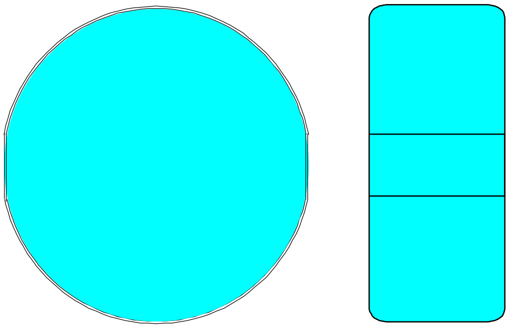

Figure 1 The basic shape of all core optic components

2.2.1.1 Shapes.

The basic shape of all COC elements is taken to be the right circular cylinder. The dimensions of the various optic types are summarized in Tables one and two. The exact right circular cylindrical shape will be modified in four ways:

- Mirror secondary surface wedge, < 3° for all optics except the BS, discussed below. The exact wedge angle will be determined by analysis of the entire IFO configuration and beams layout as described in LIGO-T010076. 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, $<1^{o}$. 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^{o}, 2mm height on each leg to the virtual corner.

- All primary face surfaces except for BS and FM will have spherical form, given by the values in Table 1

- All COCs except PRM and SRM will have flats polished on the OD parallel to the direction of the wedge. These flats are used for attachment of the suspension prisms. The flat size, position and polish are specified by SUS.

2.2.2 Final polishing

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 Pathfinder 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 process will be ion beam sputtering. .This technique yields dense layers with very low optical absorption.

The optical coatings will be of three types, High Reflection (HR), Anti Reflection and Beamsplitters (T/R 50/50)

2.3.1 High Reflection (HR) coatings.

These coatings will provide front surface mirrors for the IFO cavities. The coating will be fabricated of quarter wave stacks, alternating high and low index materials, designed for up to ~40 layers. (in the FM case). 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. TBD is the addition of a double layer of SiO2 for protection.

2.3.1.1 End Test Mass and Folding Mirror

At 1064 nm a 40 layer stack coating would ideally give T= 10.6 ppm. It remains to be seen what practical transmission can be achieved. At 830 KW of circulating power there will be sufficient leakage through the HR coating of the ETM to ensure good sensing signals, so these coatings should be made as highly reflective as the technology will allow.

2.3.1.2 Input Test Mass and Recycling Mirror

The number of quarter wave layers is dictated by the desired reflectivity. Matching of ITM coatings is desirable to within 1% (LIGO-T010075). Pairs of ITM of equal radii of curvature should be identified for coating in the same coating run, or provisions made with the coating vendor to assure sufficient matching.

There may be a need to change the value of the reflectivity for both PRM and SRM after the initial characterization runs of the interferometer. Sufficient spares are to be left uncoated to allow for this.

2.3.1.2 Beamsplitter coatings

Beamsplitter coatings are designed to provide 50% reflection for an incoming angle of incidence of 45°.

2.3.2 Anti Reflection (AR) coatings

These coatings will be on all secondary (wedged) surfaces. They serve to limit the beam power diverted to ghost reflections, as well as to provide pick off beams for sensing and control systems. In cases where pick off beams are needed, COC will be advised by ISC of the desired reflectivity. This should not compromise the operation of the COC in any way.

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 that are under high frequency alignment control. Table 1 explicitly states which optics have this coating.

2.4 Mounting and Stay-clear

COC will finally be used in the mounted configuration illustrated in figure 2. 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:

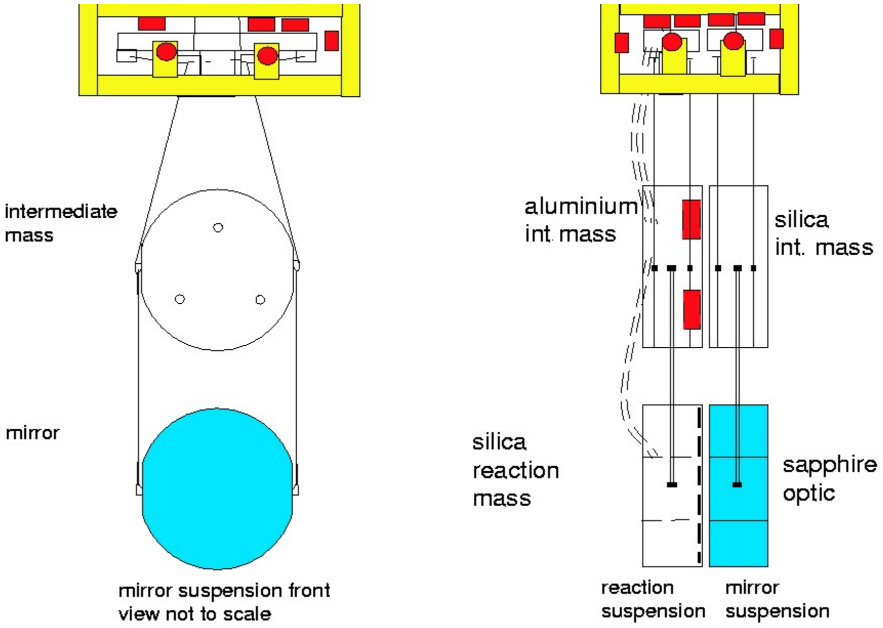

Figure 2 COC (blue) shown in suspension (graphic courtesy of GEO)

2.4.1 Effect of appendages on Q.

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

2.4.2 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 1ppm beam envelope.

2.4.2.1 End Test Mass

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.

2.4.2.2 Input Test Mass

This element requires critical stay clear on both faces.

2.4.2.3 Beamsplitter

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

2.5 Spares

The spares requirements are detailed in Table 1. In general, the spares policy is based upon one spare per type of optic. This spares approach is based on an early enough manufacture to re-polish and re-coat in the event an optic does not meet final specification.

Test masses require 100% spares because the radii of curvature must be matched more closely in the interferometer than even exceptional manufacturing tolerances will allow.

Recycling mirror spares are based on one spare for the initial installation, plus one replacement for each interferometer should the final configuration require a different recycling mirror transmission.

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

3 Supporting Design

3.1 Verification metrology

Technical development through the Pathfinder mechanism should allow all production COC to be specified and measured to a level satisfying the optical performance requirements of the DRD.

3.1.1 Automated mirror parameter measurement

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

3.1.2 1064 nm phase front interferometry.

Surface maps will be generated for each COC. These maps will cover the central 300 mm diameter. The maps will include surface frequencies up to ~17 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. It was demonstrated in LIGO 1 that typical coatings do not degrade the surface microroughness.

3.1.3 Homogeneity

Homogeneity of all sapphire blanks will be measured using phase shifting interferometry. This will enable proper assignment of the best blanks as input masses.

3.1.4 Absorption

The absorption of all sapphire ITMs will be measured in an effort to match them for use in interferometers. Beamsplitter absorption will also be verified using the automated system described above.

3.1.5 Inclusions

Incoming blank material will be inspected for bulk inclusions.

3.1.6 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 LIGO.

3.2 Coating Characterization

The coating characterization is covered under a document being drafted "Requirements and Testing of Advanced LIGO Coated Optics" (T030233)

3.3 Storage and handling

3.3.1 Storage

Optics should be stored in protective containers. These containers should protect the optical surfaces during conditions of standard commercial shipping. They should also be designed to interface with lifting and handling fixtures discussed in the next section.

The containers should 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 of the optical surfaces and the entire outer diameter.

3.3.2 Handling

A prototype mirror handling device has been designed and fabricated for lifting, moving, cleaning and testing of the core optics. Additional testing of the "Ergo Arm" remains to be performed to ensure that the coated optics are not compromised during handling. The purpose of this mechanical arm is to ensure the safety of the operator as well as the optic. There will be a set of additional tools and fixtures made for each location to handle the optics at different process stages.

For additional handling guidelines see E970034-02-D, LIGO Detector Subsystem Review Report: Core Optics Components Shipping and Handling Procedures

3.4 Cleaning and contamination

3.4.1 Cleaning

The need of a cleaning process for coated optics is yet TBD.

In the event that one is required, an aqueous cleaning process will be used to clean the optics. This process will take place by immersion in a custom cleaning system. Optics will be loaded into the tanks with a mechanical handling mechanism. High purity deionized water and a mild alkaline surfactant will be used as cleaning agents. Manual scrubbing may take place to remove particles and stubborn contaminants. Rinsing will be done by a continuous spray of warm, deionized water. The optics will be dried by slow withdrawal.

The addition of ionizing bars close to the optics during cleaning and assembly procedures will prevent electrostatic charges on the mirror surfaces as well as particle contamination.

3.4.2 Contamination

Optics should not be in contact with silicon based materials. There is evidence that contact with tape adhesives has caused trouble with bonds in LIGO1. Silicon migrates easily and so should not be used around the optics.

Optics should be kept under clean flow benches at all times and not be left exposed un-covered for more than a couple of days after final cleaning. Hydrocarbons in the air will cling to the surface and contaminate the optic.

3.4.3 In Situ Cleaning

In the event that “in situ” cleaning is required, the surfaces could be cleaned using CO2 snow . This method involves cleaning the surface with a direct stream of CO2 (“snow flakes”). However, a full assessment of this cleaning method needs to take place by inspecting CO2 cleaned surfaces with the up-graded scattering measuring system.

Table 1 Summary of COC requirements assuming Sapphire Test Masses

	PRM	**SRM**	**BS**	**FM**	**CP**	**1st 2 ifo ITM**	**3rd ifo ITM**	**ETM**
Optic size (mm)	265 x 100	265 x 100	350 x 60	350 x 60	314 x 65	314 x 130	314 x 130	314 x 130
No. Required 1st 2 IFOs	2	2	2	0	4	4	0	4
Spares 1st 2 IFOs	3	3	2	0	1	4	0	4
No. Required 3rd IFO	1	1	1	2	2	0	2	2
Spares 3rd IFO	1	1	0	1	0	0	2	0
Total Number 51	7	7	5	3	7	8	4	10
Baseline Material (fall back material is all FS)	Low inclusion FS	Low inclusion FS	Low absorption FS	FS	Low absorption FS	Sapphire	Sapphire	Sapphire
SUS coating	Yes	Yes	No	No		Yes	Yes	Yes
Clear Aperture (Diameter - 2 cm)	245	245	330	330	300	300	300	300
Sagitta (nm) over central 215 mm dia (2*_wo_ dia)	2512 ± **TBD**	2512 ± **TBD**	Flat ± **TBD**	Flat ± **TBD**	Flat ± **TBD**	2862 ± 10	2862 ± 10	2862 ± 10
Surface error -TPA (nm rms) over central 120 mm diameter	< 1.6 TBD	< 1.6 TBD	< 1.6 TBD	< 1.6 TBD	< 1.6 TBD	< 0.75	< 0.75	< 0.75
Microroughness spec over central 215 mm dia (rms)	< 0.4 nm TBD	< 0.4 nm TBD	< 0.4 nm TBD	< 0.4 nm TBD	< 0.4 nm TBD	< 0.1 nm	< 0.1 nm	< 0.1 nm
Microroughness goal over central 215 mm dia (rms)						< 0.1 nm	< 0.1 nm	< 0.1 nm
Absorption (ppm/cm)	< 20	< 20	< 1	< 20	TBD	< 40 - 80	< 40 - 80	
Homogeneity (nm) Peak to Valley	< 500	< 500	< 500		< 500	< 20	< 20	
Coating Absorption (ppm)	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Coating Absorption goal (ppm)						<0.5	<0.5	<0.5
Thickness Uniformity (%)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Side 1 (HR) Transmission	~6±0.6%	5.0 to 12 %	50 ±0.5 %	< 20 ppm	AR <100	0.5±0.05 %	0.5±0.05 %	>1ppm < 20 ppm
AR Coating (ppm) TBD	~1000	<100	<100	<300	<100	600 ± 100	600 ± 100	<300
Scatter (ppm)	<15	<15	<15	<15	<15	<15	<15	<15

Next topic…

Table 2. Specifications that differ from those for sapphire TMs if fused silica is the test mass material

	1st 2 ifo ITM	**3rd ifo ITM**	**ETM**
Optic size (mm)	340 x 200	340 x 200	340 x 200
Surface error -TPA (nm rms) over central 120 mm diameter	< 0.95	< 0.95	< 0.95
Absorption (ppm/cm)	< 1	< 1	