LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Document Type	**LIGO-T010111-00-**	**D**	10/5/01

Advanced Optics Development

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Distribution of this draft:

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of the LIGO Project..

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1 SAPPHIRE DEVELOPMENT

1.1. Sapphire Requirements

The following table gives our present best understanding of the sapphire requirements for the

Table 1:

Parameter	Value	Status	Risk level	Completion
Size	35 cm dia x 13 cm thick	in process	med	7/02
Surface Figure	1 nm rms	met		
Radius of curvature	50 +/- 5 km	in process	low	12/01
Optical homogeneity	10 nm rms spectrum(?)	in process	high	12/02
Bulk scatter	100 ppm/cm	met for 1 cm part	low	7/02
Coating birefringence	4×10^{-4} rad	met for 3" dia part	low	9/02
Absorption	10 ppm/cm	in process	high	12/02

advanced LIGO. They should be replaced as soon as possible with a detailed, system level analysis. The risk level and completion dates refer to the Crystal Systems effort.

1.2. Crystal Systems

1.2.1. Size

CS is currently building a large furnace to grow full size LIGO substrates. They expect to go through a number of growth runs and produce a full size substrate by 6/02. They have demonstrated substrate growth fairly close to the LIGO requirements, so extending the size should not be very hard. The question here is the optical quality of the large substrates, including scatter and optical homogeneity.

1.2.2. Surface Polish

The polishing of sapphire surfaces has been largely demonstrated by CSIRO to meet advanced LIGO requirements. Sapphire is a harder material than fused silica and takes longer to polish, but the requirement of 1 nm rms has been met in a demonstration polish of a 6 inch diameter part. CSIRO is now working on demonstrating that they can provide a radius of curvature of 50 km +/- 5 km. This does not appear to be high risk, and should be possible. Extending this to full size substrates is low risk.

1.2.3. Optical homogeneity

The optical homogeneity of the current test substrates is far below the LIGO needs. The requirement listed in the table is a guess, also the requirement of the spectral density of the inhomogeneity is unknown and needs a careful study. The best guess right now is that a factor of 10 attenuation of the inhomogeneity is needed before sapphire can be used. The possibilities are

- spot polish by Goodrich: this is in process with a result expected by Nov(?). The correction that may be achieved is limited by the size of the polishing tool, in this case ~1 cm. This is likely to be inadequate. I don't know if Goodrich is able or willing to try again with a smaller tool.
- spot coating by Lyon: we have a sapphire part available to be sent to Lyon to try this. Theoretically the coating correction can be made very small, however this will drive up the time and cost of the coating run. This possiblity should be investigated as soon as we learn about the results of the Goodrich test. One possibility may be to combine a corrective polish and coating.
- ion beam etching: CSIRO wants to develop this capability. Kodak already has it. This may be the way to go, as it will have high spatial resolution and possibly high speed. It may leave a degradation in surface microroughness but since it will be applied to side 2 of the optic that shouldn't be much of a problem. I don't know if it has been applied to sapphire. We should investigate it ASAP.
- substrate growth: there appears to be the possibility that the inhomogeneity may be lower for a-axis sapphire than m-axis. We have received an a-axis part with significantly lower inhomogeneity; however it is not clear whether this is due to the orientation or boule location, and if it is repeatible. We will be testing this with another a-axis growth run, but we still need to pursue the corrective procedures in parallel.

1.2.4. Bulk scatter

The requirement for bulk scatter is not very severe and it looks like we should have no trouble meeting it. The two components of the scatter are Rayleigh scattering and scattering from bubbles or inclusions. The Rayleigh scattering is low, and the inclusion level is small for the half-size parts that we have looked at. We need to see what this looks like for the full size substrates due in 6/02.

1.2.5. Coating birefringence

The measured birefringence for a 3" diameter part was 2 x 10^{-4} rad, meeting the LIGO requirement. This is not expected to change for a full size part but it needs to be tested. We should coat the 10" part currently being used for the spot polish sometime next year, and measure the coating birefringence.

1.2.6. Absorption

The nominal CS absorption is ~80 ppm/cm. We have seen air annealed samples reach 10 ppm/cm at certain points in their bulk. We have been unable to establish any correlation of absorption with starting material or boule location so we are concentrating on the annealing runs. We now suspect that contaminants from the furnaces may be causing absorption so we have purchased new high temperature furnaces with designs that should provide high levels of cleanliness. We are now also comparing absorption of samples annealed at Stanford with those annealed at CS. The general outline of absorption tests in the future is:

- 10/01: sapphire samples have absorption measured at Stanford, then divided between Stanford and CS for air annealing at ~1400 C. The samples will be remeasured at Stanford to examine the effects of annealing at the different furnaces. This may give insight as to whether the CS anneals are being limited by contamination.
- 11/01: new high temperature furnace arrives at Stanford. The annealing comparison between Stanford and CS will be repeated at ~1600 C. Possibly different sapphire starting materials will be tried.
- sometime 12/02: a new large furnace will need to be bought to extend the annealing studies to large substrates.

1.3. SIOM

1.3.1. Size

SIOM is currently designing and building a furnace to produce full size LIGO substrates by 6/02. It seems unlikely that they will be able to produce LIGO quality parts by then, since they have never attempted anywhere near this size (and quality) in the past. Still, we may learn something about optical homogeneity and absorption in the process.

1.3.2. Optical homogenetiy

We have asked SIOM to deliver a half size part for us by 3/02 so we can examine its homogeneity. Homogeneity of the full size substrate will be examined in 8/02

1.3.3. Absorption

We have asked SIOM to engage in an absorption study similar to the CS effort. They will send us 1 cm samples grown from different starting materials, annealed at different temperatures, etc, so that we can try to establish a prescription for lowering the absorption. What we learn here could possibly be transferable to CS. We should start to receive the samples sometime in 9/01.

2 COATING DEVELOPMENT

The coating R&D is aimed at reducing both mechanical loss and absorption, while at the same time keeping the scatter and birefringence at acceptable levels. The following table gives the coating requirements for both sapphire and fused silica substrates. Since little is known about these requirements for materials other than SiO_2/Ta_2O_5, I have listed the risk as medium for all, except for absorption of 0.05 ppm, which has a high risk.

Table 2: Coating requirements

Parameter	Sapphire Value	Fused Silica Value	Risk level Sapphire/FS	Completion
Mechanical loss	10^{-4}	10^{-5}	med/med	12/02
Absorption	0.2 ppm	0.05 ppm	med/high	12/02
Birefringence	2×10^{-4} rad	2×10^{-4} rad	med/med	12/02
Scatter	10 ppm	10 ppm	med/med	12/02

2.1. Mechanical loss

The mechanical loss studies will be carried out at Stanford, MIT, Syracuse, and Glasgow. The study will be done by looking for mechanisms of loss (such as # of interfaces, total thickness, substrate preparation) for SiO_2/Ta_2O_5 at Lyon, while at MLD we will be looking empirically at the loss of different materials. The substrates are provided by Waveprecision and after some false starts, we are getting the substrate preparation and surface polish that we need. We expect to get the first set of substrates to Lyon by the end of 10/01 and start the mechaical loss coating runs by 11/01.

2.2. Absorption

The coating absorption requirements are those, coupled with the substrate absorption of 1 ppm/cm (fused silica) and 10 ppm/cm (sapphire) which will allow operation of the advanced LIGO *without* thermal compensation. Stanford will supply most of the measurements. They have a new postdoc who will replace Alex (who is still consulting). The coatings will be supplied initially by MLD, expected to begin by the end of 10/01. If measured mechical loss substrates are available we will include them in the MLD coating runs. Otherwise, if a coating shows an improvement in absorption we will also examine its mechanical loss.

2.3. Birefringence and Scatter

The goal here will be to keep the birefringence and scatter at the levels shown in table 2 for coatings that show reduced mechanical loss and absorption.

2.3.1. Scatter from coating defects

Defects may appear in coatings from inclusions in the substrate or from contaminants in the coating process such as dust or target impurities. Defect scatter has not yet been measured on sapphire substrates, and it also needs to be quantified for the chosen coating vendor.

2.4. Coating test substrates

The coating test substrates will initially be fused silica. Once we have started to zero in on appropriate materials and design we will repeat the tests with sapphire substrates (expensive and long lead.)

3 INSTRUMENTATION

The following table lists where the optics measurements will take place.

Table 3:

Measurement	Where	Comment
Surface figure, radius of curvature	Caltech phase interferometer	
Optical homogeneity	Caltech phase interferometer	
Bulk scatter	Caltech inspection microscope	need to quantify for large substrates
Coating birefringence	Caltech loss scanner	Kells can do this with my help
Substrate absorption	Stanford, Caltech alexometer Caltech contamination cavity	contamination cavity (Kells?) can verify alexometer calibration
Coating mechanical loss	Stanford, MIT, Syracuse, Glasgow	
Coating absorption	Stanford, Caltech alexometer	
Coating scatter	Lyon Caltech contam cavity	Lyon has scatterometer contam cavity does ringdown
Coating defect scatter	Caltech loss scanner	Kells with my help

4 VENDOR ORDERS

The following table lists outstanding vendor orders.

Table 4:

Vendor	Item	status	cost
CS	Sapphire mechical loss substrates	deliver 11/01	$50 K
CS	35 cm dia substrates (~6 runs)	deliver 6/02	$150 K
CS	large a-axis substrate	order 10/01	$80 K
CS	absorption test samples	continuous	
SIOM	35 cm dia substrate	deliver 6/02	$250 K
SIOM	absorption test samples	deliver start 10/01	
SIOM	optical homogeneity sample	deliver 3/02	
Lyon	Mechanical loss coating runs (6)	deliver start 11/01	$350 K
MLD	Absorption loss coating runs (4)	deliver start 10/01	$25 K
Goodrich	Corrective polish	deliver 11/01	$40 K
CSIRO	Corrective polish R&D: spot polish, ion etch	?	?
Kodak	Ion beam etch	(should pursue)	

5 OTHER OPTICS R&D

5.1. Thermal noise

It is important that thermal noise of the coated substrates can be investigated. This is particularly true since we are investigating new coating designs that we have no experience with: the material parameters such as thermal conductivity, index of refraction variation with temperature, Young's modulus, etc., are not well known for thin films and directly impact thermal noise mechanisms including Braginsky's photothermal shot noise and possibly others we haven't thought of.

The possibilities for thermal noise measurement are the TNI and the coating anelastic loss measurement technique (Willems). Both should be vigorously pursued so that we have some way of examining the thermal noise of coated substrates before we settle on a final optics design. *This area remains an important gap in our ability to qualify the optics before installation in the interferometer.*

5.2. Contamination

Unfortunately, contamination studies need to be revisited for the advanced LIGO: new materials are being introduced in LIGO for the seismic system, and the advanced coating absorption requirements are tighter than those examined in the contamination work for LIGO I. We have three contamination cavities at Caltech. One should remain in the OTF for coating scatter and absorption studies but the other two can be used for contamination work. The open question of the possible contamination of the coatings from viton evolved flourine should be answered once and for all.