LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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Core Optics II

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1 OVERVIEW

The LIGO II Core Optics are comprised of the four test masses (two input and two end test masses) which make up the Fabry-Perot arms of the interferometer, a beamplitter, a power recycling mirror and a signal recycling mirror. The Core Optics provde the required light storage time in the arms and maintain the stored optical power at the beamsplitter consistent with the overall required shot noise sensitivity. This is be achieved while limiting the contrast defect at the interferometer dark port to less that ***X watts*** at the photodiode.

Reaching the LIGO II sensitivity will require reducing the displacement noise of the mirror surfaces caused by off resonance thermal noise which in turn requires very low mechanical dissipation in the test masses. The LIGO I detector uses fused silica test masses, and internal thermal noise of the masses is expected to be a limiting factor in the sensitivity at the minimum noise frequency near 100 Hz. Further reduction of thermal noise is expected principally from the use of sapphire because of its much lower mechanical dissipation ***phi<3x10-9***. Sapphire is commercially available in sizes near those required for the LIGO test masses, and its higher density will result in a reduction of the radiation pressure noise over comparable sized silica mirrors while at the same time its large thermal conductivity will result in better power handling. A lower limit to the performance of a sapphire interferometer is imposed by thermoelastic damping noise, resulting from the increased thermal conductivity of sapphire[1]. The result is that sapphire interferometer gains a factor of ~1.5 increase in sensitivity over a fused silica interferometer (see figure 1). This results in an increase of 3.4 in our best estimate of the rate of observed neutron star binary coalesnece.

Sapphire research and development is structured around four principal areas:

- Polishing: the optics surface microroughness and long-range surface figure must achieve a high level of uniformity
- Coating: the coating must be sufficiently low mechanical loss, low optical absorption, and have low birefringence
- Material: the sapphire substrate must have very low loss, low birefringence and low absoprtion
- Crystal growth: crystals must be grown for full size LIGO optics while meeting the polishing, coating, and materials requriements.

Fused silica will be maintained as a fall back position in the event that sapphire is not available at the LIGO II requirements on a time scale consistent with the LIGO II schedule. The main issues for the development of LIGO II fused silica are, substrate absorption, sample size and coating absorption.

A development program involving the study of small sapphire samples will take place in 2000, allowing information to be fed back to the manufacturer to test the growth of full size pieces in 2001-2002. Research in fused silica will proceed in parallel, maintaining its use as a fallback position. A decision on the Core Optics material will be made in 2003, allowing the optics to be fabricated, polished, and coated in time for the planned installation in LIGO II in 2005.

1. Braginsky,etc.

(figure 1 shows sapphire strain vs. fused silica)

2 REQUIREMENTS

The requirements for the LIGO II optics is given in the following table and a description of the physical basis for these requirements follows.

Table 1:

Parameter	*Sapphire Test Mass*	*Fused Silica Test Mass and Beamsplitter*	*Fused Silica Power and Signal Recycling Mirrors*
Surface Figure	0.5 nm rms	0.5 nm rms	1 nm rms
Microroughness	0.2 nm rms	0.2 nm rms	0.2 nm rms
Substrate homogeneity	10 nm rms	10 nm rms	30 nm rms
Coating absorption	0.5 ppm	0.1 ppm	0.5 ppm
Substrate absorption	10 ppm / cm	0.5 ppm / cm	50 ppm / cm
Coating Birefringence	10 mrad	10 mrad	50 mrad
Substrate Birefringence	0.1 rad	0.1 rad	0.1 rad
Mechanical Q	3×10^8	5×10^7	5×10^7

- Surface Figure: the rms deviation from a perfect sphere causes optical modal contamination and an increase in contrast defect. The requirement is consistent with the specified interferometer shot noise limited sensitivity.
- Microroughness: the local rms microroughness causes large angle scattering of the beam incident on the optics surface, resulting in loss of stored power and phase noise if the scattered light is recombined with the main beam.
- Coating and substrate absorption: absorption in either substrate or coating will result in non uniform heating in the optic, generating a thermal lens which will give rise to distortion of the wavefront propagated through the transmissive input test masses and beamsplitter. This is a problem primarily for the sidebands which resonate only in the nearly unstable recycling cavity. The requirement limits the thermal distortion of the input test masses to ~100 nm. This distortion will be reduced to the level of the substrate homogeneity requirement with the use of the Core Optics thermal compensation.
- Coating and substrate birefringence: birefringence encountered by the beam in transmission through the optics substrate or in reflection from the coatings will cause a rotation of the polarization of the light, resulting in loss at the polarization-sensitive beamsplitter. The requriement limits this loss so that the power recycling cavity stored power is at the required level.
- Mechanical Q: the Q must be sufficiently high to limit off-resonance thermal noise to acceptable levels. The Q must not be degraded below the requirements by the application of coatings or attachments to the optics.

3 REFERENCE DESIGN

The Core Optic Components for LIGO II will consist of four sapphire test masses, fused silica power and signal recycling mirrors, and a large fused silica beamsplitter. The sapphire test mass size (35 cm x 10 cm) and radius of curvature (50 km) are chosen so that the beam spot size at the test mass optics is sufficiently large (6 cm) to keep the thermoelastic damping noise (which scales as $1/spot^{3/2}$) at the level shown in figure 1, while limiting the loss due to optic aperturization to ~1 ppm. Sapphire masses of this size can currently only be grown by the heat exchanger method in m-axis orientation. The test masses will be oriented in the interferometer so that the polarization of the light is aligned with the optical axis of the crystal, minimizing any polarization rotation of the light due to substrate or coating birefringence. The beamsplitter diameter (40 cm), and signal and power recycling mirror diameters (25 cm) limit aperturization loss to ~ 100 ppm in the recycling cavity. In the fallback case of fused silica test masses, the spot size could be reduced to ~4 cm, allowing the use of LIGO-I sized optics of diameter 25 cm.

The reflectivities of the optics are listed in Table 2, for both the sapphire and fused silica test mass fallback option. All optics will contain wedges on the back, antireflection coated side to prevent back reflected light from interfering with the main beam.

Table 2:

Optic	*Reflectivity*	
	Sapphire Test Masses	*Fused Silica Test Masses*
Power Recycling Mirror	0.99	0.995
Signal Recycling Mirror	0.9	0.95
Beam Splitter	50 +/- 0.5%	50 +/- 0.5%
Input Test Mass	0.99	0.995
End Test Mass	0.99999	0.99999

The reflectivities of the optics are chosen to satisfy the shot noise requirements by achieving the proper buildup of light in the interferometer cavities, and also to limit the problem of substrate deformation due to thermal loading. In the case of sapphire test masses the power recycling gain is chosen to be 15, with an arm cavity finesse of 1000, while in the fallback case of fused sillica test masses the recyclling gain is 100, with an arm cavity finesse of 200. In both the sapphire and fused silica test mass case the coating reflectivites are chosen so that the substrate heating is equally distributed between the substrate and coating absorption, minimizing the total heat deposit. For substrate and coating absorption consistent with the requirements of Table I, both sapphire and fused silica test mass materials suffer a substrate lens caused by the thermal loading, of order 100 nm peak-valley. This distortion must be reduced by compensating the absorbed power with external heating (this is explained in the section on Optics Thermal Compensation.)

4 RESEARCH AND DEVELOPMENT

LIGO has identified ***three*** sources of sapphire that appear to have the best chances of being able to grow crystals to the necessary size and purity. The first is Crystal Systems of Salem, MA. Crystal Systems has developed a proprietary technique for growing sapphire, the Heat Exchanger Method (HEM) which currently grows 34 cm diameter boules which are 30 cm thick along the m axis crystal direction. The second potential source is the Shanghai Institute of Optics and Mechanics, Shanghai, China, which has demonstrated the growth of half-size samples of good optical quality along the c-axis direction, and the third is ***XXXX in Russia***. The following topics will require research and development in the Core Optics.

Procurement of the substrates at the required diameter and thickness will be challenging. None of the three potential sapphire vendors has yet grown sapphire crystals able to meet the full LIGO requirements. Starting in 2001, the results of the research undertaken in 2000 to understand the research issues listed below will be fed back to the vendors to attempt the growth of full size substrates. Crystal Systems has already demonstrated sapphire crystal growth in the m-axis direction at the necessary size. SIOM has to date only grown half-sized c-axis samples, and may require a capital investment in large ovens, dependent on the outcome of the research tasks of this year. The growth of samples by techniques other than the heat exchanger method is under investigation by a collaboration of ***XXX*** and Crystal Systems. Fused silica has been produced at diameters.....

The polishing of sapphire to the level of the requirements has not yet been demonstrated. Sapphire is a very hard material which requires special polishing techniques including long polishing runs. It must be polished to give a smooth surface both on small scales (microroughness), and large scales (surface figure). While the microroughness requirement has been demonstrated for small samples, the surface figure specification over the full size optic has not. In addition, compensation for the optical inhomogeneities undergone by the wavefront as it is transmitted through the non-uniform optic must obtained. This will be done by using a process of optical homogenity measurements followed by spot polishing of the optic back side. This process is now under development: several substrates will be sent to polishing vendors used in LIGO I to develop polishing techniques to meet LIGO II requirements. Preliminary measurements on a sample 15 cm in diameter and 8 cm thick show an optical homogenity of ~0.15 waves peak to valley, which would require a reduction of roughly a factor of three to meet requirements.

The substrate and coating absorption of the core optics are critical paramters which determine the thermal loading of the interferometer. Present measurements of a large set of sapphire test pieces indicate a baseline “best” substrate absoprtion of approximately 80 ppm/cm. The R&D effort is aimed at reducing this absorption to 20 ppm/cm with a uniformity of ***XX*** ppm/cm within samples and ***YY*** ppm/cm between samples. There is good reason to believe that the absorption is the result of several defects in the material including possibly metal impurities, oxygen vacancies, color centers and ***XXX’s***. Investigations are underway examining the effect of starting materials purity and charge preparation, segregation of impurities during growth, and effects of annealing temperature, duration and atmosphere. These studies have suggested that a simple selection of the best material will not be sufficient for our purposes and that it will be necessary to do post growth processing, possibly including sample harvesting, regrowth and high temperature purification. Substrate absorption in fused siica has already been demonstrated at the level indicated in table I and is expected to be realizable for full size optics. Finally, the coating absorption must be brought

down to 0.1 ppm to limit thermal loading in fused silica. Lowering of the coating absorption will be attempted by obtaining very high purity target materials for the coating which are free of impurities that may be responsible for the absorption, and possibly by doping the target materials with trace elements which would eliminate charging of the individual coating layers during the coating process. This work will be undertaken by the LIGO-I coating vendor, REO, and also by the VIRGO coating facility, in collaboration with LIGO. Previous work in reducing absorption in coatings has resulted in a decrease in the coatings over the last 15 years from 100 ppm/cm to 0.6 ppm/cm, and we are optimistic that another factor of 5 decrease in absorption will be realizable.

Birefringence is a concern for sapphire, which is an anisotropic crystal. Birefringence is of greatest concern for m-axis crystal orientation, where the anisotropy of the substrate in a plane containing the light electric field (propagating along the m-axis) is largest. It is also a concern for the plane onto which the coating is deposited; the plane will expand differentially as the coating process causes the substrate to heat, causing nonuniform strain and hence birefringence when the substrate cools. Initial measurements indicate that the birefringence in m-axis sapphire substrate and coating meet the requirements of Table I[1]. Further work is needed in mapping the birefringence over the beam spot area to ensure that variability of the birefringence does not result in an unacceptable distortion of the interferometer light polariziation.

Finally, the mechanical Q of sapphire measured for the final coated and suspended optics must be shown to meet requirements. The effect of polishing, coatings and suspension attachments on thermal noise will be investigated by measuring the mechanical Q of uncoated and unattached samples and then following up with Q measurements of the attached and coated samples.

1. Blair paper