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OPTICS DEVELOPMENT FOR LIGO

Stanley WHITCOMB*, GariLynn BILLINGSLEY, John CARRI, Alex GOLOVITSER, Doug JUNGWIRTH, William KELLS, and Hiro YAMAMOTO
LIGO Project, M/S 51-33, California Institute of Technology, Pasadena, CA 91125 USA

and

Brett BOCHNER, Yaron HEFETZ[†], Partha SAHA, and Rainer WEISS
LIGO Project, Massachusetts Institute of Technology, Room 20 B 145, 18 Vassar Street, Cambridge, MA 02139 USA

ABSTRACT

The large optical components (the test masses, beamsplitters, and recycling mirrors) represent one of the most challenging aspects for large gravitational wave interferometers. The requirements for the LIGO optical components have been derived using a computer model of the interferometer which uses an FFT-based optical propagation code. This model includes the surface figure of all optical components, the homogeneity of the substrates, an allowance for losses due to scattering and absorption in the optical coatings, and the carrier and sideband modulation/detection technique. To meet these requirements, LIGO has undertaken a program to work with industry to evaluate and improve current fabrication capabilities. Full-size LIGO test masses have been polished and measured for microroughness and surface figure. Evaluation of these optics show that it is possible to polish and measure optic substrates with surface figures accurate to < 1 nm over spatial scales from 0.2 mm to 10 cm. To measure coating uniformity, LIGO has developed a technique using measurements of the reflectivity of specially-designed two-layer coatings to extract the thicknesses of the individual layers with a precision of $\sim 0.02\%$ (rms). This paper summarizes the requirements for LIGO optics that have been derived, results from the polishing development, and preliminary data on the large-scale uniformity of ion-beam-sputtered coatings.

1. Introduction

The large optical components represent one of the most challenging aspects for large gravitational wave interferometers. The large optical components ("Core Optics") in a LIGO interferometer[1] (see Figure 1) consist of four test masses (two end mirrors and two input mirrors), a beamsplitter, and a recycling mirror. The total number required for the three initial LIGO interferometers is 20, 6 each for the Washington and Louisianna 4 km interferometers and 8 for the Washington 2 km interferometer (the 2 km interferometer also includes 2 folding mirrors which must meet requirements similar to those of the recycling mirror). In addition, a number of spares are required to insure against possible damage during the fabrication and installation processes. Because of the long time required for their fabrication, these spares must be procured along with the main optics.

The LIGO Core Optics will be made from high purity fused silica. They will

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[*] This paper was presented at the TAMA Workshop for the LIGO Project by S.E. Whitcomb.

[†] Current affiliation: Elscint, Nuclear Medicine Division, Haifa, Israel

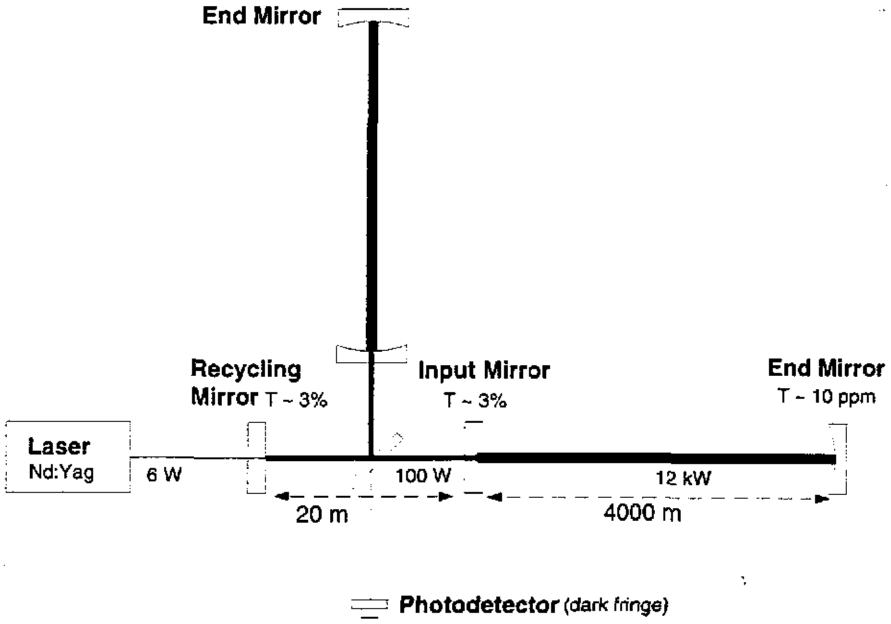

Figure 1: A schematic diagram of a LIGO interferometer showing the Core Optics.

be 25 cm in diameter × 10 cm thick (except the beamsplitter which will be ~ 4 cm thick). Beams fill some of the optics, with approximately 1 part per million (ppm) of the total intensity lost outside the mirror. All optics have enhanced reflectivity 1064 nm coatings on one surface and anti-reflective (AR) coatings on the second surface. Their principal performance requirements include:

< 50 ppm loss per surface	$\Rightarrow$ Limit loss of resonant stored energy: minimize shot noise
Surface figure errors to scatter negligible power from TEM_{00}	$\Rightarrow$ Best dark fringe
High mechanical Q ($Q > few \times 10^6$)	$\Rightarrow$ Minimize thermal noise
Low bulk (< 5 ppm/cm) and coating (< 2 ppm) absorption	$\Rightarrow$ Limit effect of thermal lensing on power and dark fringe contrast

2. Defining the Optics Requirements

The primary tool for investigating the effects of different optical parameters on the LIGO interferometer sensitivity is a computer model of a full recycled Michelson interferometer with Fabry-Perot arms.[2–5] This computer model is based on original code provided to LIGO by Jean-Yves Vinet and Patrice Hello of the VIRGO Project.[6] This computer model uses an FFT-based optical propagation code. It includes the surface figure of all optical components (either real or simulated maps of the surface errors) and the optical pathlength difference (OPD) maps of substrates for the input mirror and beamsplitter. It solves for both the carrier and the

Table 1: partial listing of requirements for the LIGO Core Optics.

Physical Quantity	**Test Mass**		**Beam splitter**	**Recycling Mirror**
	End	**Input**		
Diameter of optic (cm)	25	25	25	25
Thickness of optic (cm)	10	10	4	10
1 ppm intensity dia. (cm)	24	19.1	30.2[a]	19.2
Lowest internal mode (kHz)	6.79	6.79	3.58	6.79
Mass of optic (kg)	10.7	10.7	4.2	10.7
Nominal surface 1 radius of curvature (m) and g factor	7400 $g_2 = 0.46$	14571 $g_1 = 0.72$	inf	9998 $g = 0.98$
Tolerance on radius of curvature (m)	absolute: ± 220 matching: ± 111	-1000, +145	> -720 km convex, > 200 km concave	-100, +500

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[a] For these 45° angle of incidence optics, this is the smallest diameter circle centered on the optic face which is everywhere outside of the 1 ppm intensity field.

modulation sidebands, and combines them to realistically model the demodulated gravitational wave signal. Important features of the code include its adaptation to a supercomputer[4] and development of a fast convergence algorithm,[3] enabling full recycled interferometers to be modeled rapidly. It has been tested in a variety of limiting cases against a semianalytic modal model that was developed independently.

This model has been used to develop a set of requirements for the LIGO Core Optics. These requirements include the size of the optics (to ensure that diffractive losses are not too large), surface figure, scatter losses, and tolerances on radii of curvature. Some of these requirements are sumarized in Table 1.

3. Optics Development Program ("Pathfinder")

To ensure that LIGO can obtain suitable optics for its inital detectors, an optics development program (called "Pathfinder") has been underway for some time. The purposes of this program were to evaluate the state of the art in optical fabrication and metrology, to initiate work to further the state of the art where needed, and to identify companies with the ability to fabricate the LIGO Core Optics. The main steps in this program were:

- Purchase and evaluate fused silica blanks (5/94)
- Best effort polishing of substrates (8/95-4/96)
- Independent substrate metrology (4/96-8/96)

- Coating uniformity development (7/95-ongoing)
- Coated optic metrology (expected in early 1997)

Industrial partners were engaged in all phases of this effort. Data from the Pathfinder are analyzed in the LIGO computer model to assess the performance of the optics against the requirements.

4. Substrate Material Results

The Pathfinder program began in 1994 with the ordering of a number of large fused silica blanks to be fabricated into finished components. These blanks were specified to have bulk index of refraction variations $\delta n \leq 5 \times 10^{-7}$ through the 10 cm thickness. The order was placed with Corning and other specifications were consistent with their specifications for OAA Grade 7940 fused silica. Optical homogeneity maps were provided with each Pathfinder fused silica blank and these were evaluated using FFT model. These analyses indicate sufficient homogeneity that optical distortions due to transmission thorough the beamsplitter and input mirror substrates would not degrade the optical performance of the initial LIGO interferometers.

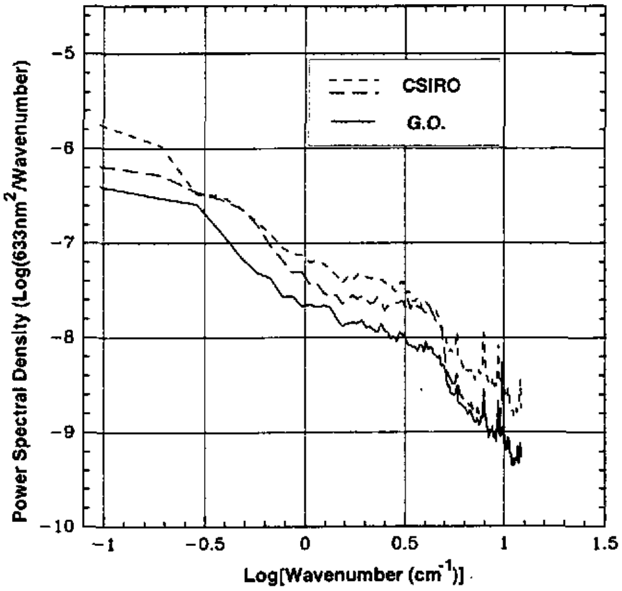
Mechanical Q's for the five lowest-frequency internal vibrational modes were measured on one of the Pathfinder substrates after polishing.[7] For these modes, the average Q was $> 5 \times 10^6$. These values meet the requirements for the initial LIGO interferometers.

In late 1995, the LIGO project made a decision to switch from using visible Argon ion lasers to using Nd:YAG lasers operating at 1064 nm. This change made the Corning fused silica unsuitable in one way. The large dependence of the index of refraction with temperature dn/dT in fused silica requires very low absorption to avoid thermal lensing of transmitted beams in the beamsplitter and input mirrors. Measurements by the VIRGO project[8] have shown a correlation between 1064 nm absorption and OH concentration. Typical high purity fused silica contains 500-1000 parts per million (ppm) OH giving 10-20 ppm/cm absorption, which is too high for the input mirrors and beamsplitters. Fortunately, the VIRGO project has determined that Heraeus has a process which yields fused silica with $\sim$200 ppm OH ($\sim$5 ppm/cm absorption). In the initial LIGO interferometers, the low absorption of the Heraus substrate material is only critical for input mirrors and beamsplitters where the laser light is increased by the recycling cavity.

Orders for approximately 40 blanks were placed in 1996, with delivery scheduled for 1997. Heraeus was selected for input mirrors and beamsplitters and Corning for all others. The total number of blanks ordered allows for both spare finished optics and for any problems during the fabrication process.

5. Core Optics Polishing Demonstration

The Core Optics polishing demonstration was carried out through best effort polishing and metrology of full-size substrates. Three companies participated in this



One dimensional power spectra from NIST metrology of curved surfaces. Z(0,0),Z(1,1) Z(2,0),Z(2,2),Z(3,1),Z(3,3),Z(4,0) removed

Figure 2: Comparisons of the power spectra of the deviations from the perfect figure of the CSIRO and GO pathfinder substrates as measured by NIST.

effort: Commonwealth Scientific and Industrial Research Organization (CSIRO), General Optics (GO), and Hughes-Danbury Optical Systems (HDOS). Each of these companies polished full size substrates with characteristics typical of the LIGO Core Optics. The specification called for the optics to be polished concave on one side with a radius of curvature of 6000 m and flat on other side.

The requirements for these polishing efforts were derived using the FFT optical model for the LIGO interferometers and tailored to the known capabilities of different classes of polishers. For CSIRO and HDOS, the primary goal was to demonstrate "mid scale" surface figure errors (after removing focus error and astigmatism) < 0.8 nm rms over the central 8 cm diameter; a second requirement was to achieve simultaneously a microroughness < 0.4 nm rms. For GO, the requirements were a surface figure error $< \lambda/20$ with a microroughness of < 0.1 nm.

To provide a consistent comparison of the figure errors in the polished sustrates, independent metrology was performed by Chris Evans, Robert Parks, and Paul Sullivan at the National Institute of Standards and Technology (NIST). The technique used involved multiply redundant measurements on an existing 633 nm phase shifting interferometer, analyzed to give absolute metrology at the subnanometer level. With care, measurements at < 1 nm level proved possible. Reproducible features were seen and consistent intercomparisons demonstrated at this level. The instument used gave information on spatial scales from its full aperture (15 cm) down to 3mm. Figure 2 shows power spectral densities of the figure errors for the GO and CSIRO substrates derived from these measurements. The HDOS results were

Table 2: Comparison of microroughness of polished substrates as measured by REO (using a Micromap instrument with a 20X objective).

Polisher	**Serial Number/ Surface**	**Microroughness (Å) (Ave. 5 Locations)**
CSIRO (< 4 Å reqt.)	006/Curved	3.6
	006/Flat	2.8
	002/Curved	2.7
	002/Flat	3.1
GO (< 1 Å reqt.)	005/Curved	0.85
	005/Flat	0.88

overall comparable to those for CSIRO.

The most important conclusion from Figure 2 is that polished surfaces with rms deviation (after removing focus and astigmatism) < 1 nm over ~ 20 cm diameter are achievable! In some cases, apparent deviations ~ 0.5 nm were measured.

To evaluate the microroughness of the various substrates, comparative surface roughness measurements were made at Research Electro-Optics (REO). Table 2 shows the result of these measurements. Microroughness contributes to large-angle scattering, and thus is particularly important for the test masses where the light intensity is greatest. Again, the HDOS results were comparable to those for CSIRO.

Based on the Pathfinder results and on competive proposals, GO and CSIRO have been selected to polish the LIGO Core Optics.

6. Coating Uniformity Development

In developing coating uniformity, the LIGO project has collaborated with Research Electro Optics (REO). The goal of this effort is to scale REO's low-loss ion-beam-sputtered coating technology to LIGO diameters. Preliminary work has focussed on developing the techniques needed to quickly measure coating thickness variations over both long and short spatial scales and optimizing the coating process.

The technique developed for measuring coating uniformity[9] involves mapping the reflectivity of specially-designed two-layer AR coatings (see Figure 3). Near the reflectivity minimum, the reflectivity depends on the interference of the fields from the three interfaces in a two layer stack and is thus a strong function of the thickness of the two layers. By mapping the reflectivity at different angles of incidence and polarizations, one can derive maps of individual coating layers by fitting the observed reflectance maps through a least-squares minimization process. A standard set of measurements consists of six maps at 2 polarizations and 3 different angles of incidence.

The AR coating design which was selected for initial testing is the design shown

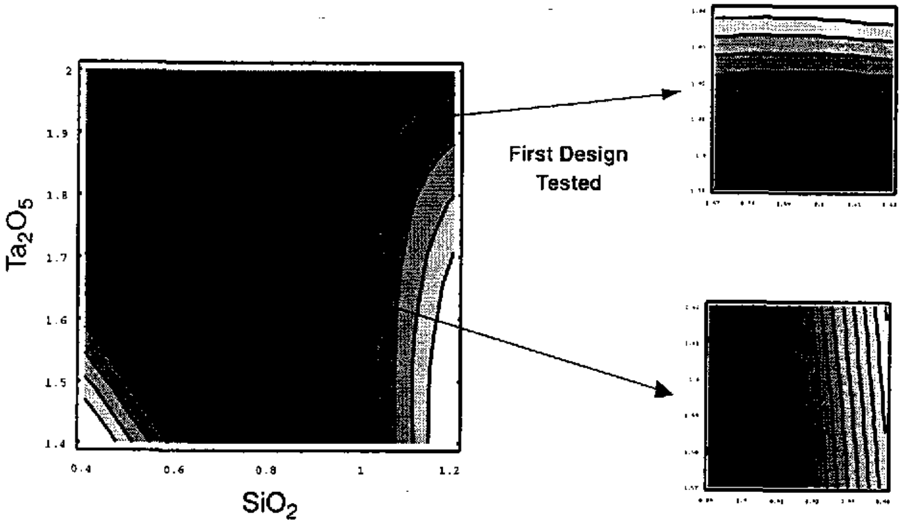


Figure 3: A contour map of the reflectivity of a two layer stack highlighting designs with predominant sensitivity to Ta_2O_5 (top right) and to SiO_2 (bottom) thickness.

in the top right of Figure 3. This coating is primarily sensitive to the thickness of the Ta_2O_5 layer. A 24 cm diameter test piece was coated with this design. Reflectance measurements were made with the apparatus shown in Figure 4. Typical reflectance scan data show good reproducibility ($< 0.2\%$); because of the steep dependance of reflectance on layer thickness this permits the thickness variations of the Ta_2O_5 layer to be determined with a precision of $\sim 0.02\%$. One advantage of this technique is that it is insensitive to the surface figure of the underlying substrate, thus permitting multiple iterations in the coating chamber with easily obtainable, inexpensive substrates.

After a complete set of measurements is performed, individual maps of thicknesses for the two layers are determined by a least squares minimization process. This minimization takes into account known instrumental effects and uncertainties. For the initial test coating, maps of the thickness of the SiO_2 and Ta_2O_5 layers are shown in Figure 5.

To evaluate this coating against our requirements, we fit the maps in Figure 5 with Zernike polynomials up to tenth order. Residual deviations from the fits are consistent with measurement errors indicating that the fine structure observed in Figure 5 is dominated by noise in the measurements and therefore not a real property of the coating. These layer maps are then stacked in a coherent way to synthesize a predicted phase map for a HR coating. (The coherent stacking assumes that the observed structure is systematic and represents a worst case assumption about how the individual layer stack.) The predicted map produced in this fashion is shown in Figure 6.

The map in Figure 6 was then tested in the FFT optical model to assess its suitability in a LIGO interferometer. The shot-noise limited sensitivity for an in-

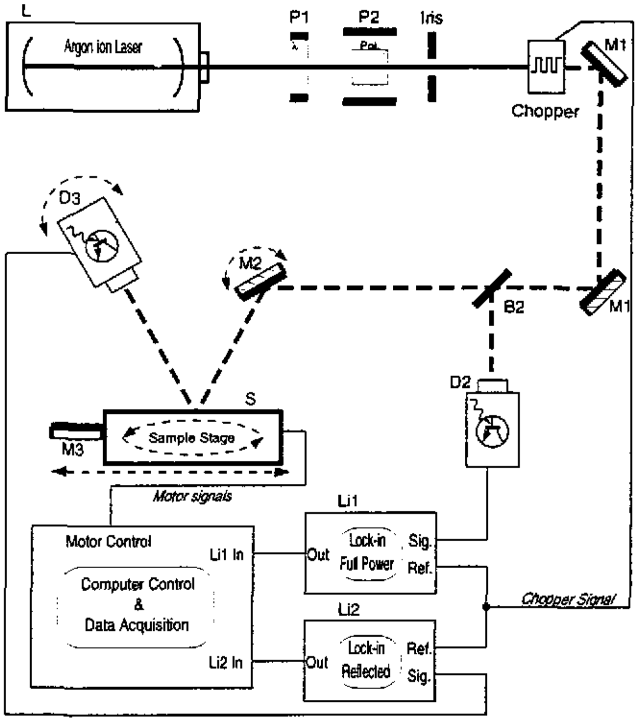


Figure 4: A schematic diagram of the apparatus used to test coating uniformity. A chopped Argon ion laser is used to illuinate the AR test piece which is mounted on the sample stage. Photodetectors D2 and D3 are used to measure the incident and reflected power respectively. The signals are synchronously detected and recorded by a computer which controls the motion of the motorized stage to map the reflectivity automatically. A quarter wave plate and polarizer are used to control the polarization of the incident light and the angle incidence can be adjusted by mirror M2.

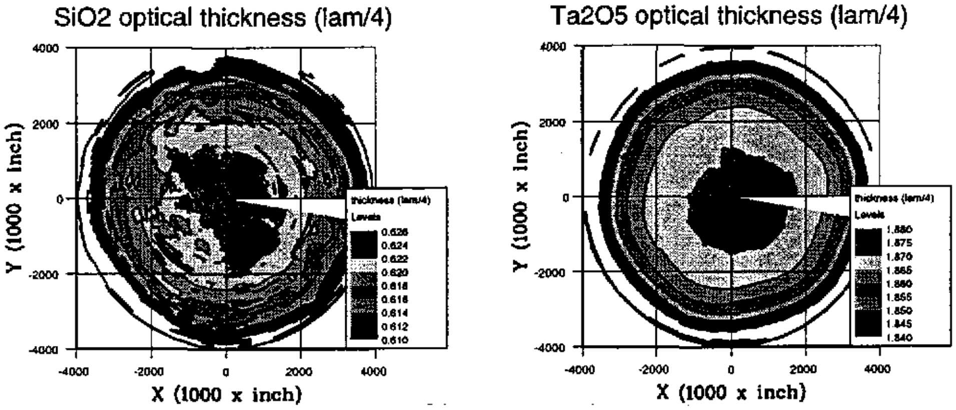


Figure 5: Maps of the thickness of the SiO_2 and Ta_2O_5 layers of the test coating. The smoother appearance of the Ta_2O_5 map is due in part to the fact that this map was made for a Ta_2O_5-sensitive coating, and thus noise in the measurement affects the derived Ta_2O_5 thickness less than that of the SiO_2.

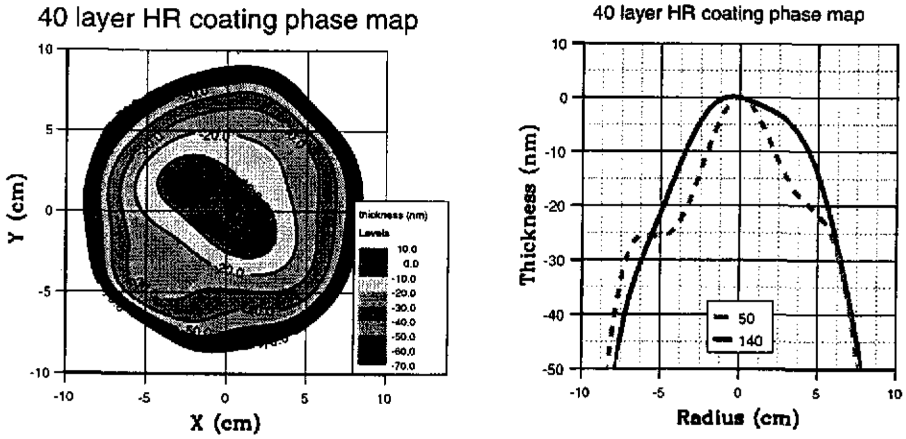


Figure 6: A simulated map of a 40 layer high reflector (HR) stack constructed from the individual layer maps from Figure 5. The graph at the right shows cuts through the map at two different angles.

terferometer with this surface profile used for end mirrors (and a similar one used for input mirrors) is compared with a standard configuration in which all of the mirrors have surface figures derived from maps of bare polished substrates in Table 3. Two measures of interferometer performance are compared in the table: the recycling factor and the shot noise limit to sensitivity at 100 Hz. These runs show some loss in sensitivity due to the coating non-uniformity, but the relatively modest degradation indicates that the coating non-uniformities are not too far from the required level.

The next steps in developing improved coating uniformity are beginning immediately. REO is making adjustments to their coating chamber and masking to reduce curvature. Once these are completed, they will make two new test AR coating runs, one identical to the coating tested above and one designed for high sensitivity to the SiO_2 thickness. If these are satisfactory then the Pathfinder optics will be coated with with HR coatings (at 633 nm). These will then be measured at NIST to confirm scaling from single layers to HR coatings.

> *Note: After this paper was presented at the Workshop, another iteration of the coating uniformity development was completed by REO, and the preliminary analysis of test data indicate that the uniformity has been improved by approximately a factor of 5 over the central 20 cm diameter region, and that the* SiO_2 *layer is similar, but not identical, to the* Ta_2O_5 *layer.*[10]

7. Summary

The Pathfinder program to develop the optics for LIGO is nearing its conclusion. It has enabled us to put in place the tools and techniques (both experimental and analytical) to evaluate optics against the LIGO requirements. The capabilities of

Table 3: Very preliminary estimates of the effect of coating nonuniformities on interferometer sensitivity.

Run Conditions	**Surface Figure (Årms)**	**Recycling Factor**	h(100Hz) ($\times 10^{-23}\mathrm{Hz}^{1/2}$)
Standard Configuration: Measured substrate OPD's Surface phase maps based on polished substrates	0.8	52	1.39
Standard Configuration, except 40 Layer HR substituted on End Mirror	3.8 (ETM)	17	2.14
Standard Configuration, except 16 Layer HR substituted on Input Mirror	1.9 (ITM)	33	1.73
Standard Configuration, except End and Input Mirror substituted	3.8 (ETM) 1.9 (ITM)	15	2.52

industry to manufacture substrate material and to polish the substrates appear to be adequate for initial LIGO interferometers. The main ongoing activity is the development of coating uniformity. Preliminary coating uniformity data are promising, and further improvements and testing are expected within the next few months. Procurement of the LIGO substarates and their polishing are underway.

Acknowledgements

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References

1. A. Abramovici, et al. *Science* **256** (1992) 325-333.
2. H. Yamamoto, in *Proceedings of the TAMA Workshop on Gravitational Wave Detection*, ed. K. Tsubono (Universal Academic Press, Tokyo. 1997).
3. P. Saha, submitted to *J. Opt. Soc. Amer.* (1997).
4. B. Bochner, Ph. D. Thesis, Massachusetts Institute of Technology, in preparation.
5. B. Bochner, to be submitted to *Phys. Rev.* **D** (in preparation).
6. J. Vinet, P. Hello, C. N. Man, and A. Brillet, *J. Phys. I France* **2** (1992) 1287.
7. J. Carri, Ph. D. Thesis, California Institute of Technology, in preparation.

8. B. Y. Baures and C. N. Man, *Optical Materials* **2** (1993) 241.
9. A. Golovitser, D. Jungwirth, and H. Yamamoto, to be submitted to *Appl. Opt.* (in preparation).
10. G. Billingsley, A. Golovitser, D. Jungwirth, W. Kells, R. Lalezari, S. Whitcomb, and H. Yamamoto, to be submitted to *Opt. Letters* (in preparation).