Science
Circulate

TECHNICAL NOTE

LIGO-T970255-00-D

Development of low-loss sapphire mirrors

D. G. Blair, M. Notcutt, C. T. Taylor, E. K. Wong, C. Walsh, A. Leistner, J. Seckold,
J.-M. Mackowski, P. Ganau, C. Michel, and L. Pinard

We report on the successful development of low-loss sapphire mirrors for use at a 1-μm wavelength. Methods for polishing and coating are described. The analysis of each process shows a roughness of better than 0.1 nm, a coating scattering of 1 ppm, and a surface scattering of 13 ppm. The mirrors have been characterized in a Fabry–Perot cavity, having a finesse of 100,000. Mode doublets result from the birefringence of the coatings. © 1997 Optical Society of America

Key words: Sapphire, mirrors, float polishing, low-loss coatings.

1. *Introduction*

Low-loss sapphire substrate mirrors have several important applications in metrology and precision measurements. Both the optical and the mechanical properties of sapphire make it an ideal material as a substrate for mirrors in gravitational wave detectors[1] and Fabry–Perot reference cavities.[2]

The optical components for these experiments should have minimal scattering and wave-front distortion for a beam transmitted through the mirror substrate, conduct away heat deposited in the coatings with as low a gradient as possible, and have minimal amplitude of mechanical thermal excitation that could introduce noise to a length measurement or standard.

In transmission through the mirror substrate, sapphire causes 30 times less wave-front distortion from thermal lensing than silica for a given amount of absorbed power.[3] This reduces the fraction of light not coupled into the TEM_{00} cavity mode. The absorption of sapphire has been shown to be as low as bulk fused silica,[4] ~5 ppm/cm.

Although the fractional losses expected in traveling through the substrate are 10 times larger than those in the mirror coatings, the cavity beam is F/π times higher in power (F being the finesse). The importance of these effects is determined by the interferometer or cavity configuration. Considering the relative thermal resistances of the reflective coating and the substrate, heat conduction away from the beam spot is through the substrate rather than the coating material. In this case the thermal conductivity of sapphire is an advantage in the reduction of thermal lensing in coatings.

The very high cryogenic thermal diffusivity of sapphire (8×10^{-4} m^2 s^{-1} at 77 K and 4×10^{-2} m^2 s^{-1} at 4 K) and its very low coefficient of thermal expansion ($\alpha = 5 \times 10^{-13} T^3$ K^{-1}, where T is the temperature and the constant has units in K^{-4}) indicates that sapphire Fabry–Perot cavities are well suited to the construction of ultrahigh-stability laser frequency standards[2] with sapphire spacers at cryogenic temperatures.

The very low acoustic losses in sapphire and the very high sound velocity make it a material with intrinsically low thermal noise. This is important for the construction of low-phase-noise optical cavities, particularly for laser interferometer gravitational wave detectors and their associated mode cleaner cavities where thermal noise is expected to set a measurement floor in long-baseline experiments.[5] We note, however, that the intrinsic Rayleigh scattering, which increases as the fourth power of the refractive index, is substantially higher for sapphire than silica and has a magnitude of ~19 ppm/cm.[6] This does not create thermal lensing but leads to unavoidable losses when beams transit the bulk material. This is relevant in recycled interferometer configurations.

For these reasons we have embarked on a program

D. B. Blair, M. Notcutt, C. T. Taylor, and E. K. Wong are with the Department of Physics, Australian International Gravitational Research Centre, University of Western Australia, Perth, Australia. C. Walsh, A. Leistner, and J. Seckold are with the Division of Applied Physics, National Measurement Laboratory, CSIRO, Sydney, Australia. J.-M. Mackowski, P. Ganau, C. Michel, and L. Pinard are with the Institut de Physique Nucleaire, Université Claude Bernard, Lyon, France.

Received 2 January 1996; revised manuscript received 1 August 1996.
0003-6935/97/010337-05$10.00/0

of development of sapphire mirror technology. In this paper we report the first results of a collaboration between CSIRO Division of Applied Physics, Optical Technology Program (sapphire polishing technology), the Institut de Physique Nucleaire (IPN), Université Claude Bernard (substrate coating and scattering measurements), and the University of Western Australia (UWA), Australian International Gravitational Research Centre (testing Fabry–Perot cavities).

Two mirrors were polished and coated, one flat, the second with a radius of curvature of 220 mm. This is a suitable combination for a Fabry–Perot cavity 150 mm long.

2. Substrate Polishing

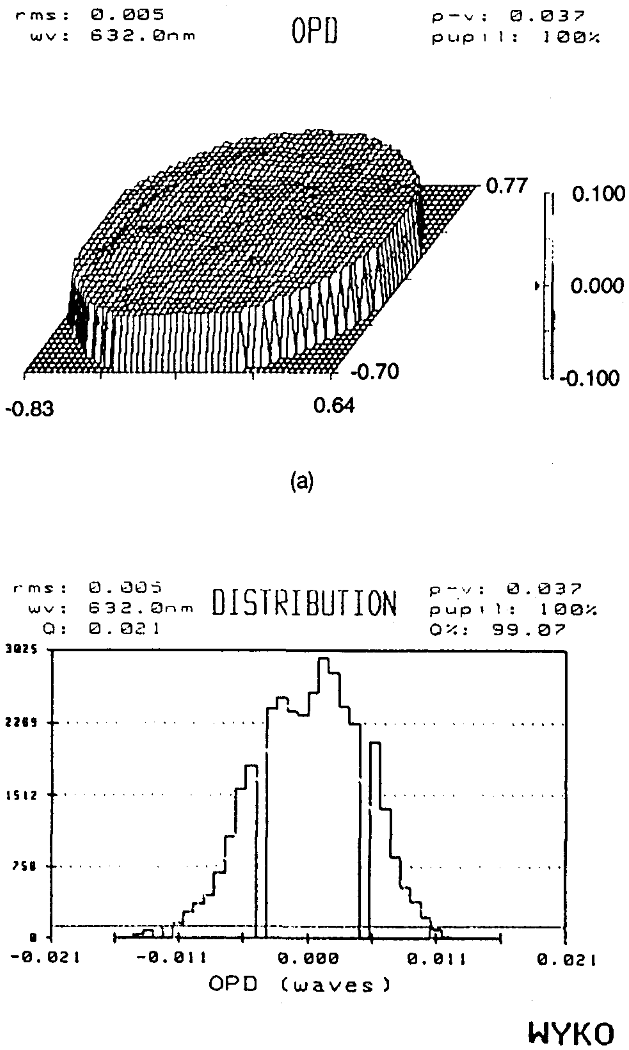
The substrates were cut from a 30-mm-diameter sapphire rod manufactured by Union Carbide. The *C* axis was in the plane of the mirror owing to the crystal orientation in the rod. The material was recycled from another experiment, which is the reason for the nonoptimal axis alignment.

The sapphire substrates were polished by the float polishing technique.[7] This is characterized by an aquaplaning effect in which the substrate rides above the lap and is hydrodynamically supported by the high flow rate of polishing liquid onto the lap, a high spindle velocity, and a rapid motion of the workpiece across the lap. This technique was found to give both an excellent surface figure and surface finish.

Our float polisher is a small ophthalmic machine that was modified for this research through the addition of an eccentric arm drive system (to move the substrate across the lap) and a variable speed motor to drive the main spindle. Spindle rotation rates were typically around 80 rpm for the sapphire-polishing work reported here. The polishing slurry used was colloidal silica (Ultrasol 500 s, diluted 10:1 with distilled water).

A tin lap 210 mm in diameter with a spiral groove was used to polish the substrates. This was conditioned on a flat lap. The lap was measured interferometrically to be flat to within several waves over the central 150 mm. The surface figure of the lap was not optimized because it was not as important in determining the final surface figure of the sapphire as the distribution of pressure applied to the substrate during polishing. Polishing times ranged from less than an hour to several hours, with interferometric measurements being performed at the conclusion of each run to test the surface figure. Polishing parameters such as the pressure on the substrate were varied from run to run to optimize the surface figure. No crystal orientations other than the one referred to above were investigated during this research.

The surface characteristics of the bare substrates were measured before being sent for coating. The surface figure was measured with a digital phase-shifting interferometer and was typically better than λ/20. An example of a surface profile and the statistics of the surface are shown in Figs. 1(a) and 1(b). The surface roughness of the substrate was measured with a quantitative interference microscope and a stylus instrument to be better than 0.1 nm rms.



(a)

(b)

Fig. 1. Characterization of the flat substrate highly polished surface: (a) interferometric measurement of the flatness of the 30-mm-diameter substrate by a digital phase-shifting interferometer; (b) statistics of interferometric measurement pixels. OPD, optical path difference.

These results were obtained on substrates of 30-mm diameter. Should they be reproducible on large substrates, surfaces on substrates suitable for laser interferometric gravitational wave detectors could be produced with the float polishing process.

3. Coating

The technology needed to meet the low-loss requirements is the reactive dual ion beam sputtering system (DIBS). This technique guarantees very low scattering levels, 0.5–1 ppm.

A. Experimental Setup

The IPN Lyon DIBS coater is a fully automated, in-house constructed system. The vacuum chamber is

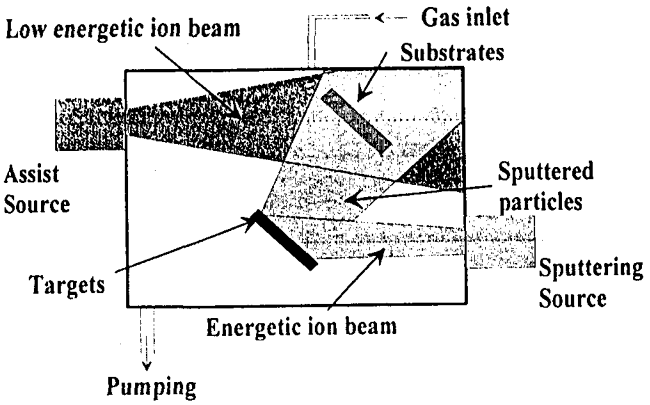


Fig. 2. Schematic of DIBS coating apparatus.

stainless steel with a cryopumping facility. Base pressure ranges between 10^{-7} and 10^{-8} Torr in 1 h.

A Kaufmann type or equivalent ion source is used to sputter (1200-eV) very pure targets of high- and low-index elements. The energetic ion beam is neutralized to prevent electrical breakdown and beam spreading. The sputtered atoms are condensed onto the substrates located on a planetary sample holder. The sample holder angle and target angle have been optimized by our simulation program to increase thickness homogeneity.

The assistance ion source that provides low-energy oxygen ions (100 eV) is used to control the stoichiometry and the density of the growing layer. A schematic drawing of this system is given in Fig. 2.

A classical quarter-wave design, centered at 1064 nm with a total physical thickness of 5.72 μm, is used for the high-reflectance mirrors: (HL)*17 HLL, which gives a theoretical residual transmission of 7 ppm. The high-index material (H) is tantalum pentoxide, whereas the low-index material (L) is silicon dioxide. Both are amorphous. The layers are deposited on a very clean (less than 50 particles of 0.2 μm cm^2) and a very smooth (0.7-Å rms) sapphire substrate.

B. Absorption Loss

To evaluate the absorption level at 1064 nm, we have used a photothermal deflection spectrometry device.[8] This system is very sensitive so that absorption levels lower than 1 ppm can easily be detected with good accuracy. One can do mappings to measure the surface inhomogeneity by moving the mirror in its plane. The absorption level reached for these mirrors is typically 0.5 ± 0.1 ppm. Time-dependent absorption measurements have been done (500 h at 10 kW/cm^2), and no degradation has been observed.

C. Scattering Loss

To measure the scattering, we used a commercial CASI scatterometer (complete angle Scan Instrument) from TMA. From the bidirectional reflectance distribution function (BRDF) it is possible to determine the total internal scatter by integration over the scattering angle. The spot size can be varied from 0.5 to 3 mm as it strikes the sample in quasi-normal incidence (from 2° to 3°).

To obtain a realistic scattering measurement, we have done mappings of the entire sample surface so that all the point defects on the mirror are well located and taken into account (Fig. 3). Last, this apparatus can also be used as a very sensitive wattmeter to determine the low-loss mirror transmission loss.

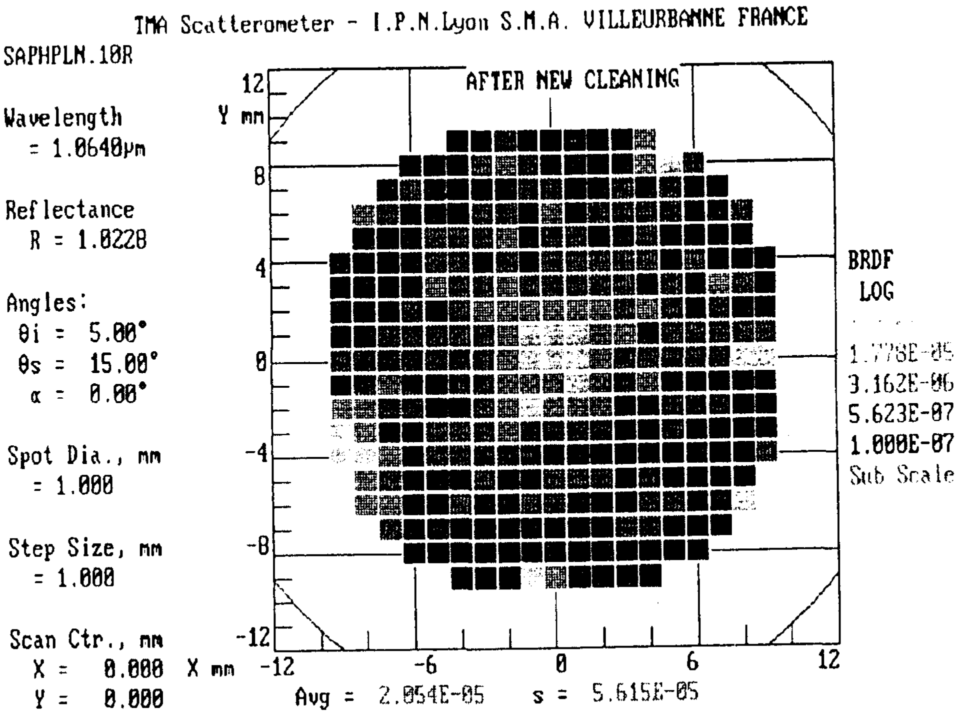


Fig. 3. Scattergram of the same mirror surface after a coating, which shows scatter approximately correlated with surface profile.

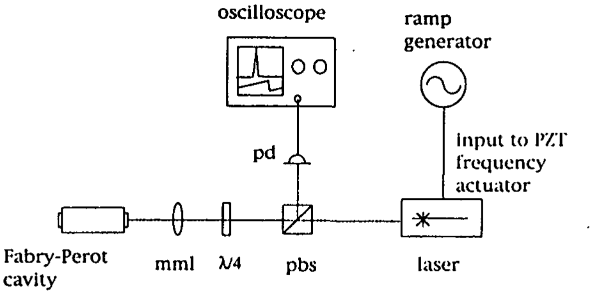


Fig. 4. Schematic of arrangement for testing sapphire mirrors: λ/4, quarter-wave plate; pbs, polarizing beam splitter; mml, mode-matching lens; pd, photodiode. The frequency of the laser was scanned, and the amplitude response of the reflected cavity was beam monitored.

For the plane mirror, at 1064 nm, we reached 13 ± 0.2 ppm scattering with a residual transmission of 8.7 ppm. The scattering of the curved mirror is 9 ppm over 12 mm and 14 ppm over 16 mm. The residual transmission is close to 7 ppm. This highest scattering value comes from the presence of some large point defects near the mirror center, possibly intrinsic in the material.

4. Testing of Sapphire Mirrors in a Fabry–Perot Cavity

The mirrors were packed in a clean airtight container. The container was stored on a laminar flow clean bench for several days before it was carefully opened and quickly clamped at each end of a sapphire spacer to form a Fabry–Perot cavity. This was mounted in a vacuum-tight copper can with one window. To minimize turbulent airflow during evacuation, the can was initially pumped through a capillary tube with a time constant of ~6 min, until a pressure of ~1 mbar was reached. The can was permanently sealed by crimping the copper pump-out line when the can pressure reached $\sim 10^{-6}$ mbar.

A 350-mW diode-pumped Nd:YAG (monolithic non-planar ring) laser was used in the experimental arrangement shown in Fig. 4, with ~10 mW incident on the cavity. The laser frequency could be scanned through about a third of the free spectral range of the cavity (1 GHz) with a piezoelectric actuator integral to the laser. Scanning the laser frequency to align and test the Fabry–Perot cavity, each mode appeared as a doublet, with the same spacing, ~80 kHz. The finesse was different for the two members of the doublet, ~100,000 and 80,000. In our 150-mm-long cavity the former gives a bandwidth of ~10 kHz.

Table 1. Mode Doublet Splitting for Various Cavity Configurations and Temperatures

Mirrors	Doublet Splitting (kHz)	Finesse (Higher of Two)
Two sapphire mirrors at T = 300 K	80	100,000
One sapphire, one fused silica at T = 300 K	40	30,000
Two sapphire mirrors at T = 4 K	160	80,000

To investigate the doublet occurrence we replaced the birefringent sapphire input mirror with a nonbirefringent fused-silica Newport high-finesse mirror (F = 30,000). This allowed us to interrogate the cavity with the light of varying angles of linear polarization. With the fused silica mirror, the doublet spacing halved (see Table 1) and a clear dependence of mode amplitude on polarization angle could be seen. The intensity coupled into each mode with a varying polarization angle is shown in Fig. 5. We conclude that the mirror coatings (SiO_2 and Ta_2O_5) have assumed the anisotropic properties of the sapphire substrate to some extent. It is thought that the coatings have been stressed during the anisotropic cooling of the sapphire substrate after the coating deposition, causing birefringence. The degree of birefringence $\Delta n/n \sim 2 \times 10^{-5}$.

The all-sapphire Fabry–Perot cavity has been cooled to 4 K. Splitting the two polarization modes at this temperature is 160 kHz (see Table 1), approximately double that of the room-temperature splitting. At 4 K the finesse is reduced by 20% from its room-temperature value, in line with the observations of those first to look at cryogenic Fabry–Perot cavities.[9] The splitting of polarization modes is not expected if the C axis is perpendicular to the mirror face as in our next batch of mirrors.

Two suggestions concerning the coating birefringence were put forward by the referees. The first was that the birefringence was caused by the high average angle of incidence of the assist beam. If this were the case, birefringence would result in all mirror coatings regardless of substrate material, and this is not found. The second suggestion was that the birefringence was due to structure on the mirror surface resulting from the different polishing action along the two crystal axes (C and A). The mirror surface and coating properties were measured carefully, and indeed a subtle structure of this type was seen, shallow striations with a wavelength of ~500 μm. The larger cavity mode spot size is 300 μm, and this structure is not expected to have much effect when the spatial wavelength is larger than the beam diameter. The temperature dependence of the bire-

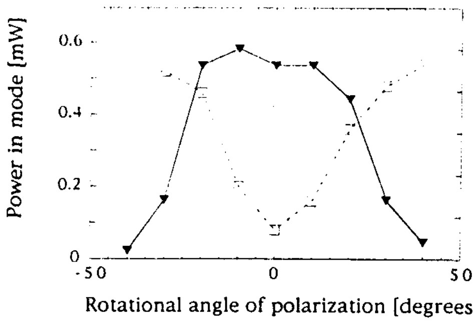


Fig. 5. Dependence of the power in each mode of the doublet as a function of the angle of injection of linear polarization.

fringence, seen from the doubling of the mode splitting from 300 to 4 K, supports the idea of stress birefringence, and neither of the above effects is likely to be temperature dependent to the same extent.

5. Conclusion

A finesse of 100,000 has been achieved in an all-sapphire Fabry–Perot cavity. Birefringence was observed in the coatings, probably because of the anisotropy of the substrate. This led to a splitting of the cavity modes by ~100 kHz. The mode splitting could be suppressed by correct alignment of the mirrors. This, however, requires excellent alignment to avoid degrading the finesse. The observed finesse is consistent with the measured scattering in the coatings because of the residual surface roughness. We believe that improved surface roughness will be achievable in future mirrors and that birefringence will not be observed in mirrors polished normal to the direction of the symmetry axis.

We thank Alain Brillet and Nary Man for support and encouragement in this project and for hospitality during collaborative visits. We thank Keith Taylor of the Anglo-Australian Observatory for administrative support. We are very grateful to the IPN-Lyon team for preparing the samples and the physics workshops at UWA for technical support, particularly Derek Newman. This research was partially funded by the International Science and Technology exchange program of the Department of Industry, Science and Technology (Australia).

References and Notes

1. W. Winkler, K. Danzmann, A. Rudiger, and R. Schilling, "Optical problems in interferometric gravitational wave antennas," in *Proceedings of the Sixth Marcel Grossmann Meeting on General Relativity* (World Scientific, Singapore, 1992).
2. C. T. Taylor, M. Notcutt, and D. G. Blair, "Cryogenic, all-sapphire Fabry–Perot optical frequency reference," Rev. Sci. Instrum. **66**, 955–960 (1995).
3. The ratio of (the temperature dependence of the index of refraction)/(thermal conductivity) in fused silica is 1000 and in sapphire is 60.
4. D. G. Blair, Department of Physics, University of Western Australia, Nedlands, 6907; F. Cleva and C. N. Man, VIRGO Project, CNRS, Universite Paris-Sud, 91405 Orsay Cedex, France, "Optical absorption measurements in monocrystalline sapphire at 1 μm" (personal communications, January 1996).
5. A. Gillespie and F. Raab, "Thermally excited vibrations of the mirrors of laser interferometer gravitational-wave detectors," Phys. Rev. D **52**, 577–585 (1995).
6. M. Felt, Crystal Systems Inc., Salem, Mass. 01970 (personal communication, 1995).
7. J. M. Bennett, J. J. Shaffer, Y. Shibano, and Y. Namba, "Float polishing of optical materials," Appl. Opt. **26**, 696–703 (1987).
8. A. C. Boccara, D. Fournier, and W. Jackson, "Sensitive photothermal technique for measuring absorption in optically thin materials," Opt. Lett. **5**, 377–379 (1980).
9. J.-P. Richard and J. J. Hamilton, "High finesse measurements at low temperatures," Appl. Opt. **30**, 3560–3561 (1991).