Development of Low Loss Sapphire Mirrors

D.G. Blair, M. Notcutt, C.T. Taylor, E.K. Wong
Australian International Gravitational Research Centre, Dept. of Physics,
University of Western Australia, Perth, Australia

C. Walsh, A. Leistner, J. Seckold
Division of Applied Physics, National Measurement Laboratory, CSIRO, Sydney,
Australia

J.-M. Mackowski
Institut de Physique Nucleaire, Universite Claude Bernard, Lyon, France

ABSTRACT

We report the successful development of low loss sapphire mirrors for use at 1 micron wavelength. Methods for polishing and coating are described. Analysis of each process shows roughness better than 0.1nm and coating scattering of 14ppm. The mirrors have been charcterised in a Fabry-Perot cavity, having a finesse of 100 000. Mode doublets result from birefringence of the coatings.

Keywords :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 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 wavefront 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 wavefront 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], approximately 5ppm per centimetre.

While the fractional losses expected in travelling through the substrate are ten times larger than that in the mirror coatings, the cavity beam is F/π times higher in power (F being the Finesse). The importance of these effects are determined by the interferometer or cavity configuration. Coatings are typically made of layers of SiO_2 and TiO_2 or Ta_2O_5. None of these materials has good thermal diffusivity and 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 ($8\ 10^{-4}\ m^2s^{-1}$ at 77K and $4\ 10^{-2}\ m^2s^{-1}$ at 4K) and its very low coefficient of thermal expansion ($\alpha = 5 * 10^{-13}\ T^3\ K^{-1}$) means that sapphire Fabry-Perot cavities are well suited to the construction of ultra high stability laser frequency standards [2] with sapphire spacers at cryogenic temperatures.

The very low acoustic losses in sapphire and the very high sound velocity makes 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].

For these reasons we have embarked on a program 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, Universite Claude Bernard (substrate coating and scattering measurements) and the University of Western Australia, Australian International Gravitational Research Centre (testing of Fabry-Perot cavities).

2 SUBSTRATE POLISHING

The substrates were cut from a 30mm diameter sapphire rod manufactured by Union Carbide. The C-axis was in the plane of the mirror due to the crystal orientation in the rod.

The sapphire substrates were polished using the float polishing technique [6]. This is characterised 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 excellent surface figure and surface finish.

The surface characteristics of the bare substrates were measured before being sent for coating. The surface figure was measured using a digital phase shifting interferometer and was typically better than $\lambda/20$. An example of a surface profile and the statistics of the surface are shown in figure 1 A and B. The surface roughness of the substrate was measured using a quantitative interference microscope anda stylus instrument to be better than 0.1nm RMS.

These results were obtained on substrates of 30mm diameter. Should they be reproducible on large substrates, surfaces on substrates suitable for laser interferometric gravitational wave detectors could be produced using 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 techniques guarantees very low scattering levels.

Experimental Setup

The IPN Lyon DIBS coater is a fully automated, in-house constructed system. The vacuum chamber is stainless steel with a cryopumping facility. Base pressure ranges between 10^{-7} and 10^{-8} torr in one hour.

A Kaufmann type or equivalent ion source is used to sputter (1200eV) very pure targets of high and low index elements. The energetic ion beam is neutralised 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 optimised by our simulation program to increase thickness homogeneity.

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

A classical quarterwave design is used for the high reflectance mirrors: (HL)*17 HLL which gives a theoretical residual transmission of 7ppm. The high index material H is a tantalum pentoxide monolayer whereas the low index material (L) is a silicon dioxide one. Both are amorphous. The layers are deposited on a very clean (less than 50 particles of 02.mm per cm^2) and very smooth (0.7Å RMS) sapphire substrate.

Absorption loss

To evaluate the absorption level at 1064nm we have used a photothermal deflection spectrometry device [7]. This system is very sensitive so that absorption levels lower than 1ppm can easily be detected with good accuracy. Mappings can be done to measure the surface inhomogeneity by moving the mirror in its plane. The absorption level reached for these mirrors is typically 0.5ppm± 0.1ppm. Time dependent absorption measurements have been done (500hr at $10kW/cm^2$) and no degradation has been observed.

Scattering Loss

To measure the scattering, we used a commercial CASI scatterometer (Complete Angle Scan Instrument) from TMA. From the Bidirectional Reflectance Distribution Function (BDRF) it is possible to determine the Total Internal Scatter (TIS) by integration over the scattering angle. The spot size can be varied from 0.5 to 3mm as it strikes the sample in quasi-normal incidence (from 2^o to 3^o).

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

For the plane mirror, at 1064nm, we reached 13ppm±0.2ppm scattering with a residual transmission of 8.7ppm. The scattering of the curved mirror is 9ppm over 12mm and 14ppm over 16mm. The residual transmission is close to 7ppm This highest scattering value is coming from the presence of some large point defects near the mirror centre, 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 carefully opening and quickly clamping at each end of a sapphire spacer to form Fabry Perot cavity. This was mounted in a vacuum tight copper can with one window. To minimise turbulent airflow during evacuation, the can was initially pumped through a capillary tube with a time constant of ~ 6 mins, 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.

Scanning the laser frequency to align and test the Fabry-Perot cavity, each mode appeared as a doublet, with the same spacing, ~80kHz. The finesse was different for the two members of the doublet, ~100,000 and 80,000. In our 150mm long cavity this gives a bandwidth of ~10kHz.

To investigate the doublet occurrence we replaced the sapphire input mirror with a fused silica Newport high finesse mirror (F= 30 000). This simplified the process of interrogating the cavity with light of varying angles of linear polarisation as due to the alignment of C and A axes of the sapphire, in the all sapphire cavity we had to contend with a birefringent substrate. With the fused silica mirror, the doublet spacing halved and a clear dependence of mode amplitude on polarisation angle could be seen. The intensity coupled into each mode with varying polarisation angle is shown in Figure 4. 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 coating deposition, causing birefringence. The degree of birefringence $\Delta n/n \sim 2.10^{-5}$.

The all sapphire Fabry-Perot cavity has been cooled to 4K. The splitting of the two polarisation modes at this temperature is 160kHz, approximately double that of the room temperature splitting. At 4K 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 [8]. Splitting of polarisation modes is not expected if the C-axis is perpendicular to the mirror face as in our next batch of mirrors.

6 CONCLUSION

A finesse of 100,000 has been achieved in an all sapphire Fabry-Perot cavity. Birefringence was observed in the coatings, due probably to the anisotropy of the substrate. This lead to a splitting of the cavity modes by about 100kHz. 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 due to 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 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 ~19ppm/cm [9]. This does not create thermal lensing, but leads to unavoidable losses when beams transit the bulk material.

Acknowledgments

We wish to thank Alain Brillet and Nary Man for their support and encouragement in this project, and for their hospitality during collaborative visits. Thanks to Keith Taylor of the Anglo-Australian Observatory for administrative support. We are very grateful to the SMAA-IPNL team, P Ganau and C Michel, for their preparation of the samples and the Physics workshops at UWA for their technical support. This work was partially funded by the International Science and Technology exchange program of the Dept. of Industry, Science and Technology (Australia).

References

1. W. Winkler, K. Danzmann, A. Rudiger and R. Schilling, "Optical problems in interferometric gravitational wave antennas", Proceedings of the Sixth Marcel Grossmann Meeting on General Relativity, World Scientific, Singapore (1992).

2. CT Taylor, M Notcutt, DG Blair, Cryogenic, All-Sapphire Fabry-Perot Optical Frequency Reference., Rev. Sci. Inst., 66, pp 955-960 (1995).

3 It is the ratio of (the temperature dependence of the index of refraction) / (thermal conductivity) that fused silica is 1000 and sapphire is 60.

4 DG Blair, F Cleva & C.N. Man
Optical Absorption measurements in monocrystalline sapphire at 1 micron. Submitted to Optical Materials

5 A. Gillespie & F Raab
Thermally excited vibrations of the mirrors of laser interferometer gravitational-wave detectors, Phys. Rev. D, 52, pp 577-585 (1995)

6. J.M. Bennett, J.J. Shaffer, Y. Shibano and Y. Namba, Float Polishing of Optical Materials, Applied Optics, 26, pp 696-703 (1987)

7. A.C. Boccara, D Fournier & W Jackson, Optics Letters, 5, pp 377-379 (1980)

8 J-P Richard & J.J. Hamilton, High Finesse measurements at low temperatures
Applied Optics 30, pp 3560-3561 (1991)

9 Crystal Systems Pty. Ltd. - private communication.

Figure Captions

[1] Characterisation of the flat substrate highly polished surface

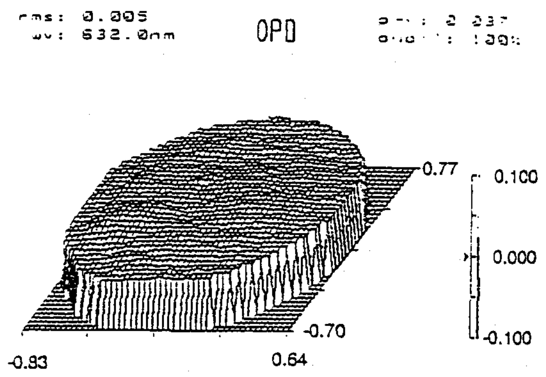
(A) Interferometric measurement of the flatness of the 40mm diameter substrate by a digital phase shifting interferometer.

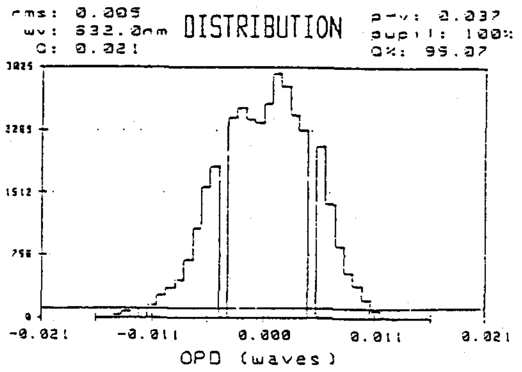
(B) Statistics of interferometric meaurement pixels.

[2] Schematic of DIBS coating apparatus.

[3] Scattergram of same mirror surface after coating which shows scatter approximately correlated with surface profile.

[4] Dependence of the power in each mode of the doublet as a function of angle of injection of linear polarisation.


rms: 0.005
wv: 632.0nm
OPD
p-v: 0.037
pupil: 100%
0.77
0.100
0.000
-0.100
-0.70
-0.83
0.64


rms: 0.005
wv: 632.0nm
C: 0.021
DISTRIBUTION
p-v: 0.037
pupil: 100%
Q%: 95.07
3025
2269
1512
756
0
-0.021
-0.011
0.000
0.011
0.021
OPD (waves)

WYKO

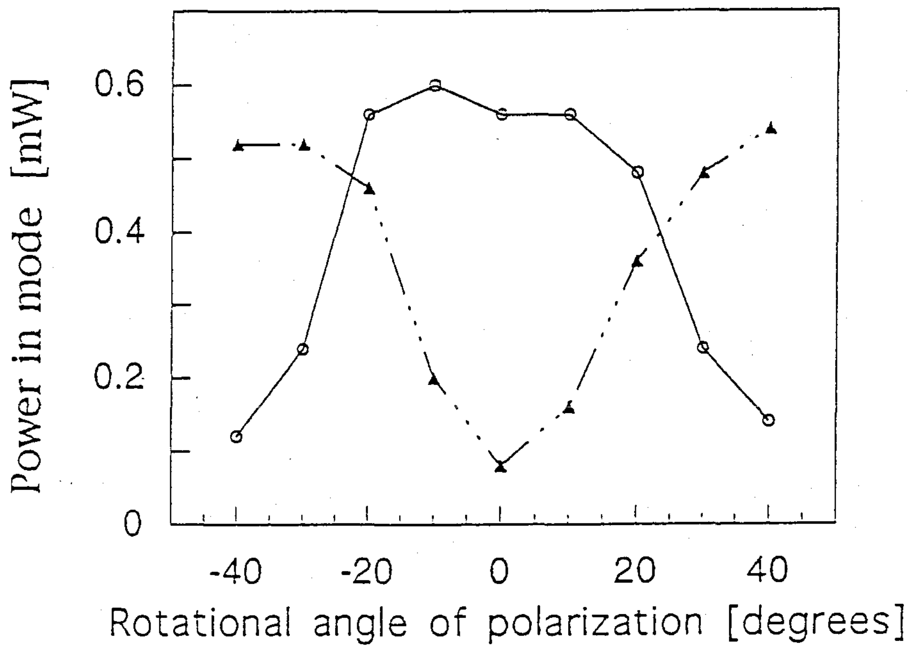


Figure 4 Dependence of the power in each mode of the doublet as a function of angle of injection of linear polarisation.

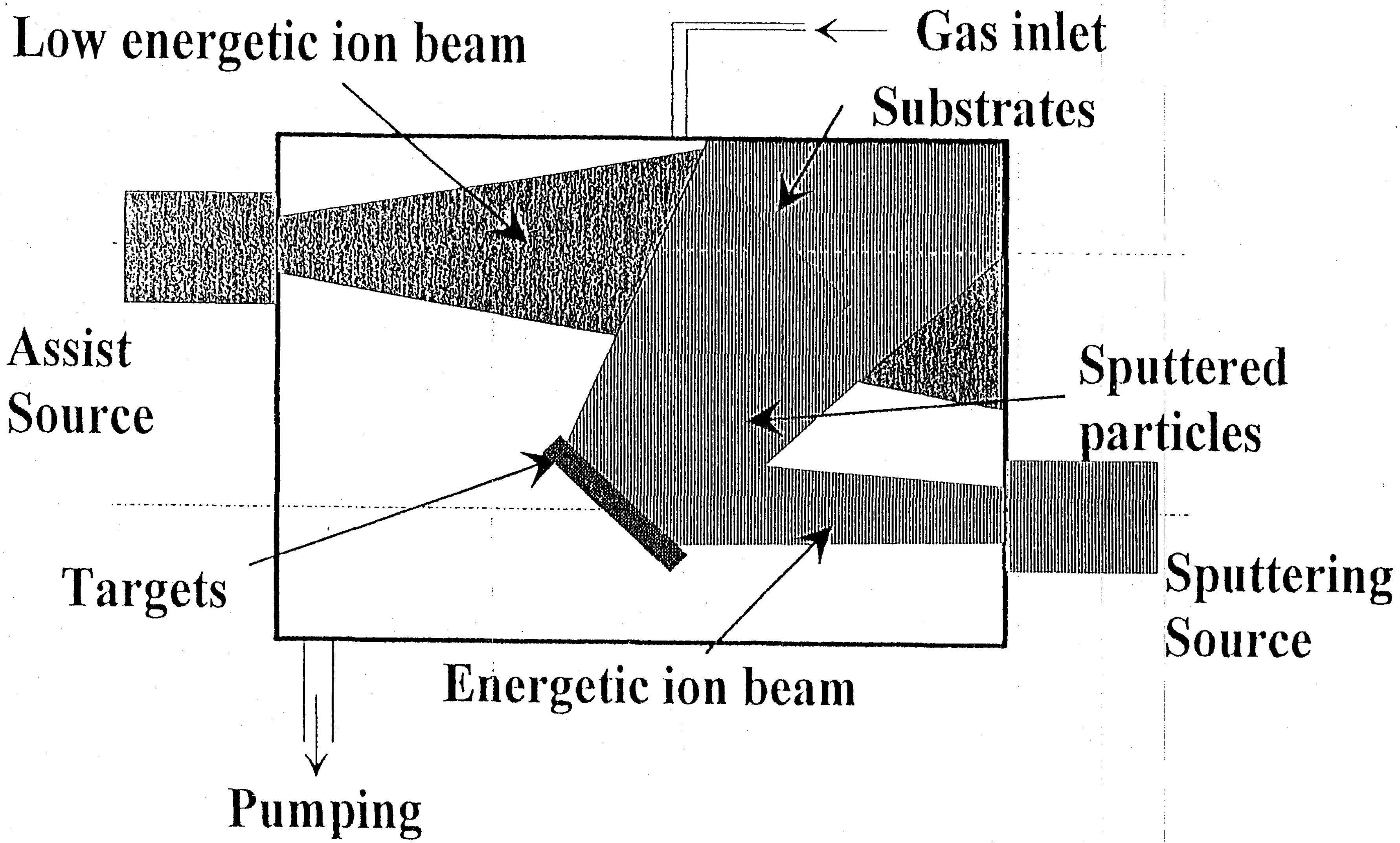


Figure 2 Schematic of DIBS coating apparatus.