Meas. Sci. Technol. **10** (1999) 146–151. Printed in the UK PII: S0957-0233(99)97872-4

The suitability of sapphire for laser windows

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Received 28 September 1998, in final form 16 November 1998, accepted for publication 26 November 1998

Abstract. The present paper deals with the experimental measurement of absorption coefficients using (i) the differential dual-beam spectro-photometry method and (ii) an intra-cavity optical loss measurement technique. The absorption coefficient is measured experimentally in the region from the visible to the near IR. Criteria for choosing sapphire windows of optimum thickness, when they are subjected to a pressure difference of 1 atm, to avoid fracture or significant optical distortion of the laser beam are studied. Intra-cavity optical losses in such windows for Brewsterization and skew-angle inclusions are estimated. The study relates to various laser wavelengths, namely 337.1 nm, 448.0 nm, 632.8 nm, 1.15 μm, 1.315 μm, 2.7 μm and 3.8 μm.

Keywords: optical transmission, laser window material, diagnostics

1. Introduction

Sapphire is known as an optical material of outstanding merits. Nonetheless, its high cost, scarcity in pure quality and crystalline impurities have limited its use in the optical and electro-optical industry. Modern technology has now made it possible to obtain bulk sapphire crystals of excellent purity. Consequently, sapphire is now emerging as a challenger to the conventional optical materials like fused silica and boro-silicate glasses in the visible region. Particularly for high-power laser optics and for military applications, for which reliability and ruggedness become important deciding factors, in addition to the optical quality, sapphire is most likely to replace the existing optical materials. The feasibility of utilizing high-power lasers for directed energy weapons has already been established and their deployment for actual engagement in the next century is being projected. For this purpose the earlier candidate laser had been the DF laser (lasing at 3.8 μm) but the present analysis reveals that, for all such military applications, the best suited laser would be the chemical oxy-iodine laser (COIL) operating at 1.315 μm. For such a critical role, it is imperative to investigate the suitability of sapphire as a laser window material in the UV and visible ranges and particularly in the near-IR regions. Also, it is noteworthy that the refractive index (Maliston 1962) of sapphire is around 1.76 (see table 1); hence it is possible to fabricate a few specific laser mirrors by using a combination (Patel and Ben Bouzid 1984) of plane-parallel flats, thereby eliminating the multi-layer dielectric coatings having an inherently lower power handling capacity, limited due to the damage to the coating caused by the laser intensity.

Table 1. Physical constants of sapphire relevant to the present study.

Hardness	Moh 9
Young's modulus	(5.0–5.6) × 10^7 psi
Poisson's ratio	-0.02
Modulus of rupture	65 000–100 000 psi
Indices of refraction	$\mu_e = 1.760$
	$\mu_o = 1.768$
	(sodium D-line birefringence)

2. The physical suitability of sapphire material

The most important consideration in selecting a material for a laser window is that its bulk absorption coefficient must be very low (Patel and Charan 1975, Patel 1990). High absorption not only reduces the laser power but also produces undesirable heating of the optical components which may eventually result in their thermal runaway. The surfaces of the optical components can also contribute substantially to the optical losses, but they are largely dependent on the polishing techniques and can be suitably controlled. In addition, it is desirable that an optical material has the following properties: (i) high mechanical strength, (ii) chemical inertness and high resistance to environment-related causes of deterioration, (iii) high-temperature stability, (iv) wear and abrasion resistance, (v) zero porosity, (vi) high thermal conductivity and (vii) high electrical resistivity. Sapphire is really unique in possessing the aforesaid qualifications. Being one of the hardest materials, sapphire can only be scratched, besides by itself, by a few substances such as diamond and cubic boron nitride. It is chemically inert in almost everything at room temperature and can be attacked only by chemicals like hydrofluoric acid at temperatures

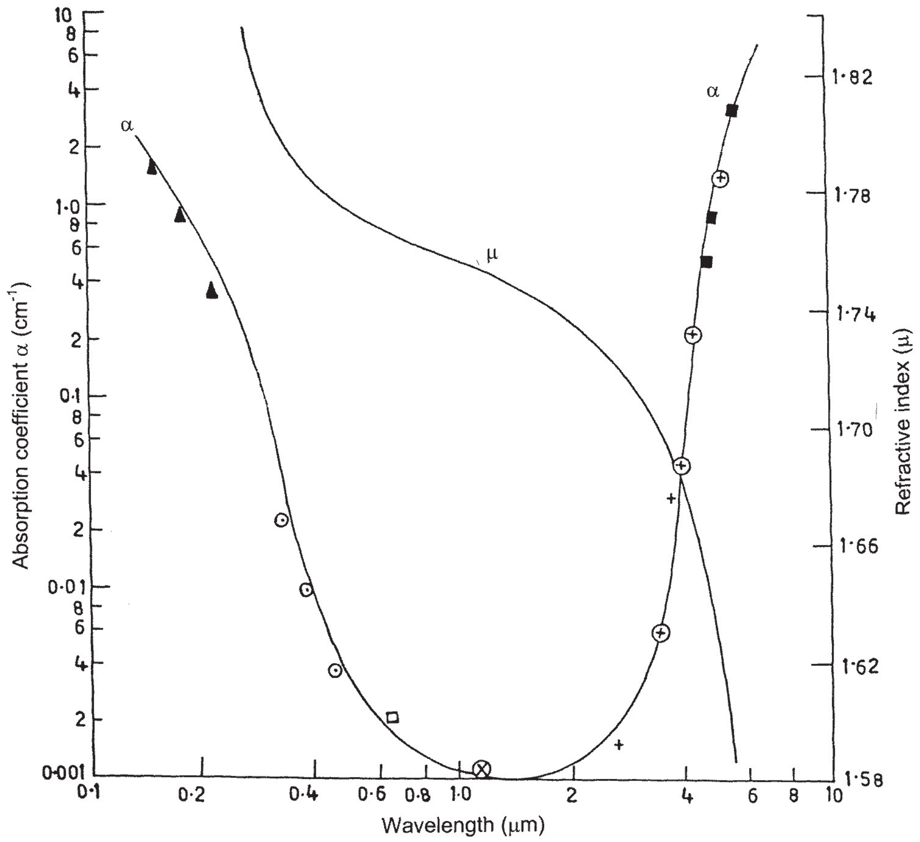

Figure 1. The absorption coefficient (α) and refractive index for the ordinary ray (μ) of sapphire as functions of the wavelength (λ). Sources of data for plotting absorption coefficient curve are as follows: ⊕, Deutsch (1975); +, Harrington *et al* (1976); ▲ Thomos *et al* (1988); Innocenzi *et al* (1990); and in the present investigations: ⊙ using spectrophotometer, □ using a He–Ne laser at 632.8 nm and ⊗ using a He–Ne laser at 1.15 μm.

above 300 °C. This property allows one to obtain ultra-clean sapphire components through the use of chemical reagents. It is for this reason that sapphire optics can be used for HF and DF lasers. Other relevant qualities are obvious from the properties listed in table 1. Its energy band gap is 10 eV, which is one of the largest for the oxide crystals. Hence it exhibits remarkable transmission from 150 nm in the vacuum-UV region to 6.0 μm in the middle IR. However, its optical suitability for laser windows in this transmission range will be investigated in this study.

Sapphire is an optically negative uniaxial crystal in the visible region and exhibits anisotropy in its physical properties. Generally most Czochralski-grown sapphire crystals have the C axis (or the optical axis) inclined at an angle of 60° to the growth axis. The results of Innocenzi *et al* (1990) on absorption in sapphire at room temperature indicate that absorption coefficients of 60°-oriented crystals are low relative to those of 0°-oriented crystals for photons having energies in the range 5–9 eV. Hence, if the use of optical components with 0° orientation in order to avoid the undesirable birefringence is preferred, they should be fabricated from large high-quality growth-oriented crystals. Sapphire has been grown by conventional methods such as the Verenuil, Czochralski and floating-zone techniques. But a more modern method (Schmid-Viechnicki 1973) yields high-quality crystals of up to 30 cm diameter and 15 cm length.

3. The absorption coefficient

Although the optical transmission band of synthetic sapphire is well known, it is not possible to assess its suitability for laser windows unless its absorption data are accurately found. Several investigators have measured the absorption coefficient at a few wavelengths in the infra-red (Deutsch 1975, Harrington *et al* 1976, Thomos *et al* 1988). Figure 1 summarizes some of these results. Using a combination of lasers and a Fourier-transform spectrometer, infra-red transmission and absorption coefficients in the range 2–20 μm have been measured (Thomos *et al* 1990). Using lasers and accurate calorimetry (Innocenzi *et al* 1990), absorption coefficients in the range 10^{-5}–10^{-1} cm^{-1} have been measured. Also utilizing such calorimetry, absorption coefficients (Innocenzi *et al* 1990) of sapphire grown at 60° orientation and at 0° orientation have been measured in some visible, UV and VUV ranges. The present paper reports an accurate study of the bulk absorption coefficient of sapphire in the range 0.4–2 μm. Two methods are employed for this study, namely (i) differential dual-beam spectrophotometry (Deutsch 1973) and (ii) an intra-cavity optical loss measurement technique (Patel and Charan 1975, Patel 1977, 1990) using lasers at various wavelengths. The second method is more accurate, but it is limited by the availability of a laser at the wavelength of measurement.

On the other hand, the first method offers the advantage of being useful over various wavelengths, but its lower accuracy restricts its utility in the region where the absorption coefficient is large enough to be measurable.

The absorption coefficient envisaged in the region of 300–400 nm is around 0.005 cm^{-1} so that dual-beam spectrophotometry can be employed. The experimental procedure is similar to one reported earlier (Deutsch 1973). It basically consists of measuring the transmission of thick samples obtained from bulk crystals grown at 60° orientation at various wavelengths. Then, taking samples of varying thicknesses, a graph of the relationship between the transmission and the sample thickness is plotted. From the slope of this graph, the absorption coefficient has been calculated. The limitation of this method arises from the fact that the accuracy of measurement is to within about 1% and hence it has been essential to take samples of thickness more than about 5 cm to allow measurement of absorption coefficients of about 0.002 cm^{-1}. With this method, the absorption coefficient is measured at a few wavelengths in the range 330–460 nm. The results are shown in figure 1. For wavelengths greater than 460 nm, the results were not reliable and the other method had to be used because the absorption in the test samples became very low and the inaccuracies of measurements became too large.

The laser intra-cavity loss measurement technique (Patel and Charan 1975, Patel 1977, 1990) has the capability of measuring absorption coefficients of about 10^{-4} cm^{-1} using thick samples and hence is ideally suited to measurements in the visible and near-IR regions. A 50 mW He–Ne laser is used for the experimental work and the procedure is similar to one reported earlier (Patel 1977). Thick samples of sapphire are used to keep the error of measurements low, to the level of 10^{-4} cm^{-1}. A He–Ne laser is operated at 632.8 nm and then at 1.15 μm to obtain the absorption coefficients at these wavelengths. The results are shown in figure 1.

Figure 1 elaborates the absorption coefficient of sapphire for the complete range of its optical transmission. In figure 1, the refractive index (Maliston 1962) of sapphire for the ordinary ray is also plotted, since this information is essential for the study of the suitability of sapphire for windows.

3.1. The optical absorption limitation of sapphire for laser windows

Figure 1 can now be employed to obtain the working wavelength range for sapphire laser windows. For any material to be useful as an intra-cavity laser window, it is essential that the optical absorption losses due to its inclusion do not exceed 0.2% per transit (even for a high-gain laser medium). If a typical window has a diameter of up to 2.5 cm, its thickness could be 0.5 mm (it will be seen later that such a choice of laser window dimensions is quite adequate). Now, imposing the condition that a window of 0.5 mm thickness should have (at the most) a single-transit bulk-absorption loss of 0.2%, one infers that the material must have a maximum absorption coefficient of 0.04 cm^{-1}. When this restriction is imposed on the sapphire windows, figure 1 reveals that the working wavelength range of sapphire for laser windows reduces to 330 nm to 4.0 μm only. However, even this reduced range is really significant since several gas lasers operate in this region, including the nitrogen laser (337.1 nm), chemical oxy-iodine laser (COIL) at 1.315 μm, argon-ion laser (448.0 nm), He–Ne laser (632.8 nm and 1.15 μm), HF laser (2.7 μm) and DF laser (3.8 μm). The optical suitability of sapphire windows for these lasers can, therefore, be investigated.

4. The thickness limitation of sapphire laser windows

Our data on the absorption coefficient can now be utilized for studying the thickness limitation of sapphire laser windows. Thin windows are obviously desirable because they offer low bulk absorption. However, gas-laser windows generally have to withstand a pressure difference across them which produces a uniformly distributed load over the window. Hence the window could either fracture or introduce an optical distortion of the laser beam transmitted through it.

When the fracture of the window poses a limitation, one can utilize the formula of Sparks and Cottis (1973) and choose a minimum thickness t_f of the window for withstanding a pressure P such that

$$t_f = 0.433D(PS/A)^{1/2} \qquad (1)$$

where A is the modulus of rupture, D the diameter of the window and S the safety factor (taken here as 4, which would give twice the fracture-limited thickness). Figure 2 shows a plot of t_f against D. The values of A chosen for the calculation is 65 000 psi, being the lowest in its spread (table 1 indicates values ranging from 65 000 to 100 000 psi), and the pressure P is 1 atm.

The pressure-induced optical distortion of a laser beam passing through the window can also cause a limitation on its thickness. Utilizing the formula of Sparks and Cottis (1973) for such cases, a maximum thickness t_o, to restrict the distortion to within a reasonable limit, is required:

$$t_o = 0.87D[(\mu - 1)(P/E)^2(1 - \sigma^2)^2(D/\lambda)]^{0.2} \qquad (2)$$

where E is Young's modulus, σ Poisson's ratio, λ the wave length of the radiation and μ the refractive index. Being a uniaxial crystal, sapphire has one refractive index μ_e for the extraordinary ray and another μ_o for the ordinary ray (see table 1). If the laser window is kept at the Brewster angle, then D would refer to the major axis of the ellipse of contact. Equation (2) assumes that the window is either rigidly held or stuck near the circumference to the laser plasma tube. Figure 2 also shows the plot of t_o against D for a pressure P of 1 atm for the sapphire window at various wavelengths of interest.

It is interesting to note that the maximum thickness is mostly limited by the optical distortion of the laser beams rather than by fracture. This is all the more so for the shorter wavelengths. Also, if the window diameter is more than 4.5 cm, the limitation is always due to optical distortion at all the wavelengths considered. This is to be expected of a material of high mechanical strength. Generally, windows of about 2.5 cm diameter are used in most experimental work; hence, for them 0.5 mm thickness is sufficient to withstand a pressure difference of 1 atm for all the wavelengths considered here.

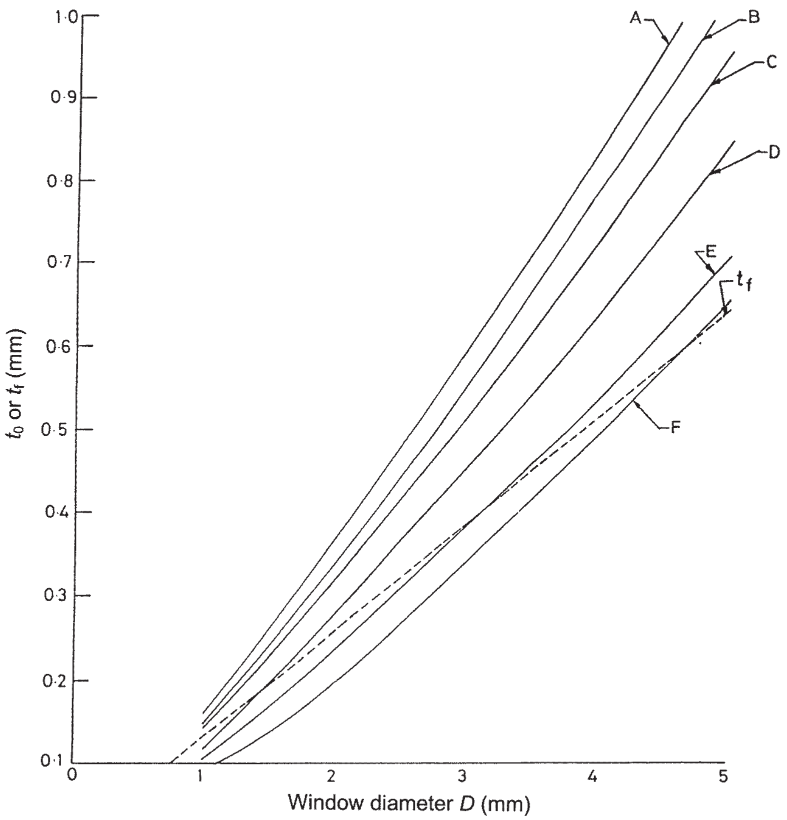

Figure 2. Minimum thicknesses t_o and t_f of sapphire windows limited by optical distortion and fracture respectively plotted against the window diameter for various wavelengths. The pressure difference across the windows is 1 atm. The plots corresponding to various wavelengths are: A, for 337.1 nm; B, for 448.0 nm; C, for 632.8 nm; D, for 1.15 μm and 1.315 μm; E, for 2.7 μm; and F, for 3.8 μm.

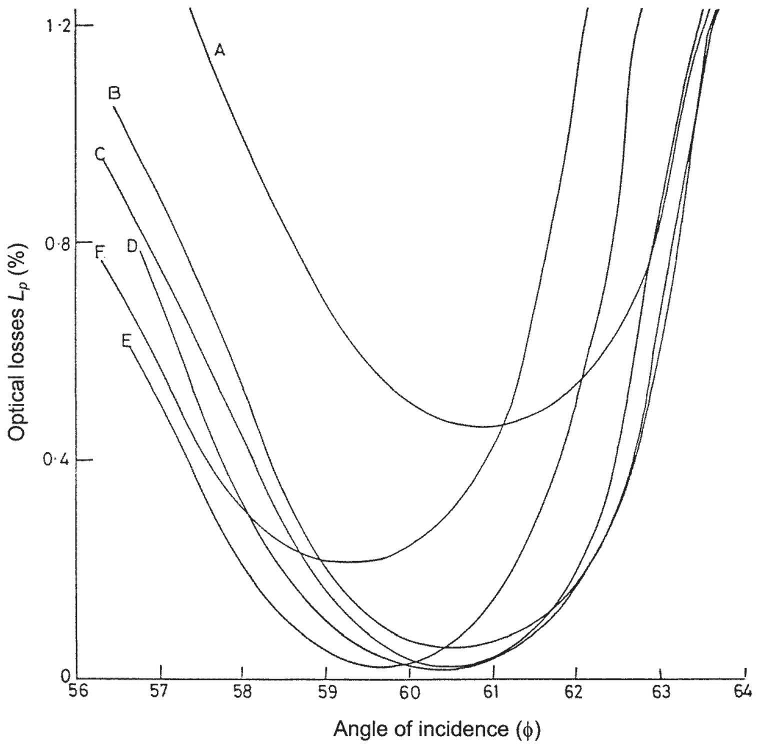

Figure 3. Intra-cavity losses L_p introduced by sapphire Brewster windows as a function of the angle of incidence ϕ around the Brewster angle θ at various wavelengths. Curves corresponding to laser wavelengths are: A, for 337.1 nm; B, for 448.0 nm; C, for 632.8 nm; D, for 1.15 μm and 1.315 μm; E, for 2.7 μm; and F, for 3.8 μm.

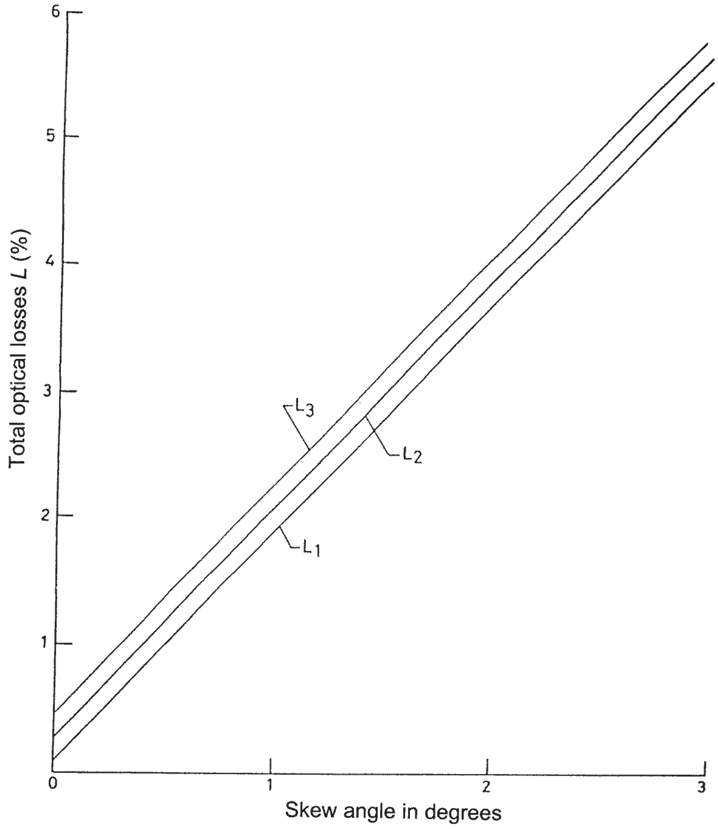

Figure 4. Total intra-cavity optical losses L introduced by sapphire Brewster windows (kept within their Brewsterization tolerances) as a function of the skew angle ψ at various wavelengths. Plots corresponding to laser wavelengths are: L_1, for 448.0 nm, 632.8 nm, 1.15 μm, 1.315 μm and 2.7 μm; L_2, for 3.8 μm; and L_3, for 337.1 nm.

Table 2. Brewsterization tolerance for 0.5 mm thick sapphire windows at various laser wavelengths.

Wavelength tolerance	ϕ (degrees)	L_p at $\phi \approx \theta$ (%)	Brewsterization tolerance range
337.1 nm	60°54′	0.460	60°15′ to 61°30′
448.0 nm	60°36′	0.041	59°48′ to 61°12′
632.8 nm	60°30′	0.023	59°42′ to 61°12′
1.15 μm	60°18′	0.014	59°42′ to 61°18′
1.315 μm	60°15′	0.012	59°42′ to 61°18′
2.7 μm	59°47′	0.021	58°54′ to 60°32′
3.8 μm	59°18′	0.207	58°24′ to 60°12′

5. The optical suitability of sapphire for Brewster windows

The use of Brewster windows within a laser in order to obtain output in a fixed polarization is desirable. Also they eliminate the limitation on the power-handling capacity of the otherwise AR-coated flat windows due to damage to such coatings. Figure 1 can now be used to study the optical suitability of sapphire for Brewster windows.

The surfaces of the Brewster windows can be made to a flatness of about $\lambda/20$ finish and then further polished to obtain negligible scattering at 632.8 nm. The faces of the plate can be made parallel to within a second of arc. The final thickness of 2.5 cm diameter windows is now chosen to be 0.5 mm, as discussed above. For such Brewster windows, the main sources of optical losses are (i) error in setting the incidence angle ϕ close to the Brewster angle θ, (ii) error occurring due to there being a small skew angle ψ between the two Brewster plates and (iii) absorption in the bulk material (which has an absorption coefficient of α cm^{-1}). The overall optical losses L introduced in the laser cavity for a round-trip traversal of the beam can be expressed using results obtained by Patel and Charan (1975) to within a good approximation as

$$L \approx 2\alpha d + 4(R_p \cos\psi + R_n \sin\psi)_{\phi\approx\theta} \tag{3}$$

where R_p and R_n are the reflectivities of the surfaces of the window plate for laser oscillations with the electrical vector parallel and normal to the plane of incidence respectively and d is the actual single-pass distance traversed by the laser beam in the window material of thickness t (taken as 0.5 mm). Also these can be expressed as follows:

$$R_p = \tan^2(\phi - \beta)/\tan^2(\phi + \beta) \tag{4}$$

$$R_n = \sin^2(\phi - \beta)/\sin^2(\phi + \beta) \tag{5}$$

$$d = t \sec\beta \tag{6}$$

$$\beta = \sin^{-1}[(\sin\phi)/\mu] \tag{7}$$

μ being the refractive index of the material at a given wavelength.

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