ANGULAR DISTRIBUTION OF LIGHT SCATTERING IN BULK GLASS AND FIBRE WAVEGUIDES

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Measurements of the angular distribution of light scattering in samples of optical quality glass and in cladded glass fibres have been made and the total scattering loss over the wavelength range 0.5–1.0 μm has been obtained. The scattering shows a Rayleigh distribution indicating that (a) in similar samples the scattering loss can be inferred from a single measurement of the Rayleigh ratio at an angle of 90° to the incident beam and (b) no large inhomogeneities are introduced during the fibre-drawing process.

1. Introduction

In a recent publication [1] Rawson points out that estimates [2] of the scattering loss in bulk glass made from the single measurement of the intensity of light scattered at 90° and based on the assumption of essentially Rayleigh scattering can be seriously in error if scattering centres comparable in dimension to a wavelength are present. Apparently, investigation [1] of samples of experimental glass by the techniques of small-angle X-ray scattering and electron microscopy has shown the presence of such inhomogeneities. Following calculations based on the Mie theory Rawson goes on to recommend that when the total scattering loss in bulk glass samples is to be found the scattered light intensity should be measured as a function of angle. We wish to report that we have carried out such measurements in several samples of optical quality glass and for two orthogonal polarisations. In addition the total scattering loss has been obtained over the wavelength range 0.5–1.0 μm.

2. Scattering in bulk glass

The samples were in the form of rods 10 cm long and of 4 cm^2 rectangular cross section and were completely immersed in a tank containing index-matching liquid [3]. Two light sources were employed, one being a highly-stabilized xenon arc lamp, the output beam of which was collimated by a series of apertures and passed axially along the sample. The other was a helium/neon laser. The sample was placed against a thin dividing wall containing, at the centre point, a rectangular aperture of 1 cm width. Light scattered through the aperture was collected by a prism mounted on a rotating arm and immersed in the index-matching liquid and was then passed via a fibre-optic light guide to a cooled photomultiplier. The general arrangement is shown schematically in fig. 1. The intensity of the transmitted beam was also measured, after attenuation by reflection from a barium sulphate screen, so that absolute values of scattering could be obtained. The low intensity of scattered radiation was recorded by a photon-counting technique and precautions were taken to ensure a sufficiently wide range of linearity including the avoidance of errors due to the overlapping of adjacent pulses. The accuracy of the equipment was checked by making measurements of the scattering from benzene.

Polar scattering diagrams for light polarized in the plane containing the beam and the detector $U_h(\theta)$

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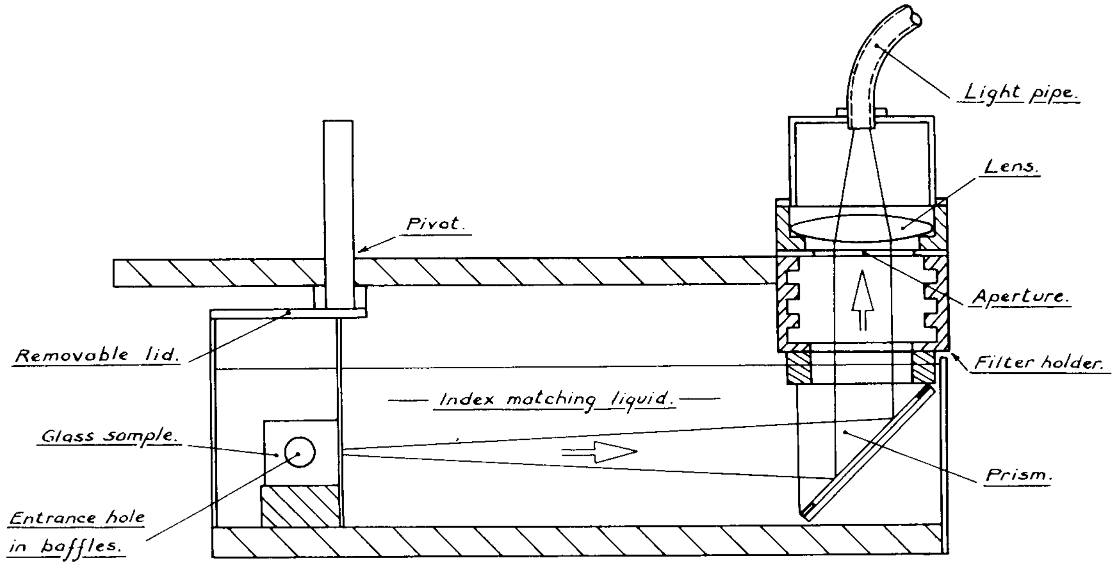

Fig. 1. Sectional view of scattering apparatus looking along axis of sample to be measured. Scattered photons are reflected by the prism into the fibre bundle and transmitted to a cooled photomultiplier.

and in the orthogonal plane $U_v(\theta)$ have been measured for several optical glasses. Typical results for Schott SSK2 glass obtained at 633 nm using the helium/neon laser are shown in fig. 2 where the points are experimental values and the solid lines are theoretical curves calculated from the depolarization ratio $\rho(90) = U_h(90)/U_v(90)$ measured in a direction at an angle of 90° to the incident beam. The limitation on the measurements to the angular range shown is due to mechanical factors such as the finite thickness of the scattering aperture. However within this range the scattering is within 3% of the ideal Rayleigh form and it is therefore possible to determine the total scattering by integration over a solid angle of 4π using the experimental results shown. The total integrated scattering as a function of wavelength is shown in fig. 3. As may be seen the points fall accurately on a straight line of slope −4.3 which is close to the value of 4.0 that is characteristic of Rayleigh scattering. It may be assumed therefore that in these samples of normal commercial quality optical glass the scattering centres are small compared with the wavelength and the number of particles present with a diameter greater than, say, 0.1 μm is negligible. It is therefore valid, at least for the glasses we have studied, to estimate the total bulk scattering loss α from

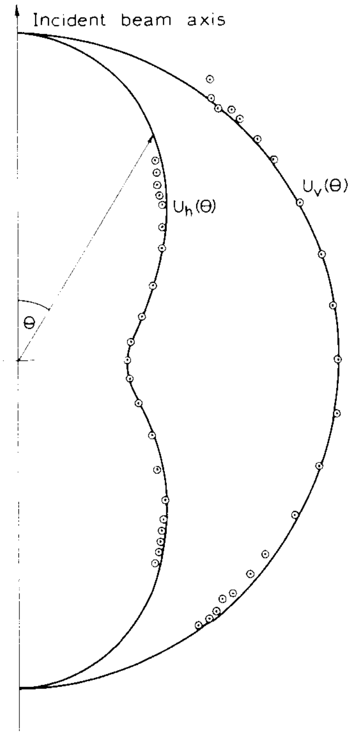

Fig. 2. Polar scattering diagram for SSK2 glass at 633 nm. Experimental values of $U_v(\theta)$ and $U_h(\theta)$ superimposed on theoretical curves.

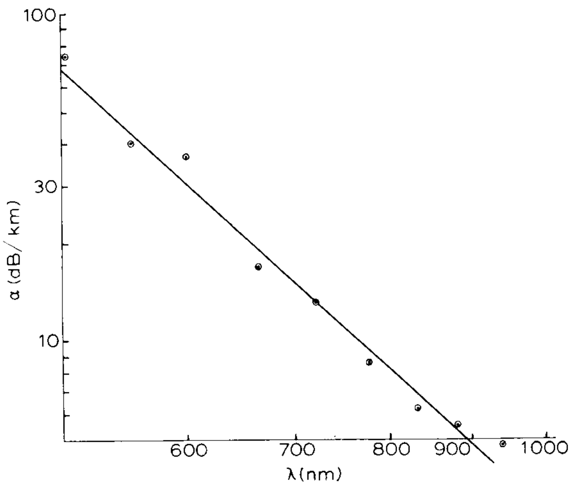

Fig. 3. Total scattering loss over the wavelength range 0.5 to 1.0 μm for SSK2 glass.

a measurement of the intensity of light scattered at 90°, using the equation

$$\alpha = R(90)\frac{8\pi}{3}\,\frac{2+\rho(90)}{1+\rho(90)}, \qquad (1)$$

where $R(90)$ is the Rayleigh ratio. The magnitude of the scattering at a wavelength of 0.9 μm is seen to be < 5 dB/km and if such glass can be pulled into fibres without increasing the amount of scattering then the loss due to this cause in a practical fibre waveguide will not be serious. Similar measurements with benzene give a slope of -4.0 and a Rayleigh ratio in satisfactory agreement with other published experimental and theoretical values.

3. Scattering in cladded glass fibres

In order to see whether the results obtained in bulk glass apply also to fibres, and as a check on the quality of the fibre manufacturing process, we have made cladded glass fibres with core diameters ranging from 2 μm to 100 μm using samples of one of the optical quality glasses, namely Schott F7 which is a lead-based glass. Fibre scattering measurements are, of course, more difficult because of the small cross section of the fibre. The technique used was similar to that for the bulk glass rods with the fibres immersed in a liquid of refractive index matching that of the cladding. As explained below great care has to be taken to obtain an accurate match to the refractive index of the cladding in order to ensure that there is no internal reflection, even for low-angle rays, at the cladding/liquid interface and a mixture of appropriate liquids [4] is normally used. Care has to be taken in launching [4] into the fibre since the introduction of light into the cladding can cause a scattering lobe in the forward direction.

Corrections have to be applied to the measurements to take into account the circularity of the fibre and the difference in refractive indices of the core on the one hand and the cladding and index-matching liquid on the other. A detailed analysis of these corrections is too complex to give here and will be published elsewhere but it is based on the assumption that:

(a) The fibre is cylindrical and straight over the measured length.
(b) The refractive index of the matching liquid is equal to that of the cladding (in practice the difference is less than 0.001).
(c) The light propagates in an axial direction along the core and with a uniform transverse distribution. In our case the aperture of the launching optics referred to the core is f16 but the resulting correction which has to be applied in the calculation of the Rayleigh scattering function is very small.
(d) The scattered light intensity is uniform about the fibre axis, which is consistent with (a) and with the use of unpolarized light.
(e) All light striking the core/cladding interface at an angle less than the critical angle eventually leaves the core, albeit after several partial reflections. This is true for a low-loss core.

There are two main corrections to be made. The first is due to the fact that the solid angle subtended at the detector is different for the core and the cladding/liquid combination. Secondly, a small portion of the scattered light strikes the core/cladding interface at an angle greater than the critical angle and gives rise to skew-ray propagation in the core. The correction factor thus involves the product of two terms which vary with the observation angle. For the fibres

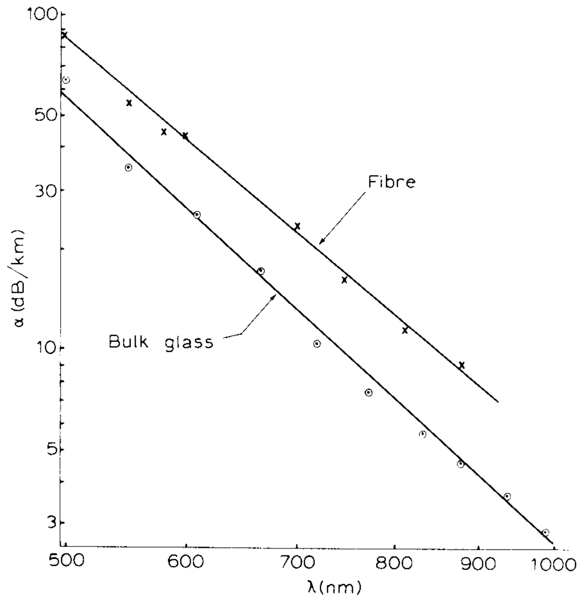

Fig. 4. Total scattering loss over the wavelength range 0.5 to 1.0 μm for bulk F7 glass and for a fibre with a core of 50 μm diameter F7 glass and ME1 cladding.

reported here, consisting of an F7 core cladded with ME1, the correction factor is less than 15% for angles between 30° and 150°, and less than 5% between 55° and 125°.

The results indicate that the angular dependence of scattering in our fibres over the angular range 30° to 150° and the wavelength range 0.5 to 1.0 μm again shows a Rayleigh distribution similar to that of the bulk core glass within the accuracy of measurement. In addition the variation of scattering at 90° with wavelength is also similar to that for the bulk. The depolarization ratio ρ cannot be measured directly for the fibre so that the total scattering loss as a function of wavelength has been calculated using the value for the bulk F7 glass. Since $\rho \approx 0.1$ the resulting error is negligible as may be seen from eq. (1). Fig. 4 shows that the fibre scattering/wavelength curve has a slope, −4.1, which is close to the ideal Rayleigh value, and the total scattering loss is within a factor of two of that of the bulk core material. At the semiconductor laser wavelength of 0.9 μm the fibre attenuation due to scattering is about 7.5 dB/km. This result indicates that scattering is not likely to be a serious problem with cladded glass optical waveguides and that our method of drawing fibres does not produce any appreciable number or size of scattering centres.

Acknowledgement

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