MEASUREMENT OF PROFILE DISPERSION IN OPTICAL FIBRES: A DIRECT TECHNIQUE

Indexing terms: Optical dispersion, Optical waveguides

A new technique allows direct determination of the wavelength-dispersive material properties of glasses within the fibre. Results obtained over a wide wavelength range are reported for both borosilicate and fluorine-doped cladding materials. The latter exhibits low profile dispersion.

Introduction: The group-velocity differences between modes in a multimode fibre may be effectively equalised by appropriate choice of the refractive-index profile.[1] It has been shown,[2] however, that the optimum profile which minimises pulse broadening is strongly influenced by the dispersive properties of the materials comprising the core and cladding. Measurements of the wavelength dependence of the refractive index of bulk-glass samples[2-4] have demonstrated that the optimum fibre index profile departs considerably from that predicted assuming a nondispersive medium. Assuming at all wavelengths a linear relationship between refractive index and the dopant concentration, the optimum profile parameter α is given by $\alpha \simeq 2-2P$, where P is the profile dispersion defined in Reference 2.

We report here a new method for the determination of P which enables measurements to be made on the fibre, and illustrate its use with results obtained for borosilicate and fluorine-doped glass systems. The profile dispersion of fluorine-doped silica has not been previously reported. The technique measures the wavelength dependence of the numerical aperture directly, thereby yielding the difference in dispersion between core and cladding and hence the profile dispersion P. It provides accurate data over a wide wavelength range and requires minimal sample preparation. The only other measurements on fibres reported to date require the preparation of a thin cross-sectional slice for interference microscopy.[5]

Experiment: The wavelength dependence of numerical aperture is determined by comparing the fibre throughput under two excitation conditions, as shown schematically in Fig. 1.

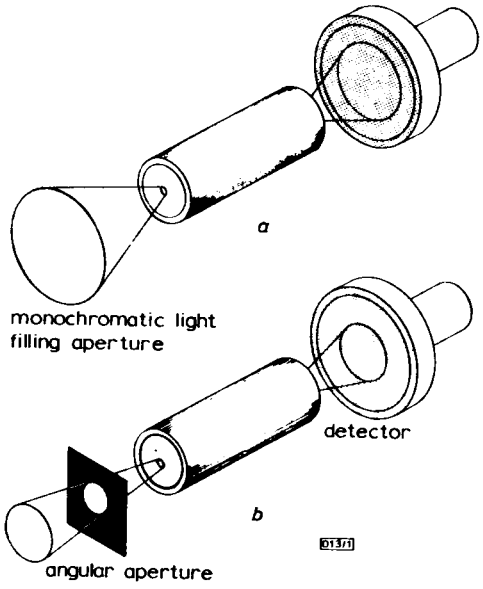

Fig. 1 *Schematic representation of experimental arrangement*
The fibre is fully excited in (*a*) and exhibits a wavelength-dependent acceptance angle, owing to the dispersive properties of the core and cladding glasses. In (*b*) the beam is angularly restricted to provide the reference measurement

A lamp followed by a monochromator provides a variable-wavelength Lambertian source which is spatially apertured and imaged onto the fibre endface to form a spot with diameter about one-tenth of that of the core. The small spot is necessary to avoid the excitation of leaky modes which have a wavelength-dependent loss.[6] In the first measurement (Fig. 1*a*) the fibre acceptance angle is completely filled by the source, and therefore the transmitted power depends on the numerical aperture. The second measurement (Fig. 1*b*) provides a reference and is made with the beam arranged so that it is restricted to about 0·7 of the fibre acceptance angle, and no dependence on numerical aperture occurs.

The total output power from a short length of straight fibre is measured at each wavelength for both apertured and nonapertured excitation. The ratio of the two measurements provides source compensation, eliminates the effect of fibre attenuation and yields the wavelength dependence of the numerical aperture.

Analysis: We fit the experimental data with a mathematical function chosen to take advantage of the fact that the refractive-index variation with wavelength λ of optical glasses is known to be accurately described by a 3-term Sellmeier equation.[7] The transmitted power ratio is proportional to $(\text{n.a.})^2 = n_1^2 - n_2^2$, where n_1 is the refractive index of the core at the point of illumination and n_2 is the cladding refractive index. It follows that $n_1^2 - n_2^2$ obeys a 6-term Sellmeier law, where two terms have resonance wavelengths in the infrared (typically 8 to 12 μm) and four terms are centred in the ultraviolet (of order 0·1 μm or less). Since such a form is rather unwieldy, we utilise the physical nature of the equation to write a simple expansion (defining $2n^2\Delta$ in the usual way[1]):

$$(\text{n.a.})^2 = 2n^2\Delta = A + B\lambda^2 + C\lambda^4 + D/\lambda^2 + E/\lambda^4 \quad . \quad (1)$$

Note that the constants A to E have a degree of physical significance. Using eqn. 1, we perform a least-squares fit to the measured power-ratio variation with wavelength and hence determine the constants. Differentiation then yields values for the profile dispersion P:

$$P = \frac{\lambda n}{N}\frac{\Delta'}{\Delta} = \frac{n}{N}\left(\frac{\lambda}{n^2\Delta}\frac{d(n^2\Delta)}{d\lambda} - \frac{2\lambda n'}{n}\right) \quad . \quad (2)$$

where N is the group index and the prime denotes differentiation w.r.t. λ. As a check on the accuracy of this procedure, the second derivative may also be computed and, if refractive-index data of either core or cladding are known (usually silica[7]), the material dispersion[8] of the other component may be deduced.

An alternative approach to that outlined above is to fit the data by using a standard polynomial expansion. However, this could sometimes lead to the prediction of refractive-index behaviour for a glass which would preclude its being described by a Sellmeier equation. The present approach using eqn. 1 does not allow this embarrassing possibility.

Results: Fig. 2 shows the measured value of $(\text{n.a.})^2$ for two step-index fibres having pure silica cores with claddings containing boric oxide or fluorine. The fibres had apertures of 0·13 and 0·14, core diameters of 100 and 155 μm, respectively, and a length of about 30 cm. Also shown are the least-squares fits to the data, using the curves of eqn. 1. Although the accuracy of the fits is high (0·5% and 0·3% r.m.s. error), some evidence of the individual mode cut-offs may be seen, particularly at longer wavelengths.

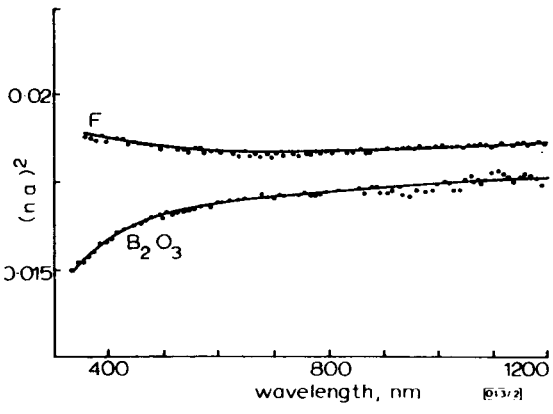

Fig. 2 *Variation of $(\text{n.a.})^2$ with wavelength for two cladding materials indicated*
For fibre details see text

The profile dispersion parameter obtained from the data is given in Fig. 3 for the two compositions. The result for borosilicate may be compared with that obtained on unquenched bulk samples by Fleming[3] for a similar glass

composition (shown broken). The present results imply an optimum α of 1·86 at a wavelength of 0·9 μm, falling to 1·84 at 1·06 μm; these values are close to those predicted by Fleming. The recent results of Presby and Kaminow,[5] however, are somewhat lower and indicate a nonlinear relationship between index and B_2O_3 concentration.

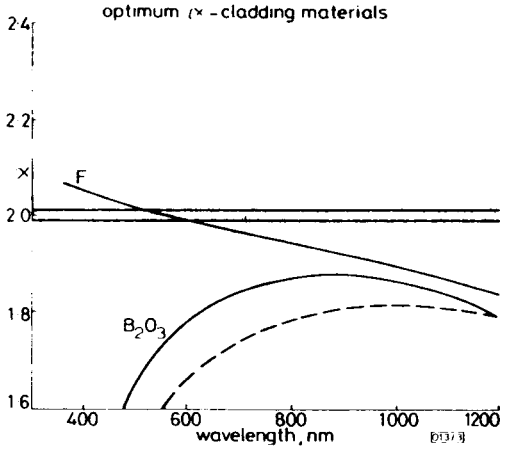

Fig. 3 *Profile dispersion shown as function of wavelength for borosilicate and fluorine-doped fibres*
The broken line indicates the result obtained by Fleming for a B_2O_3–SiO_2 combination

The result for fluorine is of interest in that it exhibits a small variation of α, the value falling from 2·05 to 1·86 between 400 and 1100 nm. This characteristic permits the waveguide to be operated over a wide range of wavelengths while maintaining the index profile at near-optimal α.

Although not shown here, the computed material dispersion for both cladding glasses lies very close to that of pure silica. The results indicate that the three sets of values do not differ by more than 10 ps/nm/km over the wavelength range 500–1200 nm.

Conclusions: Direct measurement of the numerical aperture can be used to determine the dispersive material constants of a fibre waveguide. The method is not restricted to step-index fibres, although care must be taken to eliminate leaky modes, especially in graded-index fibres. The technique is convenient to use, requires little sample preparation and the results confirm existing data on the borosilicate glass system. The profile dispersion of fluorine-doped silica has been measured for the first time and exhibits an optimal α close to 2 over a range of wavelengths.

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