WAVELENGTH-DISPERSIVE PROPERTIES OF GLASSES FOR OPTICAL FIBRES: THE GERMANIA ENIGMA

Indexing terms: Optical dispersion, Optical fibres

A comparative study is made of the wavelength-dispersive properties of germania-doped glass for optical-fibre waveguides and some important discrepancies are revealed. New results are presented for profile dispersion of this material over an extended wavelength range.

A considerable amount of data is now available concerning the wavelength dependence of the refractive index of silica doped with germania and, in principle, this should aid the design of multimode fibres with minimal pulse spreading. However, there would seem to be considerable discrepancies between reported data from different sources, leading to confusion as regards both the optimum index profile and the operating wavelength that minimises material dispersion. In this study, new results are presented and compared with those available from other sources, the latter being processed where necessary to reveal the relevant parameters.

Theoretical background: Olshansky and Keck[1] have considered pulse broadening in fibres fabricated from dispersive materials and which have α-law profiles. They predict an optimum α-profile described by $\alpha = 2 - 2P - 12\Delta/5$, where Δ is the relative-index difference between core and cladding and P is the profile dispersion parameter, defined as

$$P = \frac{n_1}{N_1}\frac{\lambda}{\Delta}\frac{d\Delta}{d\lambda}$$

Here λ is the wavelength, n_1 is the index at the core centre and $N_1 = n_1 - \lambda dn_1/d\lambda$ is the corresponding group index. Implicit in the theory is the assumption that P is purely a property of the additive used to modify the refractive index of the base glass and is not a function of its concentration; thus P is assumed constant throughout the core of a graded-index fibre. If this is not the case, other more complex forms of theoretical analysis are required,[2-4] leading to an optimal index profile which is not of the power-law type.

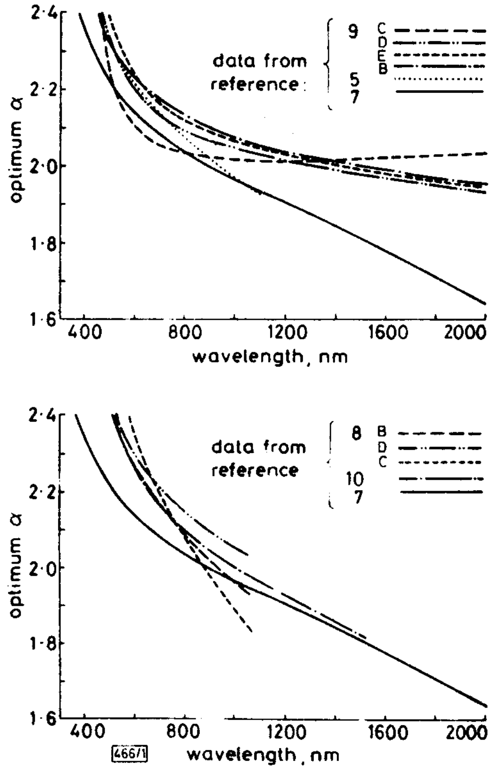

Fig. 1 *Optimum $\alpha = 2 - 2P$ given as a function of wavelength for germania-doped fibres*

The data is taken from the References given in the key; SiO_2 data is taken from the well known NBS results

The material-dispersion parameter M, which describes the pulse dispersion caused by the wavelength dependence of the group delay τ, is given by

$$M = -\frac{d\tau}{d\lambda} = \frac{\lambda}{c}\frac{d^2 n_1}{d\lambda^2}$$

where c is the speed of light *in vacuo*.

Profile dispersion in germania-doped silica fibres: It is clear that the design of optimal graded-index fibres requires measurement of the profile dispersion parameter P as a function of wavelength for common additives. Furthermore, in order to test the assumption that the profile dispersion is homogeneous throughout the core of a graded-index fibre, it is desirable to perform measurements on a range of binary glasses with various concentrations of the additive. P may be measured on doped silica fibres,[5-7] or may be computed from published refractive-index values for bulk samples.[8-10]

Fibre measurements have been reported by Presby and Kaminow,[5] who have presented results obtained by an interference method over the wavelength range 500-1100 nm. On the other hand, the technique developed in our laboratories[6] determines P directly by measurement of the variation of fibre numerical aperture with wavelength. Recently, considerable improvements in the accuracy of the latter measurement have been obtained by extension of the range to cover wavelengths from 350-1900 nm.[7] The two measurements are shown in Table 1 and Fig. 1.

Table 1 MEASUREMENTS REPORTED ON GeO_2/SiO_2 GLASSES

Sample		GeO_2 m/o	Wavelength range	Number of wavelengths
			nm	
Sladen *et al.*[7]		13·1	350-1900	156
Presby & Kaminow[5]		22·0	500-1100	13
Fleming I[8]	B	13·5	430-1080	12
Fleming I[8]	C	7·0	430-1080	12
Fleming I[8]	D	4·1	430-1080	12
Kobayashi *et al.*[9]	B	3·1	400-2440	21
Kobayashi *et al.*[9]	C	3·5	400-2440	21
Kobayashi *et al.*[9]	D	5·8	400-2440	21
Kobayashi *et al.*[9]	E	7·9	400-2440	21
Fleming II[10]	B	13·5	430-1530	14

Refractive-index measurements on bulk GeO_2/SiO_2 glasses have been reported by Fleming[8, 10] and Kobayashi *et al.*;[9] details are given in Table 1. From the data given in References 8-10 it is a simple matter to calculate P for a set of GeO_2-doped fibres with a composition at core centre equal to that of the measured bulk sample, and whose cladding consists of pure SiO_2, the index data for which is well known. The computed results are given in Fig. 1. There is a significant difference in the curves, even for quite similar concentrations, between the bulk-glass results of Kobayashi *et al.* and Fleming; furthermore, there is little agreement between bulk-glass results and those obtained on fibres. Fleming's results would clearly indicate an inhomogeneous profile dispersion and hence the departure of optimum fibre index profiles from the α-law type. On the other hand, the results of Kobayashi *et al.* would imply a profile dispersion somewhat closer to linear, particularly for their samples B, D and E.

Discussion: On the basis of the fibre and bulk measurements given above, various theoretical predictions have appeared in the literature. Using their values of P determined on a 22 m/o GeO_2-doped fibre and assuming P independent of concentration, Kaminow and Presby[11] have predicted a fibre based on a ternary $P_2O_5/GeO_2/SiO_2$ glass that exhibits a profile close to optimum over an extended wavelength range. Adopting the

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diametrically opposed assumption of nonlinear profile dispersion, however, and using the measurements of Fleming,[8] Arnaud[2] has calculated optimum profiles (not of the α-type) for fibres with germania-doped cores and boron-doped claddings. More recently a hybrid theory—the 'multiple-α profile'—has become available.[3] Using a modified form of this theory, in which the profile dispersion is required to be linear, and the measured data from References 8 and 9, an optimum configuration has been proposed[4] based on GeO_2 and B_2O_3 as dopants (although we note that both References 8 and 9 predict nonlinear profile dispersion for GeO_2 over a wide range of compositions).

From the foregoing, it may be seen that little agreement on the wavelength-dispersive properties of GeO_2-doped glasses exists at present and therefore that predictions for optimised fibre structures should be treated with some caution, at least until measurements of the properties of this material can be substantiated.

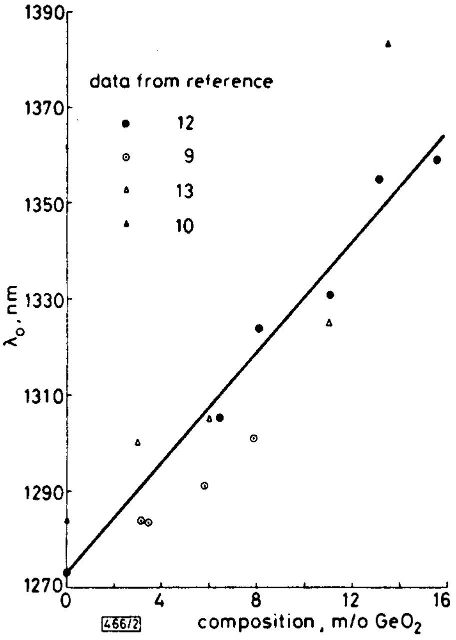

Fig. 2 *Wavelength of zero material dispersion λ_0 as a function of germania concentration*

The data is taken from the References given in the key. The solid line is the best fit to our own data (solid points)

Wavelength of zero material dispersion: The material-dispersion parameter M has been measured in multimode germania-doped fibres[12,13] and in bulk samples.[8-10] The wavelength λ_0 corresponding to zero material dispersion for various concentrations of germania has been reported for graded-index[13] and step-index[12] multimode fibres and also for bulk samples measured in two different laboratories[9,10] by an identical technique. These results are summarised in Fig. 2, which also shows the data from our own laboratories, extended by the incorporation of two further points.

For the measurements on germania-doped fibres, the step-index results of Payne and Hartog[12] lie in general above the graded-index results obtained by Chinlon Lin *et al.*[13] However, as pointed out in Reference 14, it is difficult to interpret data obtained on graded-index fibres since the results represent a weighted mean of the properties of the core and cladding compositions. Consequently it is not possible to determine material properties directly from the results of Reference 13 since they represent a mixture of core and cladding values, the proportion of each depending on the excitation conditions. The fact that the result for a graded-index fibre having a certain composition at core centre is lower than that of an equivalent step-index fibre is consistent with this observation.

It is again clear that little agreement for the wavelength of zero material dispersion exists between results from various sources, a fact which is perhaps not surprising, at least for the bulk glass measurements, since the values for M (derived from the second derivative of index) are likely to be even more at variance than the values for P (obtained from the first derivative).

Conclusions: We have presented further results obtained in our laboratories for both profile and material dispersion and compared these with the results obtained elsewhere. It is clear that several fundamental questions remain to be resolved. The results published to date reveal little as to the linearity or otherwise of the profile dispersion, since major discrepancies exist in results even for similar compositions. Furthermore, large differences exist in the predictions for the wavelength of zero material dispersion.

It is hoped that the presentation of data given here will serve to caution designers in their selection of available results, since the use of inappropriate values could result in an order-of-magnitude error in predicted bandwidth.

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