DETERMINATION OF THE WAVELENGTH OF ZERO MATERIAL DISPERSION IN OPTICAL FIBRES BY PULSE-DELAY MEASUREMENTS

Indexing terms: Optical dispersion, Optical fibres

Pulse-delay measurements on fibres are reported, made over a wide wavelength range straddling the zero of material dispersion. Results for phosphosilicate and a range of germania-doped fibres indicate that the wavelength of negligible material dispersion lies in the range 1270–1400 nm. The optimum wavelength depends on the concentration for fibres containing germania.

Introduction: The bandwidth of an optical transmission line is limited by (*a*) transit-time differences which exist between modes, (*b*) waveguide dispersion caused by the frequency dependence of the group velocity of the individual modes and (*c*) the wavelength dispersive properties of the glass refractive index, known as the material dispersion. The intermodal time-delay differences can be effectively equalised by an appropriate choice of the core refractive-index profile, leaving the limitation of waveguide and material dispersion. The latter dominates when using GaAs devices with their characteristically-broad spectral spread and in many applications results in a curtailment of the potential bandwidth of both single and multimode fibres.

Extrapolations from previous fibre measurements[1,2] indicate that the material dispersion becomes negligibly small at wavelengths near 1270 nm for fibres based on phosphosilicate glass. Thus it was suggested[2] that a shift of operating wavelength from 850 to ~1300 nm would result in increased transmission capacity, particularly when using an l.e.d. as the source. Recent developments have further emphasised the importance of this spectral region: (i) very low losses[3] have been obtained at a similar wavelength in fibres produced by c.v.d. and (ii) both l.e.d.s[4,5] and lasers[6] have become available operating at longer wavelengths. It is clear, therefore, that a more detailed knowledge of the material-dispersion behaviour would be an advantage in the design of future optical communication systems. Although further results have since become available, based on bulk glass[7] or fibre[8] measurements, the data are not yet available over a sufficiently broad spectral range.

We present here measurements made by a pulse-transmission technique at wavelengths on both sides of the zero of material dispersion and which cover the entire wavelength region currently of interest to optical communication. The results enable the wavelength λ_0 of the material dispersion zero to be determined both in phosphosilicate fibres and in a variety of germania-doped fibres having different compositions.

Experiment: The pulse-delay technique used is similar to that reported previously,[1] whereby the transit time of a pulse through a length of fibre is measured as a function of wavelength. The nonlinear frequency dependence of the glass refractive-index causes the pulses to propagate with a different group velocity for each wavelength, from which the material dispersion may be computed. A dye laser followed by a temperature-tuned $LiNbO_3$ parametric oscillator provides pulses at 10 pulses/s in the wavelength range 780–2600 nm, while the dye laser alone covers wavelengths from 580–620 nm. Pulses of 0·5 ns duration suitable for injection into the fibre are extracted from the output by means of a Pockels-cell pulse slicer.

The transmission delay of the pulse through the fibre is measured by a digital time-delay generator in conjunction with an oscilloscope. The delay generator provides the time delay necessary to display the pulse emerging from the fibre on the oscilloscope at a sweep speed of 0·5 ns/division. Thus the major portion of the transit time is offset by the delay generator, permitting small variations to be read with high accuracy from the oscilloscope display. Measurements of the transmission delay are made at intervals of 10 nm in the ranges 580–620 nm and 780–1800 nm. A small region near 1300 nm proves to be inaccessible, owing to the presence of an absorption peak in fibres with an above-average OH content.

Theory: To least-squares fit a curve to the experimentally determined variation of transmission delay with wavelength, we make use of a technique developed earlier,[9] whereby the known physical behaviour of the glass refractive index is exploited to process the data. Neglecting a small waveguiding effect, the transit time τ of a pulse is given as a function of wavelength λ by

$$\tau = \frac{L}{c}\left(n - \lambda \frac{dn}{d\lambda}\right) \quad (1)$$

where L is the fibre length and n is the refractive index. Since it is well known that the wavelength dependence of the index n is accurately described by a three-term Sellmeier equation,[10] it follows that eqn. 1 may be written in the form of a Sellmeier and its derivative. This form is rather unwieldy, so we perform a simple series expansion to yield

$$\tau = a + b\lambda^{-2} + c\lambda^{-4} + d\lambda^2 + e\lambda^4 \quad (2)$$

Eqn. 2 may be readily used to r.m.s. fit the data and determine the coefficients a to e. The material-dispersion parameter M is then given by

$$M = d\tau/d\lambda$$

As a check on this procedure, pulse-delay results have been simulated by using the data for pure silica[10] and processed using eqn. 2. The resulting values for M are within 0·05 ps/nm/km and the zero determined to an accuracy of 1 nm.

Results: A phosphosilicate fibre and a series of three germania-doped fibres with increasing germania content have been tested. The fibre parameters are given in Table 1 and their measured transmission delay relative to that at 580 nm in Fig. 1, omitting VD150L, whose result lies close to that of VD202L. It is clear that an increasing GeO_2 content is accompanied by a larger variation in transit time and a minimum delay point

Table 1 CHARACTERISTICS OF FIBRES TESTED

Fibre	Type	Length	Composition m/o		
			P_2O_5	GeO_2	SiO_2
		km			
VD150L	Graded	0·568	15·0	0·0	85·0
VD202L	Graded	1·239	5·4	6·4	88·2
VD208L	Step	0·818	0·0	8·1	91·9
VD210L	Step	1·217	0·0	13·1	86·9

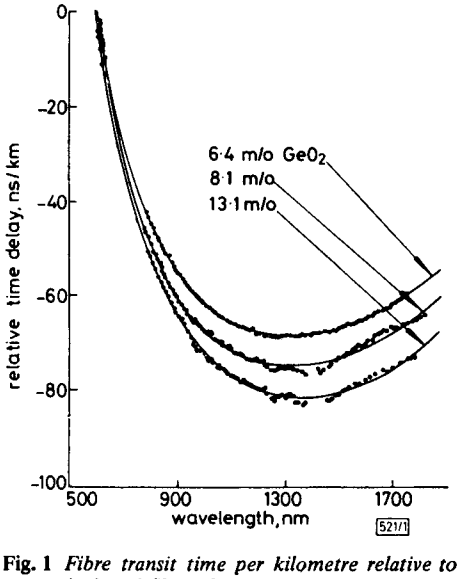

Fig. 1 *Fibre transit time per kilometre relative to that at 580 nm for germania-doped fibres shown*

which shifts to longer wavelength. The fitted curves are also shown in the Figure and the coefficients a to e given in Table 2, together with the r.m.s. error. The fit is excellent for fibres VD150L and VD202L, with a somewhat larger error for the other two, an effect which is attributable to differential mode

Table 2 COEFFICIENTS OF EQN. 2

Fibre	$a \times 10^3$	$b \times 10^7$	$c \times 10^{11}$	$d \times 10^{-6}$	$e \times 10^{-13}$	R.M.S. error
						%
VD150L	2·75134	2·18078	−3·59136	8·44963	−0·947283	0·005
VD202L	6·04230	4·01648	6·63281	11·5794	7·49017	0·003
VD208L	3·95212	1·31063	33·7132	−8·25446	39·1966	0·009
VD210L	5·82382	4·10387	13·2256	6·53814	16·4955	0·011

λ in nanometres gives τ in nanoseconds for the fibre lengths of Table 1

attenuation near absorption peaks and its influence on the pulse dispersion (and hence the measured average group delay) in step-index fibres. Since the pulse dispersion is lower in graded-index fibres (VD150L and VD202L), the effect is less pronounced.

The computed material-dispersion parameter is given in Fig. 2 for fibre VD210L (13·1 m/o GeO_2) and VD150L (15 m/o P_2O_5), together with the result calculated from refractive-index data for undoped silica.[10] The curves confirm

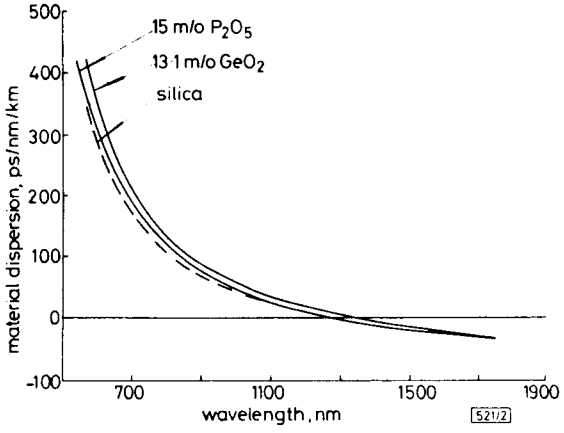

Fig. 2 *Comparison of material dispersion of fibres containing 15 m/o P_2O_5 and 13·1 m/o GeO_2 with that of pure silica*

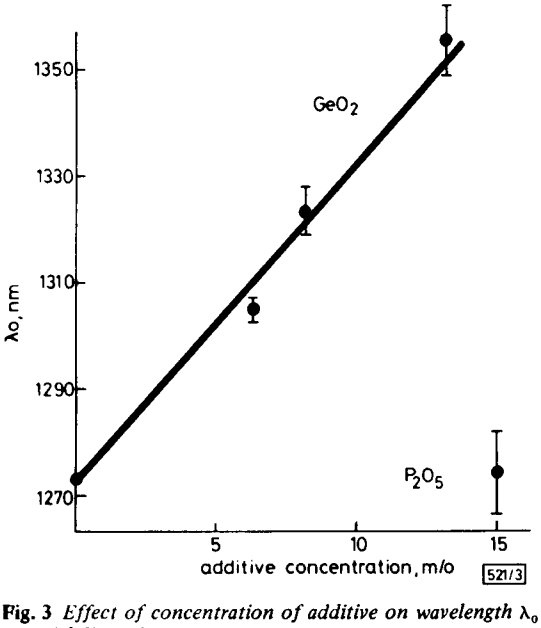

Fig. 3 *Effect of concentration of additive on wavelength λ_0 of zero of material dispersion*

The value for O m/o is calculated from the data for pure silica. Note that the 6·4 m/o GeO_2 fibre also contains P_2O_5

the earlier extrapolated result[1] that the material dispersion of phosphosilicate glass differs little from that of silica. However, the addition of 13·1 m/o germania to silica produces an increase in the material dispersion of ~25 ps/nm/km at 0·9 μm. Within the range 600–1100 nm, the latter curve is virtually identical to that determined by Fleming[10] on a bulk-glass sample containing 13·5 m/o GeO_2. However, our extrapolation of his results to longer wavelengths reveals a progressive departure of the two values, with the present measurements giving a zero at 1355 nm, compared with 1410 nm predicted by Fleming. Although given here for the sake of completeness, we note that such an extrapolation outside the range of measurements frequently produces considerable errors.

The effect of GeO_2 concentration on the wavelength λ_0 of zero material dispersion is illustrated in Fig. 3. λ_0 shifts progressively to longer wavelengths with increasing GeO_2 content,* while, in contrast, λ_0 for a 15 m/o P_2O_5 glass is found at 1272 nm, a result similar to that of silica.

Conclusions: Pulse-delay measurements on fibres over a wide wavelength range reveal that the optimum source wavelength for minimisation of material-dispersion effects in multimode fibres lies in the region 1270–1400 nm, depending on the dopant and its concentration. The importance of this spectral region is further emphasised by its proximity to the fibre minimum-loss wavelength. This should provide added impetus for the development of suitable sources to exploit these advantages.

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* During the preparation of this letter, a similar curve based on bulk-glass measurements has been presented.[11] Our measurements indicate a slightly greater zero shift with composition, an effect which may be attributable to the quenched state of the glass in the fibre form