EVALUATION OF MATERIAL DISPERSION IN LOW LOSS PHOSPHOSILICATE CORE OPTICAL FIBRES

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Received 7 October 1974

A method is described for the measurement of material dispersion in the core of an optical fibre, over a wide wavelength range. The method is relatively insensitive to the pulse dispersion caused by group delay differences between modes in the fibre. It is found that the dispersion of phosphosilicate core material is no greater than that of fused silica and is independent of composition over the range measured.

1. Introduction

The bandwidth of a multimode optical fibre waveguide is determined by material dispersion, and by transit time differences between modes. The limiting factor, particularly with broad linewidth sources, is material dispersion since the group delay differences can be made small by the correct choice of refractive index profile across the core [1] or alternatively by a mode scrambling technique [2]. Material dispersion arising from the non-linear wavelength dependence of refractive index, has been shown to produce a pulse broadening of 3.6 ns [3] in a 1 km length of fibre having a core of germania-doped silica when a light-emitting diode of 40 nm spectral width is used. Even for a GaAs laser of relatively narrow spectral width the broadening may not be negligible.

The material dispersion (as defined below) of glasses available in bulk form can be obtained by conventional techniques but, owing to the possibility of changes being caused by severe thermal processing during fibre drawing, a measurement directly on the fibre is to be preferred. In addition, for those materials difficult to form in bulk, such as the phosphosilicate glass recently used in this laboratory as the core of ultra-low loss optical fibres, the dispersion must be determined on the fibre itself.

One technique which has been reported [4] involves an analysis of the back-scattered radiation produced when a beam from a cw argon laser impinges transversely upon a fibre. This method has so far only been applied to unclad fibres and the results will be difficult to interpret in the presence of a cladding. It also gives the dispersion in a small localized region of the fibre whereas for communications purposes an effective value over a long length of fibre is of more interest. In another method [3] two self-pulsing GaAs lasers emitting at slightly different wavelengths are coupled to a length of fibre and the material dispersion is obtained from the time separation, $\Delta\tau$, between the two pulses at the output end of the fibre. Because the two wavelengths are closely spaced the difference in pulse propagation times is small and this method can only be used with fibres of very low group delay dispersion, such as graded-index fibres, where the pulse broadening is less than $\Delta\tau$. As a result the core material dispersion cannot be obtained as a function of composition since this varies with radius.

It is commonly observed that the addition of a dopant to fused silica in order to increase its refractive index also results in an increased absorption in the blue region of the spectrum, bringing with it a change in the material dispersion characteristics. This is perhaps not altogether surprising as the refractive index in the visible and near infra-red region is closely related (by the Kramers–Kronig relation) to the intensity and proximity of the strong electronic absorption in the ultra-violet. An increased refractive index implies an

intensified or shifted ultraviolet absorption band, and the tail of this band magnifies the loss in the blue spectral region. In addition the slope of the refractive index curve varies more rapidly with wavelength, giving rise to increased dispersion. Thus, for example, high refractive index optical glasses exhibit large dispersion [5] and a germania-doped silica fibre gives a higher dispersion than that of pure silica [3].

However, as has previously been reported [6,7], the addition of P_2O_5 to silica results in an increased refractive index without an accompanying increase in the low-loss characteristic of pure silica. The object of the present work therefore, was to verify the inference of this unchanged blue absorption, namely that the material dispersion characteristic would be similarly unaffected.

By employing a single laser to generate a series of monochromatic pulses of different wavelengths in the range 700–900 nm we have been able to determine the material dispersion of various phosphosilicate compositions over a wide wavelength range. The material dispersion results in differing fibre transit times for each wavelength pulse, and when this difference is measured relative to a time marker pulse the dispersion as a function of wavelength may be calculated.

2. Theory

Consider a short pulse in the form of a plane wave propagating in an infinite dispersive medium having a refractive index n which is a non-linear function of the angular frequency ω. The group delay τ per unit length is given by:

$$\tau = \frac{d\beta}{d\omega} = c^{-1}\left(n + \omega\frac{dn}{d\omega}\right), \tag{1}$$

where the phase constant β is related to the wavelength λ by:

$$\beta = 2\pi n/\lambda = \omega n/c = kn\ . \tag{2}$$

Thus in terms of wavelength we can write:

$$\tau = \frac{d\beta}{d\omega} = c^{-1}\left(n - \lambda\frac{dn}{d\lambda}\right). \tag{3}$$

If the spectral width of the pulse is $\Delta\lambda$ then signal distortion will arise as a result of this wavelength dependence of group delay. The pulse width $\Delta\tau$ after travelling unit length is given by the differences in transit times corresponding to the wavelength spread $\Delta\lambda$ namely:

$$\Delta\tau = \frac{d\tau}{d\lambda}\Delta\lambda\ . \tag{4}$$

Alternatively if two monochromatic pulses of small wavelength difference are simultaneously launched then eq. (4) gives the difference $\Delta\tau$ in propagation times of the peaks after unit distance.

Thus the transmitted pulse width or pulse separation can be determined from a knowledge of the 'material dispersion' $d\tau/d\lambda$ ‡ and the spectral width $\Delta\lambda$.

From eq. (3)

$$\frac{d\tau}{d\lambda} = \frac{-\lambda}{c}\frac{d^2n}{d\lambda^2}\ , \tag{5}$$

and $\Delta\tau$ can also be obtained from known refractive index data.

$$\Delta\tau = \frac{-\lambda}{c}\frac{d^2n}{d\lambda^2}\Delta\lambda\ . \tag{6}$$

However with optical fibres, for the reasons already stated, a much more useful and direct method is to measure $d\tau/d\lambda$ directly. This can be done by determining the group delay τ in the fibre as a function of wavelength and taking the slope of the resulting curve. In order to avoid errors arising from the fact that the delay differences are small compared with the total delay, a pulse of fixed wavelength and delay can be injected together with the pulses of varying wavelength, to act as a reference time marker. Then the variation of delay with wavelength can be measured relative to this pulse avoiding the need to accurately measure the total transit time.

In a multimode step-index fibre another dispersive mechanism must be taken into account. The pulse distortion caused by delay differences between the propagating modes is up to 5 ns/km in the fibres considered here, and the pulse separation due to material dispersion must therefore be at least 5 ns in a 1 km length. This can be achieved by judicious choice of the wave-

‡ The 'material dispersion' is taken to mean $d\tau/d\lambda = (-\lambda/c)\,d^2n/d\lambda^2$ throughout this paper. This is in contrast to the 'dispersion' of optical glass which normally refers to the first derivative of the refractive index, $dn/d\lambda$.

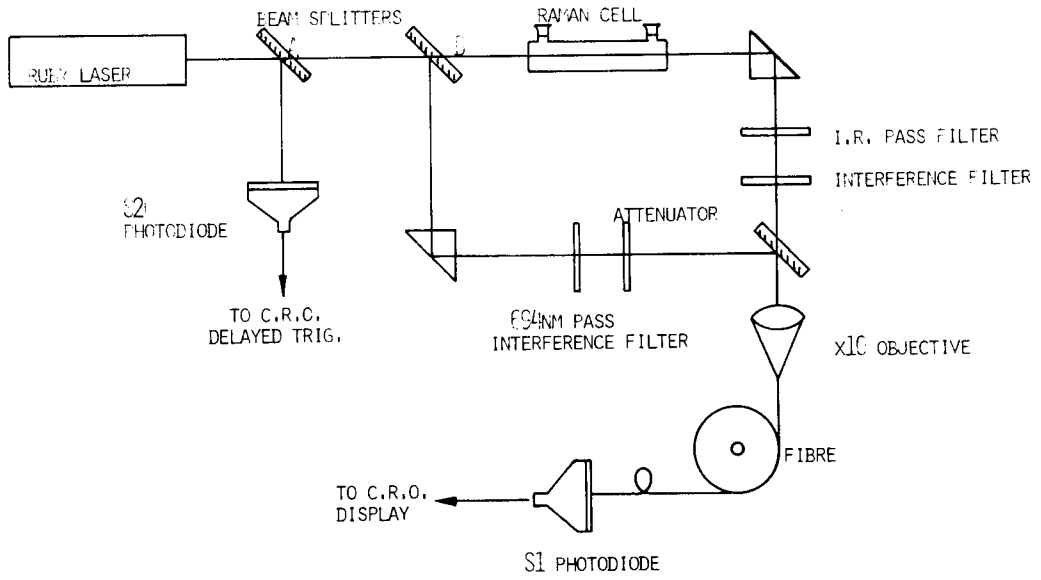

Fig. 1. Experimental arrangement.

length difference between the reference pulse and the region in which it is desired to determine the dispersion. As may be seen in fig. 2, the pulses can be sufficiently well separated, even in a multimode fibre, to enable accurate delay difference measurements to be made. It may also be seen that the pulse width is equal for the two wavelengths, so that the waveguide has equal effect on both the time marker and the probe pulse. Thus the pulse separation, as measured from peak to peak, is due only to material dispersion.

3. Experiment

Since the wavelength region of principal interest for optical fibre communications is that of the various lasers and light-emitting diodes based on gallium arsenide and associated materials, namely 800 nm to 900 nm, a ruby laser was used to provide the marker pulse from which the probe pulses at various wavelengths were derived by Raman generation. The ruby laser was simultaneously Q-switched and mode locked DDI/DCI dye solution giving trains of pulses of 25 ps duration at 694 nm and separated by 9 ns [8]. The output from the laser was first passed through a beam-splitter, A in fig. 1, where a portion was extracted and fed to a vacuum photodiode in order to provide triggering pulses for a Tektronix 7904 oscilloscope with a plug-in unit having a 500 MHz response. Of the transmitted beam 8% was removed at a second beam-splitter

Table 1
Raman shifted wavelengths available from benzene or water cell

Liquid	Frequency shift (cm^{-1})	Output wavelength (nm)
Benzene	991 (1st Stokes)	746
Benzene	991+991 (2nd Stokes)	805
Benzene	3064 (1st Stokes)	882
Water	3651 (1st Stokes)	930

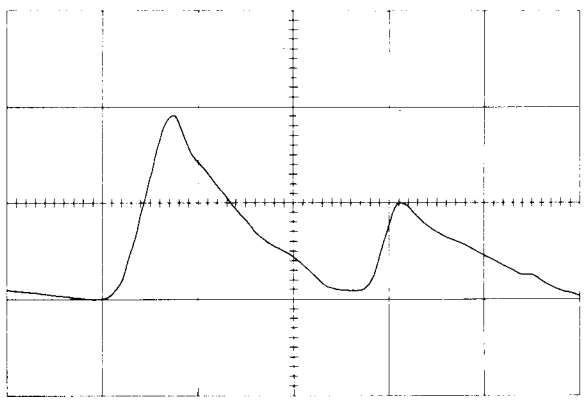

Fig. 2. Output pulses from 330 m of 50 μm core diameter phosphosilicate fibre (N.A.O. 162). The first pulse is an 805 nm probe pulse, while the second is the 649 nm time marker pulse. Time scale 2 ns/div.

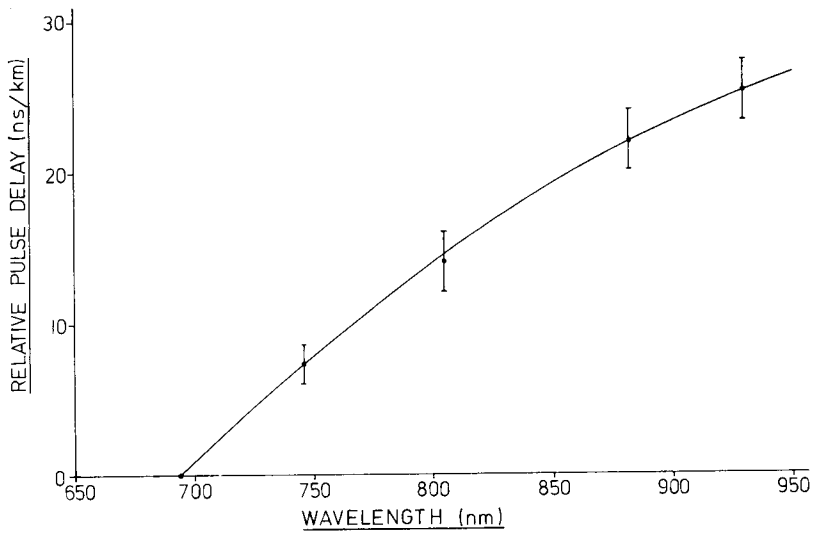

Fig. 3. Group delay of pulses of various wavelengths relative to time marker pulse of 694 nm. The curve is for all fibres tested.

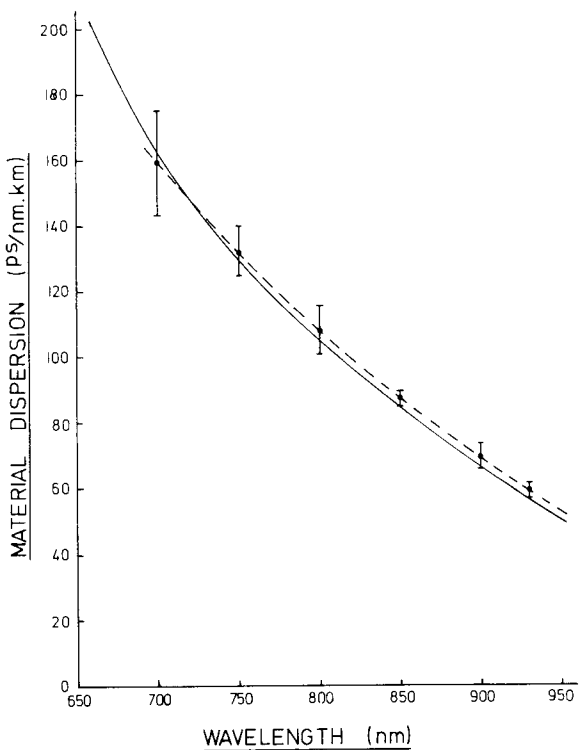

Fig. 4. Wavelength dependence of the material dispersion of phosphosilicate glass. The dashed curve was obtained using fibres of several different P_2O_5 levels. The solid curve was calculated from the refractive index data of pure silica.

B to provide the reference pulse of fixed wavelength $\lambda_1 = 694$ nm. The remaining beam traversed a Raman cell of length 20 cm containing either benzene or water. In the latter case a lens of focal length 30 cm was placed in front of the cell in order to increase the Raman gain. The wavelengths generated are shown in table 1. The output from the Raman cell was filtered appropriately to remove the ruby laser radiation (filter RGN-9) and to select the desired Raman wavelength (narrow-band interference filter). The pulse trains at the two wavelengths were recombined using a tilted plate as shown and launched simultaneously into the fibre by means of a X10 objective lens.

The output from the fibre was detected with a vacuum photodiode having an S1 response and displayed on an oscilloscope. The intensities of the input beams to the fibre at the ruby laser and Raman wavelengths were adjusted to be approximately equal at a power level of 30 W over 20 ps, a level below the non-linear attenuation threshold for pulses of this duration. The propagation delay between the probe pulses, at the wavelengths shown in table 1, and the reference pulse was measured in stepped-index multimode fibres of $\sim 50\,\mu$m core diameter for a range of P_2O_5 concentrations corresponding to numerical apertures from 0.10 to 0.18. Two fibres having a graded-index core were also measured. The lengths ranged from 0.23 to 1.15 km. The fibres had an attenuation of less than 10 dB/km

in the range measured, some samples having a loss as low as 2.7 dB/km at 830 nm. The pulse dispersion caused by group delay differences between modes was obtained from the broadening of individual pulses, and was ~5 ns/km for the stepped-index fibres and ~1 ns/km for the graded-index fibres.

Typical oscillograms showing the reference and probe pulses at the output from the fibre are shown in fig. 2. The group delay relative to that at 694 nm for all the fibres tested is given by fig. 3 which is, effectively, a curve of τ versus λ. The slope of this curve has been measured and the values of $d\tau/d\lambda$ so obtained are indicated by the points marked in fig. 4. The solid line in fig. 4 is a curve of $-(\lambda/c)\, d^2n/d\lambda^2$ for pure silica which has been calculated from published [9] refractive index data. It can be seen that there is no significant difference between the results obtained with the various fibres and the material dispersion of phosphosilicate glass does not differ from that of silica.

4. Discussion

The fact that the measured material dispersion of phosphosilicate glass does not differ from that calculated for silica is in contrast with the result obtained for germania doping [3]. The small differences in the results obtained for the various fibres are probably due to experimental scatter since there was certainly no trend towards the value for silica as the phosphorus pentoxide concentration was reduced. The value of 69 ps $nm^{-1}km^{-1}$ measured at 900 nm differs from that of silica by only 4%, this difference being within the accuracy of the experiment. The present result is consistent with the observation [6,7] that the addition of phosphorus pentoxide to silica does not increase the transmission loss in the blue region of the spectrum.

Measurements have already been carried out over a wide wavelength range of nearly 200 nm but the technique can easily be used over an extended range. Thus second-harmonic generation of the output from a Nd: YAG laser would improve accuracy in the 700 nm region, and allow wavelengths to 530 nm to be covered. The flexibility of the method can also be increased by using a Raman generated pulse as the reference.

As an example of the use of fig. 4 let us take the case of a 1 km length of phosphosilicate core fibre with a light-emitting diode source of spectral width 40 nm and mean wavelength 900 nm. The material dispersion alone (69 ps nm^{-1} km^{-1}) would give rise to a pulse broadening of 2.8 ns/km, to which must be added any mode dispersion effects.

5. Conclusions

A simple method has been described for the measurement of material dispersion $d\tau/d\lambda$, over a wide wavelength range. It can be used with both stepped-index cladded fibres, for a range of dopant concentrations, as well as graded-index fibres and therefore enables the variation of material dispersion with dopant concentration to be determined, since its application is not restricted to fibres of low pulse dispersion. Measurements with the phosphosilicate core fibre show that the addition of phosphorus pentoxide to silica does not increase the material dispersion.

Acknowledgements

Grateful acknowledgement is made to the U.K. Science Research Council for supporting the work and to the Pirelli General Cable Company for the award of a research fellowship.

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