INFLUENCE OF WAVEGUIDE EFFECTS ON PULSE-DELAY MEASUREMENTS OF MATERIAL DISPERSION IN OPTICAL FIBRES

Indexing terms: Optical dispersion, Optical fibres

The effect of the waveguide structure on pulse-delay measurements of material dispersion in optical fibres is examined. It is shown that waveguide dispersion has only a small influence on the measured values and introduces an uncertainty in the wavelength of zero material dispersion of order ±3 nm.

Introduction: Material dispersion is an important parameter in the design of both multimode[1] and single-mode[2] optical communications systems. There is a growing interest in the 1·3–1·6 μm wavelength region where fibre attenuation[3] and material dispersion[4] are lowest. As a result, measurements of the wavelength dependence of material dispersion have been performed both in bulk-glass samples[5,6] and on graded-[7] and step-index[4] multimode fibres.

Measurements on fibres involve the determination of the variation of optical transit time with wavelength. For a step-index multimode fibre, it is then normally assumed that the chromatic dispersion thus found is equal to the material dispersion of the glass forming the fibre core, i.e. that the transit time is unaffected by the waveguide structure. In a recent publication,[2] however, Jürgensen has suggested that this approximation is not valid, and that it is the origin of the discrepancy[8] between measurements on bulk samples[6] and on step-index multimode fibres.[4]

The purpose of the present contribution is to model the latter experiment and to evaluate the influence of the waveguide structure on pulse-delay measurements of the material dispersion parameter. Initially the dispersion of individual modes is investigated, and compared with material dispersion. In a multimode fibre, however, it is shown that the variation of pulse delay with wavelength cannot be predicted directly from the chromatic dispersion of each mode, since, for fixed launching conditions, the power distribution and hence the relative importance of the modes also depends on wavelength. Therefore, the pulse transit time is calculated as a function of wavelength by combining the group delay of all propagating modes. The chromatic dispersion is then evaluated and the effect of the waveguide structure is assessed.

Mode propagation in multimode step-index fibres: The relationship between the parameters of a step-index dielectric waveguide, and the group delay τ per unit length of its modes has been discussed by Gloge[9,10] and can be expressed as:

$$\tau_{\nu\mu} = \frac{1}{c} N_{\nu\mu} = \frac{1}{c}\left[\Gamma \frac{n_1}{n} N_1 + (1-\Gamma)\frac{n_2}{n} N_2\right] \qquad (1)$$

where $N_{\nu\mu}$ is the effective group index of the $LP_{\nu\mu}$ mode and c is the velocity of light *in vacuo*.

Here $n = [n_1^2 b + (1-b)n_2^2]^{1/2}$ is the effective phase index and $\Gamma = b + \frac{1}{2}v(db/dv)$ is the power confinement factor. v is the normalised frequency[9] and b the normalised propagation constant.[9] n_1 and n_2 represent the phase index in the core and the cladding, respectively. For illustration, the quantities b and Γ for the LP_{01} mode are plotted in Fig. 1.

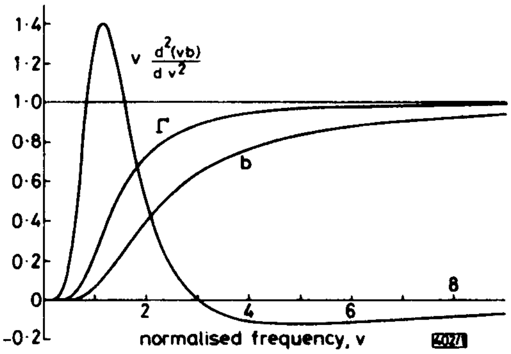

Fig. 1 *Waveguide parameters of the LP_{01}-mode in step-index fibres*

Eqn. 1 includes the effect of material dispersion in both core and cladding via the wavelength dependence of the group indices N_1 and N_2. Waveguide dispersion $-(v/\lambda)d\tau_{\nu\mu}/dv$ is also represented by the sensitivity of Γ and n to v-value. Finally, profile dispersion [usually defined as $(n_1/N_1)(\lambda/\Delta)\times(d\Delta/d\lambda)$] is implicit through $n_1/n \approx 1 + \Delta(1-b)$ and $n_2/n \approx 1 - \Delta b$, where $\Delta = (n_1 - n_2)/n_2$.

As was pointed out by Gloge,[9] for modes far from cutoff, $N_{\nu\mu}$ is approximated by N_1. This approximation forms the basis of all pulse-delay measurements of material dispersion.

Eqn. 1 may be used to obtain the variation of group delay with wavelength λ for any individual mode in the fibre. If we then process these results separately in the same way as experimental pulse-delay data,[4] we obtain an insight into the contribution of each mode to the overall observed pulse delay. Fig. 2 shows the calculated total chromatic dispersion for a few low-order modes of a step-index fibre used in the experiments of Reference 4. Fibre characteristics are also given in the Figure caption.

It may be seen that the wavelength of zero total dispersion $\lambda_{\nu\mu}$ of an individual mode is significantly shifted from the wavelength of zero material dispersion λ_{M1} of the core glass owing to the influence of waveguide dispersion. The latter is dominated by a term involving[2] $-\Delta n_2(v/\lambda c)[d^2(vb)/dv^2]$; the quantity $vd^2(vb)/dv^2$ is plotted in Fig. 1 for the LP_{01}-mode. We see that $vd^2(vb)/dv^2$ is negative for large v values, only becoming positive for $v < 3$. As a consequence, waveguide dispersion is positive for all but a few modes close to cutoff in a multimode fibre; this in combination with the negative value of material dispersion results in a shift of the wavelength of total chromatic dispersion $\lambda_{\nu\mu}$ to progressively *shorter* wavelengths with increasing mode number, as shown in Fig. 2. This contrasts with the effect in single-mode fibres ($v < 2{\cdot}4$) where as is well known[2] the shift occurs to *longer* wavelength.

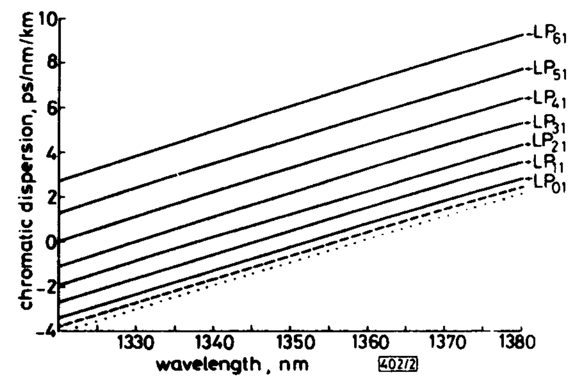

Fig. 2 *Chromatic dispersion in a step-index multimode fibre*
Solid lines: total dispersion of individual low-order modes
Dashed line: material dispersion of the core glass
Dotted lines: multimode chromatic dispersion; the modal-power distribution is $p_{\nu\mu} = 1 - u/v$
Parameters chosen are appropriate to a fibre having a germanosilicate core and silica cladding. $v = 37{\cdot}8$ at $\lambda = 1356$ nm, $\Delta = 1{\cdot}5\%$

Pulse delay in multimode step-index fibres: In multimode fibres, all modes influence the observed pulse delay. To determine the effect of modal dispersion on the overall optical transit time it is necessary to sum the individual contributions of each mode. Thus the pulse delay is given by the first moment of the impulse response:

$$\tau(\lambda) = \sum_{\nu,\mu} p_{\nu\mu}\tau_{\nu\mu} \Big/ \sum_{\nu,\mu} p_{\nu\mu} \qquad (2)$$

where the weights $p_{\nu\mu}$ are proportional to the power carried by the $LP_{\nu\mu}$-mode and take values in the range 0–1. The chromatic dispersion $d\tau/d\lambda$ is quite distinct from the dispersion $d\tau_{\nu\mu}/d\lambda$ of individual modes, since it includes the variation of the power distribution $p_{\nu\mu}$ with wavelength. Thus if the excitation wavelength increases, the v-value of the fibre is reduced, and the same power is carried by fewer modes. Therefore, in general, the weight $p_{v\mu}$ of each mode is a function of wavelength. In the special case of full excitation (i.e. $p_{v\mu} = 1$ for all guided modes), the only variations in the power distribution $p_{v\mu}$ occur at the mode cutoffs, where the power carried by the mode varies rapidly from 1 to 0 and this leads to singularities in the $\tau(\lambda)$ function. This effect is not normally observed, since modes near cutoff usually carry very little power ($p_{v\mu} \ll 1$) after propagating in long fibres.

To accurately model pulse-delay experiments, it is necessary to choose a suitable distribution $p_{v\mu}$. Since the optical power is launched using a 10 cm focal-length lens, the area of the focused spot is similar to that of the fibre core. Thus the low-order modes are most heavily excited and the distribution $p_{v\mu} = 1 - u/v$ may be employed as a realistic model. This function gives weights varying from 1 to 0 with increasing mode number and reflects the lower launching efficiency and greater losses of modes near cutoff.

The variation of pulse transit time with wavelength was calculated using eqn. 2 assuming the distribution $p_{v\mu} = 1 - u/v$, and with the same waveguide parameters and refractive-index data as in the previous section. The resultant multimode chromatic dispersion $d\tau/d\lambda$ is shown in Fig. 2 as a dotted line which now lies only slightly *below* the curve of material dispersion $(1/c)dN_1/d\lambda$. The difference between the two curves is of order 0·3 ps nm^{-1} km^{-1} and the consequent error produced in the determination of the zero of material dispersion is a negligible +3 nm.

Discussion: It is interesting to note that the waveguide contribution to chromatic dispersion in a multimode step-index fibre is opposite in sense to the waveguide dispersion of most individual modes. The reason for this somewhat surprising result lies in the change in the number of guided modes with wavelength and in the rearranging of their arrival times within the impulse response of the fibre. The chromatic dispersion of a multimode fibre is therefore determined, not solely by changes in the modal group delays, but also by the accompanying variation in the power carried by each mode and in their relative importance to the average time-of-flight.

In the measurement described in Reference 4, transit time is measured on the leading edge of the pulse, which is, in principle, coincident with the arrival of the LP_{01}-mode. The pulse risetime is degraded by the propagation in the fibre, and this indicates that a degree of mode conversion is present. The time delay which is actually measured is, therefore, *greater* than the time-of-flight of the lowest-order mode and *less* than that of the centre-of-gravity of the pulse. These two extremes, respectively, under- and overestimate the wavelength of zero material dispersion of the core glass. The specific location of the experimental result within this interval depends on the level of mode conversion in the fibre. For the fibre modelled in this letter, the use of the pulse leading edge as the time reference means that the pulse-delay technique places the wavelength of zero material dispersion in an interval ± 3 nm centred on the correct value. Thus contrary to Reference 2, which suggests an error as large as +35 nm, the pulse-delay technique accurately determines the material dispersion parameter of the core glass.

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