PROPAGATION MODEL FOR MULTIMODE OPTICAL-FIBRE WAVEGUIDE

Indexing terms: Optical waveguides, Fibre optics

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Pulse dispersions of 5 ps/m have been measured in cladded-glass and liquid-core multimode fibres. A theoretical model is proposed which gives excellent agreement with measured propagation delay and pulse dispersion. In the fibres used, there is little light scattering either in the core or at the core-cladding interface.

Introduction: Recent measurements[1] on multimode glass-fibre waveguide have shown that the propagation dispersion (i.e. lengthening) of optical pulses is very small and leads to the possibility of a pulse rate approaching 100 Mbit/s over distances of 1 km. These measured dispersions are much less than would be expected if the transmitted light scattered into all ray angles up to the critical angle at the core–cladding interface (or, in waveguide terminology, scattered into all permitted modes). Previous attempts[2] to estimate the bandwidth of multimode fibres have involved a calculation of the group velocity and dispersion of individual modes, but have been limited by a lack of knowledge of mode-conversion effects. Our dispersion measurements lead us to believe that, in well made fibres, a precise launching[3] of Gaussian beams is possible and that mode-conversion effects are much lower than has been thought. We therefore propose a simple model for propagation in multimode fibres which gives excellent agreement between theory and experiment for such paramaters as the variation of propagation delay with launching angle of incidence, and of dispersion and output-pulse shape with beam solid angle.

Measurements confirm that the output pulses from the TEM_{00} mode-locked helium–neon laser used have a temporal, as well as a spatial, Gaussian distribution. The model therefore assumes that the propagating beam in the core of the fibre can be represented by a bundle of rays which have an angular distribution of power characteristic of a Gaussian beam. Each ray forms an infinitesimal Gaussian pulse which travels to the output end of the fibre by successive reflections from the core–cladding interface. The output pulse shape is then obtained by integrating, for successive instants of time, over all input rays. The integration includes all values of ray amplitude and angle, as well as the appropriate time distribution. The details of the analysis are not given here and will be published elsewhere.

Experimental techniques: The method of measuring pulse dispersion is the same as that reported previously,[1] namely to observe the increase in full width at half maximum (f.w.h.m.) caused by propagation along a length of fibre. In the present work, however, 0·6 ns f.w.h.m. pulses are transmitted at a rate of 80 Mbit/s along 33 and 43 m lengths of cladded-glass fibre. The latter are made in our own laboratories and have core diameters, for the particular results quoted here, of 55 and 105 μm. Precise launching of the TEM_{00} beam is achieved using a special fibre mount[3] and a mixture of index-matching liquids to give an accurate match into the core of the fibre. The input solid angle is changed by using lenses of various focal lengths, and the fibre axis may be rotated to give various launching angles of incidence. The input solid angle is defined in terms of the semiangle of the cone containing points where the intensity in the far field has fallen to e^{-2} times that on the axis. The two types of avalanche photodiode available, namely EMI S30500 and TIXL56, are operated at gains which are low enough to prevent 'current tailing' on the lagging edge of the pulses.

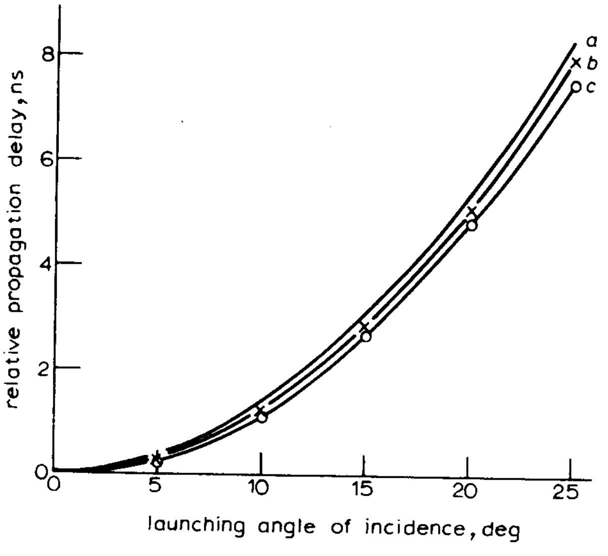

Fig. 1 *Relative propagation delay of the pulse peaks over a 43 m length of fibre for various angles of incidence*

a Calculated using the ray model
b and *c* Measured for beam semiangles in the core of 0·34° and 2·1°, respectively
The experimental points for core diameters of 55 μm and 105 μm agree almost exactly, and are therefore not plotted separately

Results: The first step in the verification of the ray model was to vary the launching angle of incidence ϕ and note the time delay of the pulse peaks relative to that at 0°. Other workers[4] have found that the calculated delay over length L, given by

$$\Delta t = \frac{nL}{c}\left[\sec\{\sin^{-1}(\sin\phi/n)\} - 1\right]$$

where n is the refractive index of the core, exceeds the measured delay by up to a factor of ten, but our results (Fig. 1) show excellent correlation between theory and experiment for both narrow and comparatively wide beam solid angles. Identical results were obtained for the two core diameters. The ray-propagation model therefore seems to predict relative pulse delay correctly.

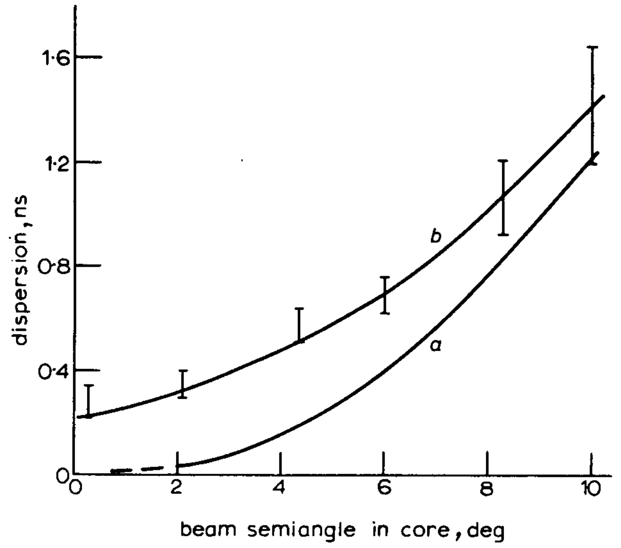

Fig. 3 *Pulse dispersion as a function of beam semiangle for zero angle of incidence*

a Calculated
b Measured

Next, the pulse distortion to be expected in a given length of fibre for different beam solid angles was calculated. The computed results (Fig. 2) indicate that the pulse broadening is strongly asymmetrical, and this is confirmed by experiment. Thus it is not possible to estimate pulse dispersion and fibre bandwidth by simply measuring the risetime of transmitted pulses, although this has been attempted by some workers.[5] Fig. 2 shows that, with a wide-angle beam, such as would be launched by a semiconductor laser or light-emitting diode, the error involved in trying to estimate dispersion from the increase in risetime rather than total pulsewidth can be as high as a factor of five.

A comparison of the calculated and measured pulse dispersions for a wide range of beam solid angles is shown in Fig. 3 for zero input angle of incidence. Again, the experimental results obtained for the two, very different, core diameters are in good agreement. The measured pulse spreading is seen to increase from 0·2 ns (in 43 m) for a beam of semiangle in the core of 0·34° to 1·4 ns at 10°, corresponding to an increase in dispersion from 5 ps/m to nearly 35 ps/m. It follows that minimum dispersion, and therefore maximum bandwidth, is achieved for input beams of low divergence. The theoretical curve, considering the simplicity of the model, agrees surprisingly well with the measurements, but, as expected, somewhat underestimates the dispersion. In a practical fibre, there are additional dispersive mechanisms which have not been included in the present model, such as the effect of the curvature of the fibre on the 11 cm-diameter supporting drum.

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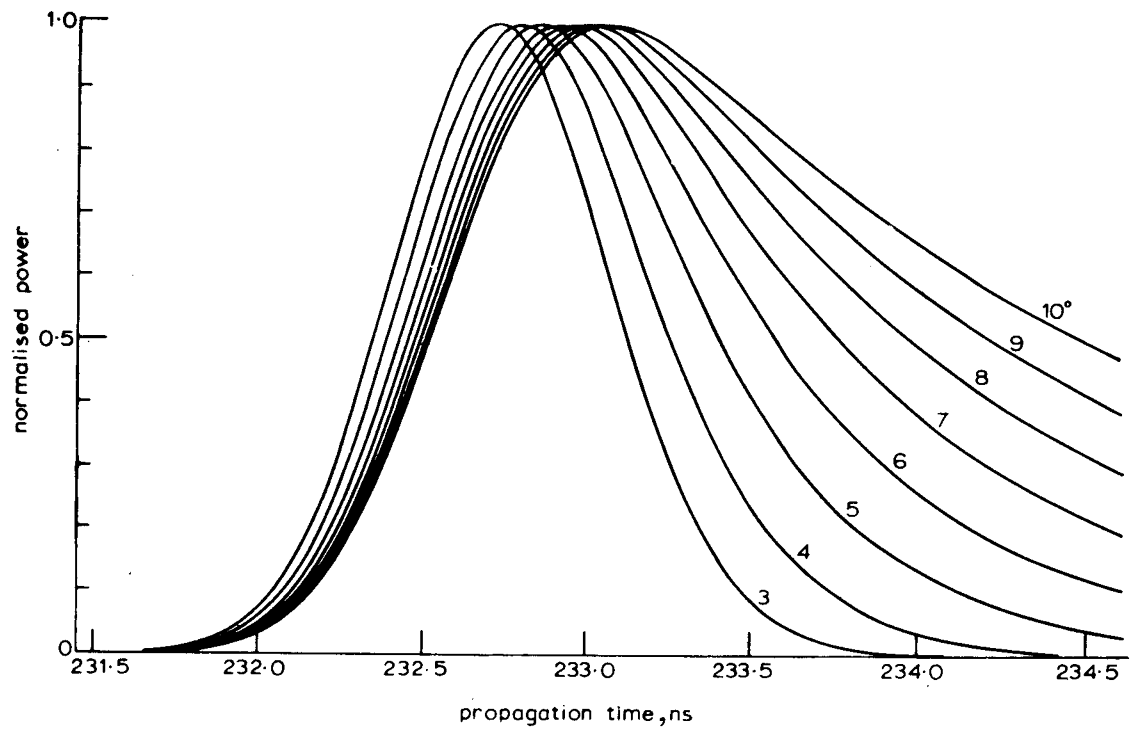

Fig. 2 *Calculated output pulse shapes from 43 m of fibre for the beam semiangles (to points of e^{-2} times maximum intensity) shown on the curves*

Since the dispersion rises with beam solid angle, it might be expected to increase progressively with angles of incidence greater than zero. Experimentally, this is found to be the case, and the rate of increase is also greater with large solid angles. For example, to prevent the dispersion in 43 m exceeding 0·3 ns, the tolerance required on the launching angle of a narrow beam is 13°, compared with 4° for a wider one. With a wide-angle, incoherent source, the effect would be much greater.

Conclusions: The following conclusions may be drawn from these results:

(*a*) The pulse dispersion in multimode cladded-glass fibres can be as low as 5 ps/m. (We have also made liquid-core fibres in lengths of 100 m or so, and obtained a dispersion of less than 5 ps/m.)

(*b*) The dispersion depends strongly on the launching conditions, and this partly explains the wide range of values reported[4, 6-8] by various workers.

(*c*) Contrary to expectation and to earlier work,[4] the ray-propagation model gives results in good agreement with experiment, and therefore provides a method for predicting propagation times, pulsewidths and shapes in multimode fibres.

(*d*) As distinct from the results obtained[8] with other fibres, the applicability of the ray model indicates that, in our case, there is comparatively little scattering of light, either in the core of the fibre or at the core-cladding interface, and that the latter is smooth and symmetrical. The degree of uniformity may be judged from the fact that a ray at an angle of, say, 5° makes almost 10^5 reflections in 43 m of fibre.

(*e*) The fact that the measured dispersion is slightly greater than that calculated shows that some small redistribution of light in the fibre does occur.

We have confirmed the latter conclusion experimentally by measuring the angular distribution of light in fibres over lengths of more than 100 m. A typical result shows that the beam spreading is detectable only at distances of 50 m or more from the input end, but even after 100 m an equilibrium distribution is not reached. Thus the quality of the fibres is satisfactory, and the low dispersion observed is not due to absorption or scattering of high-angle rays (i.e. higher-order modes).

We propose to obtain improved values for the calculated dispersions by including in the computations the measured angular intensity distributions. From this, it should be possible to obtain a factor to describe the rate of scattering or the rate of mode conversion.

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