PULSE DISPERSION FOR SINGLE-MODE OPERATION OF MULTIMODE CLADDED OPTICAL FIBRES

Indexing terms: Fibre optics, Optical waveguides

Pulse dispersions as low as 0·4 ns/km have been measured in multimode cladded fibres at a normalised frequency $V = 125$ and for a constant bend radius of 5·5 cm. Particularly when the number of launched modes is small, the pulse dispersion, as well as the polarisation and angular width of the output beam, are strong functions of the degree of mode conversion.

Introduction: An earlier report[1] of pulse dispersion in multimode, liquid-core, optical fibres showed a strong dependence on curvature, and indicated a minimum value of 1·6 ns/km at a bend radius of just under 1 m. However, the cladding capillary from which the fibres were made was rewound from the drawing machine under a constant tension, and, although the supporting drums were of polystyrene, some small distortion nevertheless occurred. An appreciable amount of mode conversion was thereby caused, the presence and dominating effect of which has been convincingly demonstrated by the present experiments, as well as by the low pulse propagation delay obtained for a narrow input beam when the input angle of incidence is varied, compared with that in an ideal fibre.[2] The former measurements have thus been repeated for a range of input conditions, which includes that for single-mode excitation[3] and bending stresses. A considerably smaller dispersion has been obtained, which is comparable with that predicted[4] and measured[5–7] in graded-refractive-index fibres. Both the polarisation and the angular width of the output beam are also strong functions of mode conversion, particularly for small input angular beamwidths, and may be used as a measure of the pulse dispersion.

Experiment: The measurements of dispersion, defined as the increase in the halfpower width of the pulse caused by propagation along the fibre, were carried out as described previously[1] with a mode-locked helium–neon laser operating at 0·633 μm. The input beam was plane polarised, owing to the Brewster windows on the laser tube, and the polarisation of the output beam was measured with an analyser,* and is defined as

$$(I_{max}-I_{min})/(I_{max}+I_{min})$$

where I_{max} and I_{min} are the maximum and minimum intensities, respectively, observed as the analyser is rotated. The output angular-intensity pattern was plotted by an automatic scanning system using a *p–i–n* photodiode to give a display on an oscilloscope. The halfwidth of the beam is defined as the angle at which the beam intensity falls to e^{-2} times that on the axis.

The fibre consisted of hexachlorobuta-1, 3-diene in a cladding[8] of internal diameter 57 μm and having a numerical aperture of 0·46. †The normalised frequency is thus $V = 125$, and roughly 7 800 modes are capable of propagating. The fibre was wound on a drum of 5·5 cm radius, initially at normal tension, but, to reduce the degree of mode conversion without changing the radius of curvature, it was gradually slackened until finally it was quite loose on the drum. Similar results have been obtained for lengths of 61, 150 and 400 m, but only those for the 61 m length are given here, as they are the most complete and the effect of mode filtering[9] due to the lossy cladding is largely avoided.

Results: The four curves in each of Fig. 1*a* and *b*, which were obtained for different tensions on the drum, show, as before,[1] that, when the angular width of the input beam, and therefore the number of launched modes, is made larger, there is an increase in the output beamwidth and also, because of the greater spread in group velocities, an increase in the dispersion. However, they now indicate, in addition, that, as the fibre is progressively slackened, at constant bend radius, the dispersion and the output beamwidth both fall, thus clearly showing that distortion of the fibre due to bending stress causes mode conversion. When the fibre is only loosely coiled on the drum, and the distortion is a minimum, it can be seen from curve (iv) of Fig. 1*b* that the output width is only marginally greater than that at the input, and the amount of mode conversion occurring is quite small. The output width and the dispersion are thus determined almost entirely by the number of modes launched, and curvature as such has little effect. It is clear, therefore, that the mode conversion evident in curves (i) to (iii) is due almost entirely to distortion, and not bending, of the fibre. This has been confirmed by inducing distortion in other ways; for example, through the application of a moderate transverse pressure.

To minimise the dispersion, the number of propagating

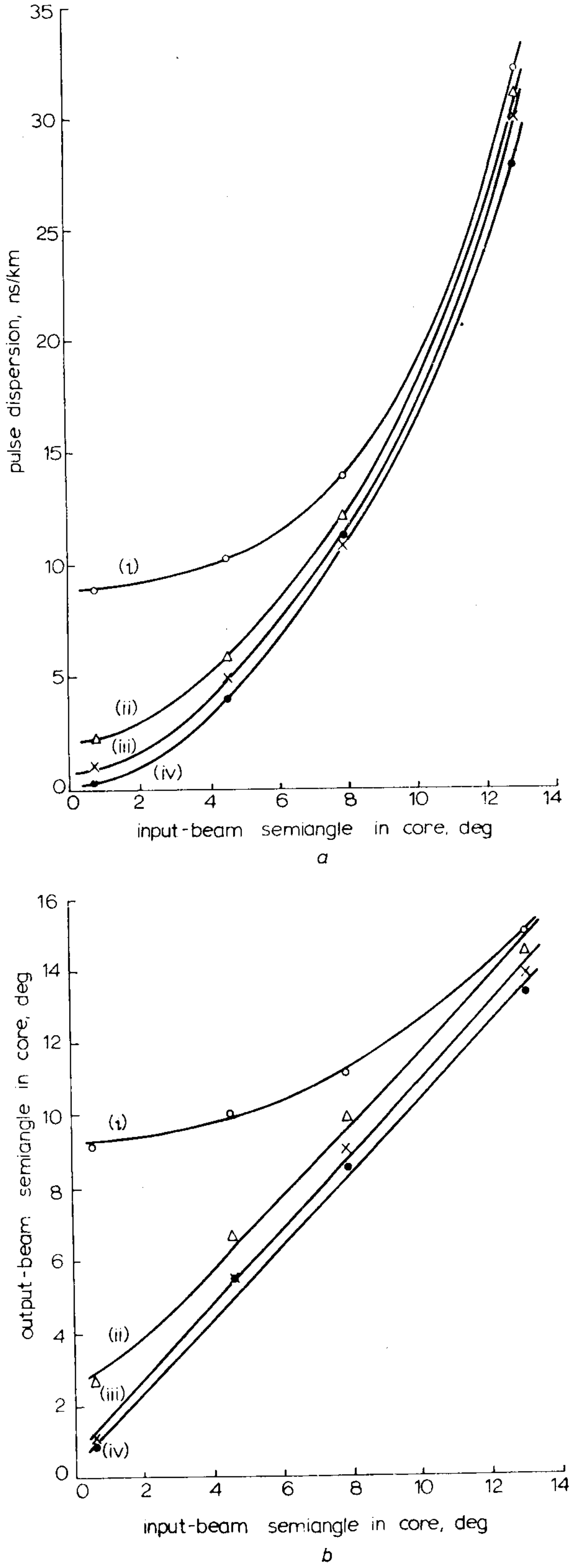

Fig. 1 *Pulse dispersion and output angular beamwidth*
a Pulse dispersion
b Beamwidth
Angular widths refer to core; values in air are approximately 50% greater. Distortion decreases from curve (i) to curve (iv)

---

* HN22
† Chance–Pilkington ME1

30

modes must be reduced, and this can be done in an unstressed fibre by an appropriate choice of the launching conditions. In fact, the input beamwidth of 0·6° in Fig. 1 corresponds nearly to the launching of only the single HE$_{11}$ mode,[3] and it can be seen that the corresponding pulse dispersion is 0·4 ns/km. This represents a reduction by a factor of 25 compared with that observed previously[1] for the same radius of curvature, and is comparable with the values obtained in the latest Selfoc fibre.[5–7]

For such quasi-single-mode operation, the polarisation of the output beam (0·88) is high, providing further evidence that little mode conversion is occurring. If, during propagation along the fibre, power is transferred to modes of different polarisation, then of course there will be depolarisation of the output radiation. It is interesting to note that, for an input angular width of 0·6°, the polarisation of the output falls from 0·88, for the unstressed fibre, to 0·62, 0·3 and 0·01 for curves (iii), (ii) and (i), respectively. Thus distortion of the fibre not only increases the dispersion and the output beamwidth, but also causes depolarisation. The latter is easily measured and can be used to give an indication of the degree of mode conversion and dispersion. The dependence of dispersion on depolarisation and beamwidth, for a 0·6° launch, is shown in Fig. 2. A direct and simple relationship between these parameters has not previously been reported.

It is interesting to compare the results with an analysis[10] of propagation in a curved cylindrical cladded multimode fibre. The theory shows that each of the HE$_{1m}$ modes launched by a symmetrical Gaussian beam couples only to those modes designated HE$_{2,m}$, HE$_{2,m-1}$, TE$_{0,m}$ and TE$_{0,m-1}$ and there is a periodic exchange of energy between them. In an unstressed fibre, only a small increase in the number of modes, and hence in the output beamwidth, is therefore expected to be caused by curvature, and the experimental results, particularly curve (iv) of Fig. 1*b*, are consistent with this prediction. For single-mode launching (HE$_{11}$), corresponding to an input angular width of 0·6°, a periodic coupling occurs only to the TE$_{01}$ (or TM$_{01}$) and HE$_{21}$ modes, so that a form of quasi-single-mode operation results in which the effects observed are a weighted average due to these, and only these, three modes. Again the low values of dispersion, depolarisation and width of the output beam for the unstressed curved fibre are consistent with the theory, which is discussed in detail elsewhere.[10]

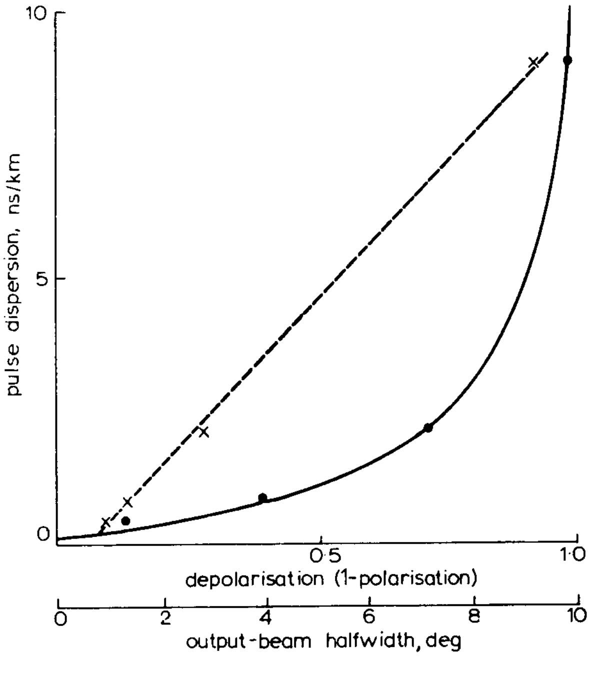

Fig. 2 *Pulse dispersion as function of depolarisation and output angular beamwidth*

Single-mode launching into curved multimode fibre
● function of depolarisation
× function of output angular beamwidth

Conclusions: In the unstressed Southampton liquid-core fibre, a negligible amount of mode conversion occurs over the lengths measured so far, i.e. up to 400 m. As a result, quasi-single-mode operation has been obtained even when the whole length is coiled, showing that bends with a radius of curvature as small as 5·5 cm do not inherently cause more than a minimal degree of mode conversion. The corresponding dispersion of 0·4 ns/km is smaller than has been reported for any other cladded fibre and is comparable with that of the latest Selfoc[7] fibre. The results are consistent with a theory[10] of propagation in a curved cylindrical fibre. It is much easier to launch a single (fundamental) mode into multimode fibre than into either a single-mode or Selfoc fibre. For example, to obtain a reasonable launching efficiency with single-mode fibre, not only must the input spot size be correctly matched, but also the transverse positioning of the beam must be accurate to a fraction of a micrometre and the tolerance on the angular alignment is small. Similar restrictions apply to Selfoc fibres if multimode operation is to be avoided. On the other hand, with multimode fibres, transverse misalignments of several tens of micrometres can be tolerated. Whether effectively single-mode operation of multimode fibres can be obtained in practical applications will depend on (*a*) the production of geometrically accurate fibres having no intrinsic, 'built-in', stresses and (*b*) the development of methods of armouring and cabling that protect the fibre from external stresses during manufacture, handling, laying etc. Suitable sources would also be necessary.

The results show, in addition, that distortion can induce mode conversion, the degree of which can be easily monitored either through the depolarisation, or the increase in angular width, of the output beam. We have observed the same effect in all the other (solid-core) fibres we have tested, including those with a small numerical aperture. When the numerical aperture (0·46) of our liquid-core fibres is not completely filled, mode conversion increases the dispersion, but has little effect on the transmission loss, because of the small amount of coupling to radiation modes. This is probably not so with fibres of low numerical aperture, where, conversely, mode conversion will affect the loss rather than the dispersion.

Acknowledgments: Grateful acknowledgment is made to the UK Science Research Council for supporting the work, and for the award of a grant to one of us (H.M.), as well as to the Pirelli General Co. for a research fellowship (D.N.P.).

W. A. GAMBLING
D. N. PAYNE
H. MATSUMURA

27th March 1974

Department of Electronics
University of Southampton
Southampton SO9 5NH, England

References

1 GAMBLING, W. A., PAYNE, D. N., and MATSUMURA, H.: 'Gigahertz bandwidths in multimode, liquid-core optical fibre waveguide', *Opt. Commun.*, 1972, **6**, pp. 317–322

2 GAMBLING, W. A., PAYNE, D. N., and MATSUMURA, H.: 'Optical fibres and the Goos–Hänchen shift', *Electron. Lett.*, 1974, **10**, pp. 99–101

3 GAMBLING, W. A., PAYNE, D. N., and MATSUMURA, H.: 'Mode excitation in a multimode optical-fibre waveguide', *ibid.*, 1973, **9**, pp. 412–414

4 GAMBLING, W. A., and MATSUMURA, H.: 'Pulse dispersion in a lens-like medium', *Opto-Electron.*, 1973, **5**, pp. 429–437

5 BOUILLIE, R., and ANDREWS, J. R.: 'Measurement of broadening of pulses in glass fibre', *Electron.*, *Lett.*, 1972, **8**, pp. 309–310

6 GLOGE, D., CHINNOCK, E. L., and KOIZUMI, K.: 'Study of pulse distortion in Selfoc fibres', *ibid.*, 1972, **8**, pp. 526–527

7 KOIZUMI, K., IKEDA, Y., KITANO, I., FURUKAWA, M., and SUMIMOTO, T.: 'New light-focussing fibres made by a continuous process', *Appl. Opt.*, 1974, **13**, pp. 255–260

8 PAYNE, D. N., and GAMBLING, W. A.: 'The preparation of multimode glass- and liquid-core optical fibres', *Opto-Electron.*, 1973, **5**, pp. 297–307

9 GAMBLING, W. A., PAYNE, D. N., and MATSUMURA, H.: 'Effect of loss on propagation in multimode fibres', *Radio & Electron. Eng.*, 1973, **43**, pp. 683–688

10 GAMBLING, W. A., PAYNE, D. N., and MATSUMURA, H.: 'Propagation in curved multimode cladded fibres'. Presented at AGARD meeting on electromagnetic wave propagation involving irregular surfaces and inhomogeneous media, The Hague, Netherlands, 1974