DISPERSION IN LOW-LOSS LIQUID-CORE OPTICAL FIBRES

Indexing terms: Fibre optics, Optical dispersion, Loss measurement

Measurements of pulse dispersion in liquid-core multimode fibres have been made for different fibre curvatures and core diameters. The results indicate the presence of mode-conversion effects, and a mode-filtering mechanism is demonstrated with a probing beam of narrow angular width. By measuring transmission loss as a function of angle of incidence, the loss in the cladding material is obtained.

There have been several reports[1, 2] of low-loss liquid-core fibres having minimum attenuations below 20 dB/km, and, in assessing whether they are likely to be useful in a practical optical-communication system, a study of their dispersion characteristics is necessary. We have carried out such measurements on fibres consisting of ME1 tubing of internal diameters 50 and 87 µm filled with hexachlorobuta-1, 3-diene. The attenuation has been measured over a length of 1 km at a wavelength of 1·08 µm, and is 7·3 dB/km, although measurements made at an independent laboratory* give a value of 6 dB/km. The attenuation is similarly low[2] over the range 1·03–1·10 µm, and is below 10 dB/km from 0·98 to 1·11 µm. At the semiconductor wavelength of 0·9 µm, the loss is 11·5 dB/km. The numerical aperture of the fibre is 0·46.

As described elsewhere,[3] 0·6 ns pulses at an 80 MHz repetition rate were produced by a mode-locked TEM_{00} helium-neon laser and were transmitted along the fibre. The pulse dispersions quoted refer to the difference between the half-power pulse durations of the input and output pulses, as monitored by EMI S30500 avalanche photodiodes. The particular virtue of these diodes is that the relatively large diameter (0·5 mm) of the sensitive area is less likely to cause artificially low dispersions to be measured, owing to incorrect positioning of the detector, than would be the case with smaller, and therefore faster, devices. Measurements were made in lengths of up to 310 m, and the specific dispersions shown in Fig. 1 are obtained by averaging over the length of fibre used. The angular width of the input beam was varied by using lenses of varying focal lengths, and the beam waist of the Gaussian laser beam was positioned centrally at the entry face of the fibre in the supporting mount. The fibres were wound on drums of 5·5 and 20 cm radius.

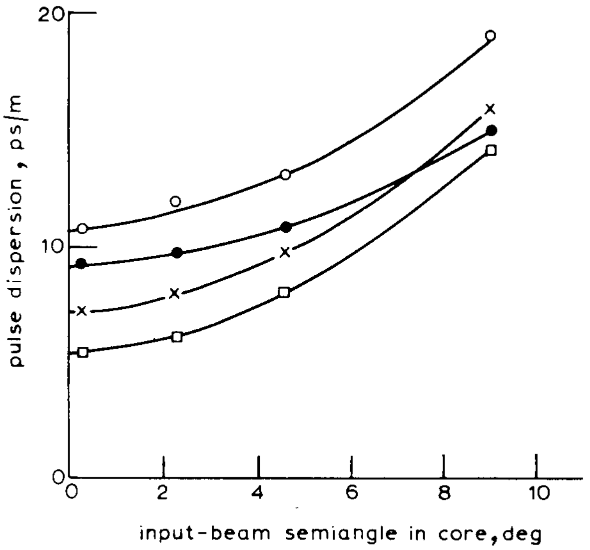

Fig. 1 *Pulse dispersions as a function of angular width of the input beam for various lengths, core diameters and fibre curvatures*

50 µm core, 20 cm radius, 310 and 180 m lengths
- - - 87 µm core, 20 cm radius, 250 and 180 m lengths
●●● 50 µm core, 5·5 cm radius, 250 and 180 m lengths
87 µm core, 5·5 cm radius, 180 m length

Results: Fig. 1 shows that, for a core diameter of 50 µm and a bend radius of 20 cm, the dispersion in this liquid-core fibre is 5·6 ps/m for an input-beam semiangular width in the core of 0·3° (0·47° in air), rising to 14·3 ps/m for a halfwidth of 9° (14° in air). The lower dispersion corresponds to a maximum pulse rate of 200 Mbit s^{-1} km^{-1}, and thus large bandwidths over kilometre lengths are possible with liquid-core, as well as solid-core, fibres. For a bend radius of 5·5 cm, the corresponding figures are 9·2 ps/m and 14·8 ps/m. When the core diameter is increased to 87 µm, the dispersion is increased by a factor of up to 30%. The effect of curvature of the fibre is treated in detail elsewhere,[4, 5] but the curves show that, when the bend radius is reduced, an increase in mode conversion, and therefore of dispersion, occurs.

The dependence of dispersion on core diameter has not been previously reported, and is particularly interesting in that, if propagation were governed by a simple ray model,[3] variations in diameter should have no effect. A possible explanation of the observed behaviour could involve a mode-filtering mechanism due to the high cladding loss. Thus, for a length of fibre of 300 m, the number of reflections at the core–cladding interface for a meridional ray at an angle of, say, 5° in the core, is $5{\cdot}2 \times 10^5$ for a core diameter of 50 µm compared with 3×10^5 in an 87 µm core. Since the loss on reflection is the same in each case, there will be an appreciably higher relative reflection loss, and hence a filtering effect, for the higher-angle rays. The core attenuation has negligible influence, since the greater path length of a 5° ray compared with an axial ray produces a relative increase in attenuation of less than 0·1 dB at 633 nm.

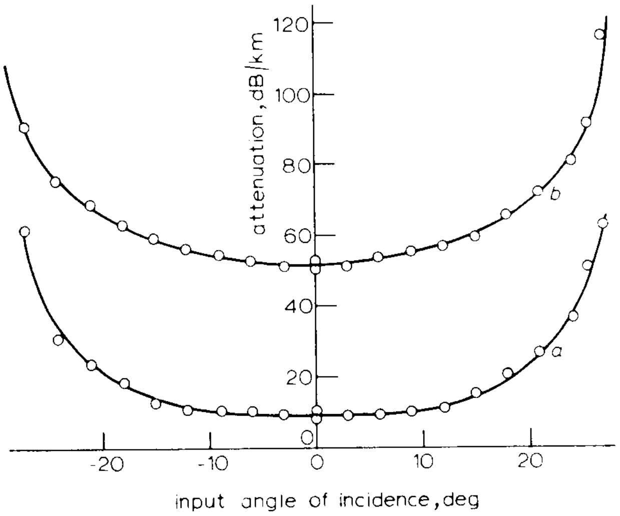

Fig. 2 *Attenuation of probe beam as a function of angle of incidence at the input to a 47 m length of fibre*

a Wavelength 1·04 µm
b Wavelength 642 µm

To investigate this possibility further, we have measured the variation in attenuation of a narrow input beam as the angle of incidence is varied over the range +30° to 0 to −30°. A white-light source was stopped with a 0·16 cm aperture and placed 10·2 cm from the input end of the fibre, to give a probe beam of 0·5° angular divergence. Wavelength selection was effected with filters combined with sideband suppressors, and a chopper disc was locked in speed to a phase-sensitive detector. The ends of the fibre were cut relatively flat to avoid possible shrouding effects due to the cladding at high angles of incidence, and the input end was placed in a suitable launching mount on a graduated circular scale. The output end of the fibre was positioned accurately on the detector surface on a thin film of core liquid.

First, the total output was noted for the full range of input angles, the fibre was shortened, and again the outputs at the various angles were observed. Complications owing to mode conversion were minimised by using a relatively short fibre length of 47 m and a bend radius of 30 cm. This was confirmed by measuring the angular distribution of light at the output from the fibre, which, for the length quoted, was the same as that at the input.

Typical results are given in Fig. 2, which shows that, at a wavelength of 1·04 µm, the attenuation has only a small dependence on the angle of incidence over the range ±10°, but then rises rapidly from 9 dB/km at 0° to 60 dB/km at ±26° as the number of reflections, and the loss per reflection, both increase. For a lossless cladding, the attenuation is expected

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to be largely independent of angle until the critical angle is exceeded, when radiation loss into the cladding causes the attenuation to rise. Thus the results shown in Fig. 2 give a strong and simple indication of the presence of mode (ray) filtering in our fibres. At the shorter wavelength of 0·642 μm, the attenuation rises a little more rapidly from the minimum point. Fig. 2 shows that the high-loss cladding has little effect on the total fibre attenuation for an angular beamwidth of ± 10° within the central portion of the curves, and this is confirmed by other measurements.[4, 5]

A detailed comparison of experimental results with a theory of propagation in multimode fibres having both core and cladding loss is to be published shortly.[6] However, the probing-beam technique which we have described can be used to estimate the transmission loss of the cladding material in its final form. Measurement of the bulk loss of glass tubing is not easy, and, even so, the properties of the glass could well be modified during the fibre-drawing process, possibly by a change of oxidation state of impurity ions which can be frozen in by the rapid fibre cooling.

By applying the equations for Fresnel reflection at the interface between two lossy dielectrics to energy propagating in the fibre, we have calculated the loss of ME1 glass in fibre form to be 7000 dB/km at 633 nm and 4000 dB/km at 1·06 μm. The effect of scattering at the interface is small and has been neglected. This result can be compared with an analysis using mode theory,[7] which has been applied to similar experimental measurements we have made with a cladded-glass fibre comprising an F7 core and ME1 cladding. The value for the ME1 cladding loss obtained with the alternative modal analysis and the glass-core fibre is 5300 dB/km* at 805 nm, which corresponds to 4000 dB/km at 1·0 μm. The agreement is therefore satisfactory.

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References

1 STONE, J.: 'Optical transmission in liquid-core quartz fibres', *Appl. Phys. Lett.*, 1972, **20**, pp. 239–240

2 PAYNE, D. N., and GAMBLING, W. A.: 'New low-loss liquid-core fibre waveguide', *Electron. Lett.*, 1972, **8**, pp. 374–376

3 GAMBLING, W. A., DAKIN, J. P., PAYNE, D. N., and SUNAK, H. R. D.: 'Propagation model for multimode optical-fibre waveguide', *ibid.*, 1972, **8**, pp. 260–262

4 GAMBLING, W. A., MATSUMURA, H., and PAYNE, D. N.: 'Some recent results obtained with multimode cladded-glass and liquid-core optical fibres'. Paper presented at first European electro-optics conference and exhibition, Geneva, Sept. 1972

5 GAMBLING, W. A., PAYNE, D. N., and MATSUMURA, H.: 'Gigahertz bandwidths in multimode, liquid-core, optical fibre waveguide', *Opt. Commun.* (to be published)

6 DAKIN, J. P., GAMBLING, W. A., MATSUMURA, H., PAYNE, D. N., and SUNAK, H. R. D.: 'Theory of propagation in lossless and lossy multimode cladded optical fibres' (to be published)

7 ROBERTS, R.: 'Propagation characteristics of multimode dielectric waveguides at optical frequencies' *in* 'Trunk telecommunication by guided waves'. *IEE Conf. Publ.* 71, 1970, pp. 39–45

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* ROBERTS, R.: Private communication

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