

# NEW METHOD FOR PRECISE CHARACTERISATION OF MULTIMODE OPTICAL FIBRES

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It is shown experimentally that short samples (about 1 m) of multimode optical fibres can be characterised by measuring the times of flight of tubular modes. There is fair agreement between measured and calculated values.

**Introduction:** As is well known, the modes of multimode optical fibres usually exhibit different times of flight, and this effect limits the useful bandwidth of the fibre. We assume for the moment that the optical source is quasimonochromatic. If the fibre material were nondispersive, the times of flight of the various modes would be the same for a square-law index profile, terms of the order of  $\Delta^2$  being neglected, where  $\Delta$  denotes the relative index difference. It is known also that if material dispersion is linear ( $dn/d\lambda$  proportional to  $n$  as the dopant concentration varies) power-law index profiles are optimum. However, index-profile dispersion measurements are subjected to large errors and it is therefore advisable to directly measure the time of flight of the various modes. It can be shown, however, that a profile that is optimum for helical rays, i.e. for rays that remain at a constant distance for axis, is optimum to all paraxial rays, i.e. does not give rise to pulse broadening, to order  $\Delta$ . Furthermore, helical rays sense the fibre dispersion properties at one specific radius (we assume that the fibre profile is circularly symmetric) and therefore corrections of errors in the profile in the fabrication of subsequent fibres should be particularly straightforward. Note that the helical rays that we are considering represent the more physical 'tubular modes'. These tubular modes exhibit minimum spread in the radial direction. The generation of tubular modes has been discussed by some of us in a previous paper.<sup>1</sup> A related technique has been proposed by Jeunhomme<sup>4</sup> in which an offset Gaussian spot excites the fibre. However, such spots excite not a single mode but groups of modes that have the same radial mode numbers but different azimuthal mode numbers, and consequently spread out radially. This makes corrective steps more difficult.

A second basic advantage of our technique over more conventional techniques is that measurements are accurately performed over short samples, of the order of 1 m. This is made possible by the use of interferometric techniques. Over such short lengths, mode coupling is negligible, and precise measurements of modal times of flight can be made. To be sure, real fibres exhibit slow (adiabatic) changes of profile along their lengths, and perhaps also exhibit mode coupling. The method that we are reporting provides a local characterisation of fibres. By measuring the response of various samples along a typical fibre length, the

overall response can in principle be synthesised. In the following Sections the details of the method are given and the experimental results are reported for two tubular modes excited at the same time. The theoretical expression for the time of flight of tubular modes is given in the Section on calculations.

**Experimental set-up:** Our method combines the technique for generating tubular modes reported in References 1 and 2, and the interferometric technique for measuring the time response of modes over short fibre samples reported in Reference 3. Because of these previous publications, we give only, in Fig. 1a and b, general outlines of the set-up. The source is a dye laser. At the moment, we use a dye in the range 0.57–0.61  $\mu\text{m}$ . The method is applicable at longer wavelengths, but beyond 1  $\mu\text{m}$  one may have to wait for new developments in dye lasers or other broadband sources. Also, the photographic plates should be replaced by scanned detectors.

The basic device is a Mach-Zehnder interferometer, followed by a monochromator. The multimode fibre under test is placed in one arm of the interferometer. Its basic dispersion ( $d^2n/d\lambda^2$ ) is compensated by a single-mode fibre placed in the other arm. The times of flight in the two arms are made somewhat different, by about 10 ps (3 mm of air),



Fig. 2 Normalised index profile  $U(r) = 1 - n(r)/n(0)$  as a function of radius  $r$ , measured with transmission method  
 $r_c = 25 \mu\text{m}$

The multimode fibre is preceded by a tubular mode synthesiser. This is a plate pierced with  $2\mu$  holes ( $\mu$  being the azimuthal mode number) with alternately high and low pressure in order to introduce  $\pi$  reversal of the phase of the optical field. In our set-up we have generated two tubular modes corresponding to  $\mu = 2$  and  $\mu = 12$  nested in each other. The mean radii of these modes at the fibre input end are, respectively,  $\bar{r} = 3.45 \mu\text{m}$  and  $11.4 \mu\text{m}$ .

The photographic plate in Fig. 1a records fringes that contain the time of flight information. When the photographic plate is exposed to laser light (Fig. 1b) the far field gives the fibre impulse response  $h(t)$ , or, more precisely,  $|h_s(t)|$ , where

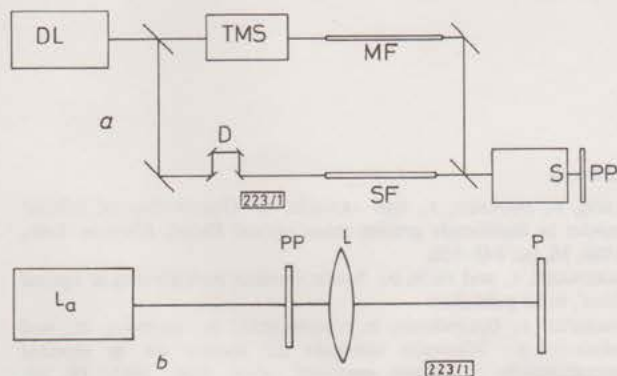


Fig. 1

a Schematic set-up of arrangement

DL = dye laser, TMS = tubular mode synthesiser, MF = multimode fibre under test, D = delay path, SF = single-mode fibre, S = spectrograph, PP = photographic plate

b Impulse response reconstruction set-up

$L_a$  = He-Ne laser, PP = same as in (a), L = lens, P = photograph shown in Fig. 3



Fig. 3 Reconstructed impulse response of multimode fibre under test with two tubular modes ( $\mu = 2$  and  $12$ ) excited only

Distances of two small bright spots on the right from large central spot are proportional to arrival times of  $\mu = 12$  mode (closest to centre) and  $\mu = 2$  mode; only the  $\mu = 12$  mode is optimally focused



$h_a(t)$  denotes the analytical signal. By defocusing at that stage, we can compensate for the mode dispersion ( $d^2\beta/d\omega^2$ ) and thereby obtain very sharp spots that enable us to make precise time of flight measurements.

**Experiments:** The experiments were made on a multimode fibre that has an almost linear profile (exponent  $\alpha$  of  $r$  of the order of unity). The precise profile  $U(r) = 1 - n(r)/n(0)$  is shown in Fig. 2. The radii of the tubular modes given previously have been selected for single-mode excitation. The result (photograph in Fig. 1b) is shown in Fig. 3. The times of arrival of the two modes ( $\mu = 2$  and  $\mu = 12$ ) correspond to the bright spots on the right-hand side of the central large spot. From this photograph one measures a difference of arrival time  $t_2 - t_{12} = 5.24$  ps. As expected for a linear-law profile, the high-order modes arrive after the low-order modes (the opposite behaviour holds for step-index fibres). We have checked that when either one of the modes is masked, the corresponding spot disappears. On the original photograph one can measure a few spurious times of flight that may be due to imperfect modal excitation and/or mode coupling.

The theoretical expression for the relative time of flight,  $\tau = t/t_0 - 1$  is given in the calculations Section. Here,  $t_0 = 4.011$  ps because  $n_0 = 1.45$  and length = 0.83 m. If one neglects material dispersion and approximate the profile in Fig. 2 by a straight line, we have from eqn. 3 with  $U = \Delta(r/r_c)$

$$t_2 - t_{12} = 6.4 \text{ ps}$$

Using the actual profile in Fig. 2 we obtain the curve in Fig. 4 and  $t_2 - t_{12} = 4.9$  ps. Note that, in order to obtain the curve in Fig. 4, the ray optics result has been convolved with a mode thickness function.

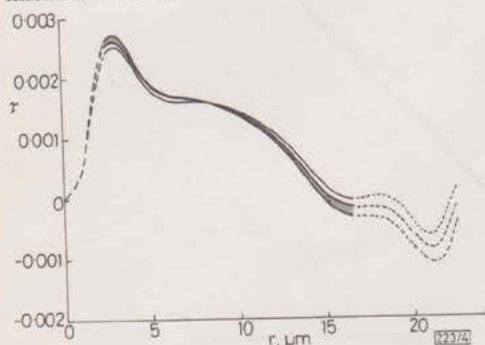


Fig. 4 Relative time of flight  $\tau = t/t_0 - 1$  of tubular modes of radius  $r$  as a function of  $r$  calculated from eqn. 3 (plain line)

Dashed part is unphysical (rays are not trapped) and dotted part corresponds to slightly leaky modes that may be unobservable. Lower curve follows from eqn. 6, shadow reflecting dispersion measurement uncertainty ( $0.025 < d < 0.05$ )

Inhomogeneous dispersion can be taken into account using eqn. 6 and the measurements quoted in Reference 5. We obtain  $5.2 < t_2 - t_{12} < 5.9$  ps. These theoretical results are in agreement with the experimental result (5.24 ps).

**Modal dispersion:** Beyond the modal time of flight measurements, the technique reported in this letter provides information about the dispersion ( $d^2\beta/d\omega^2$ ) of each mode. We have observed a slight difference between the two modes under consideration. In Fig. 3 focusing of the  $\mu = 12$  mode has been optimised. But we can improve the focusing of the  $\mu = 2$  mode while defocusing slightly the  $\mu = 12$  mode. Actual measurements and comparison with theoretical expressions derived from eqn. 6 and the comment at the end of the following Section will be reported elsewhere.

**Calculation of time of flight of tubular modes:** In this Section we give simple expressions for the times of flight  $t$  of tubular modes in circularly symmetric fibres, of profile  $n(r)$ . These expressions are based on paraxial ray optics. It is convenient to set  $R = r^2$  and

$$U(R) = 1 - n(R)/n(0) \quad (1)$$

$$\tau = t(R)/t(0) - 1 \quad (2)$$

Then we find that, for a tubular mode of radius squared  $R$ , in the absence of material dispersion

$$\tau = R(dU/dR) - U \quad (3)$$

The mode radius  $r = R^{1/2}$  is related to the azimuthal mode number  $\mu$  ( $= 0; \pm 1; \pm 2; \dots$ )

$$l^2 = (\mu/k_0)^2 = 2R^2(dU/dR) \quad (4)$$

where

$$k_0 = (\omega/c)n(0)$$

Thus, given the  $l$  (or  $r$ ) of the mode, and the index profile, it is easy to evaluate the times of flight of various tubular modes.

We take into account material dispersion in the linear approximation by setting

$$(\lambda_0/n_0) \partial n / \partial \lambda_0 = 2(d-1)U \quad (5)$$

where  $n(r, \lambda_0)$  denotes, as before, the refractive index,  $\lambda_0$  the free space wavelength and  $d \neq 1$  for a dispersive medium.

Then eqn. 3 generalises to

$$\tau = R(dU/dR) - U - 2(d-1)U \quad (6)$$

Comparison of  $\tau$  in eqn. 6 with the experimental result provides the value of the inhomogeneous dispersion parameter  $d$ .

Each tubular mode has its own dispersion  $dt/d\omega$ , which is easily obtained by differentiating  $\tau$  in eqn. 6 with respect to  $\omega$ , keeping  $\mu$  in eqn. 4 (but not  $l$  or  $R$ ) a constant. The expression involves  $d^2U/dR^2$ . It will not be given here.

**Conclusion:** We have reported a novel method that provides precise mode time of flight measurements for short fibre samples. For a practical use of the method, one should construct a set of phase transparencies, perhaps using an evaporation technique, with all  $\mu$  values from 0 to about  $V/2$ , where  $V$  denotes the fibre normalised frequency (they need not be used at the same time). Then one would get about 20 times of flight, each of them relating to a specific radius within the fibre core, to within 2 to 3  $\mu\text{m}$ , corresponding to the tubular mode thickness. The method can be automated up to a point, but it must be kept in mind that excitation of pure tubular modes require good fibre breaks and careful adjustments at the fibre input.

A. BARTHELEMY  
P. FACQ  
C. FROEHLI  
J. ARNAUD

University of Limoges  
123 rue A. Thomas  
87060 Limoges Cédex, France

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