MODE EXCITATION IN A MULTIMODE OPTICAL-FIBRE WAVEGUIDE

Indexing terms: Fibre optics, Excitation, Optical waveguides

For normal incidence of a Gaussian beam on a multimode optical fibre, theory predicts that only HE_{1m} modes are excited, and this is confirmed experimentally for a liquid-core fibre of normalised frequency $\nu = 125$. Discrete-mode propagation is observed, indicating that the amount of mode conversion due to fibre imperfections is thus very small.

Introduction: The launching of Gaussian beams into optical-fibre waveguides has been considered both theoretically[1-4] and experimentally.[4, 5] However, in practice, it is difficult to observe modes in multimode fibres, because the lower-order modes rapidly couple to those of higher order, owing to mode conversion caused by wall imperfections, bends etc.[6, 7] In measurements carried out[8, 9] with liquid-core multimode fibres, very low values of dispersion (1·6 ps/m) have been obtained, and the mode-conversion effects which are present seem to be due entirely to bending of the fibre, with a negligible contribution from wall imperfections or scattering. In an attempt to isolate mode-mixing effects due to imperfections from those due to bends, we have studied low-order-mode launching in these fibres over short, moderately straight, lengths.

Theory: A Gaussian beam launched axially into a circular fibre excites only HE_{1m} modes, and the excitation efficiency

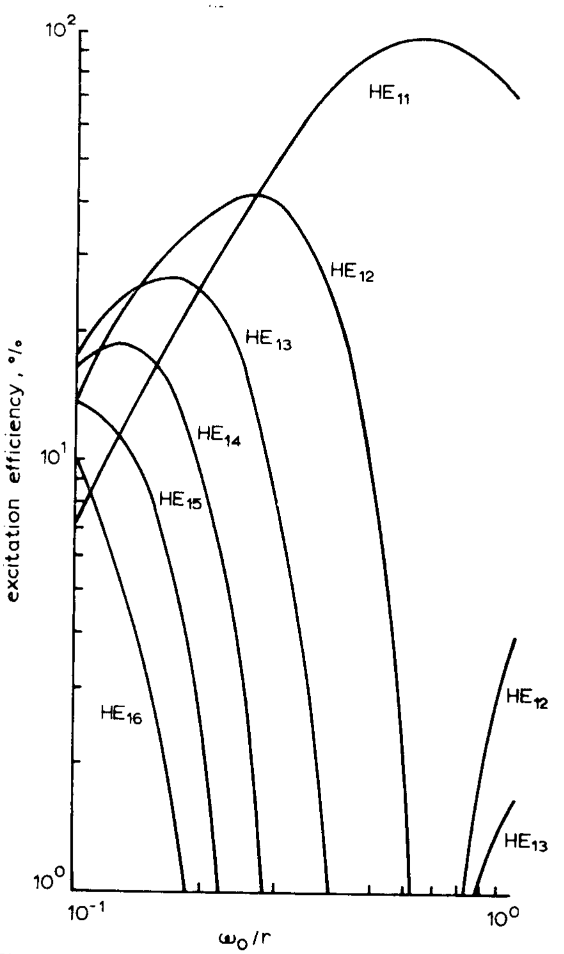
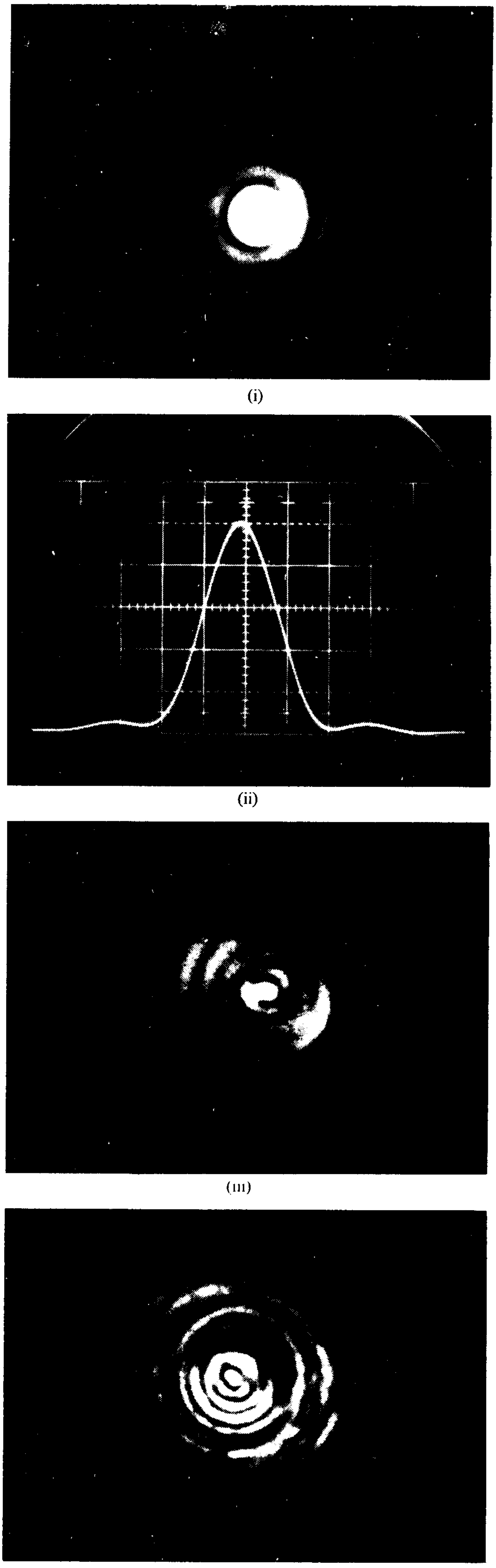


Fig. 1 *Theoretical excitation efficiency as a function of the spot size of the input Gaussian beam, for a normalised frequency* $\nu = 120$


(i)

(ii)

(iii)

(iv)

Fig. 2A *Results for* HE_{11} *mode*

(i) Output far-field pattern with near optimum launching conditions for HE_{11} mode
(ii) Angular-intensity distribution corresponding to *a*
(iii) Output far-field pattern for × 10 objective lens
(iv) Output far-field pattern for × 20 objective lens

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is given[2] by

$$P_{1m} = 2\left(\frac{U_m K_0(W_m)}{v K_1(W_m)}\frac{2r}{w_0}\left[\int_0^1 \frac{J_0(U_m R)}{J_0(U_m)}\right.\right.$$

$$\times\exp\left\{-\frac{R^2}{\left(\frac{w_0}{r}\right)^2}\right\} RdR + \int_1^\infty \frac{K_0(W_m R)}{K_0(W_m)}$$

$$\left.\left.\times\exp\left\{-\frac{R^2}{\left(\frac{w_0}{r}\right)^2}\right\} RdR\right]\right)^2 \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where w_0, r are the spot size of the Gaussian beam and the core radius, respectively; J_0, K_0, K_1 are Bessel functions and modified Hankel functions, respectively; and U_m, W_m are the dimensionless eigenvalues[2] associated with the J and K functions. v is the normalised frequency, defined by:

$$v = (2\pi/\lambda)\, n_1 r\{1-(n_2/n_1)^2\}^{1/2}$$

and n_1 and n_2 are the refractive indices of the core and cladding, respectively.

Fig. 1 shows how the launching efficiency varies with mode number and with the ratio w_0/r for a typical normalised frequency for multimode fibre of $v = 120$. At $w_0/r = 0{\cdot}68$, the HE_{11} mode is preferentially launched at an efficiency of 97%, with only a very small amount of power entering higher-order modes. If a Gaussian beam is incident on the end of a fibre under this condition, any higher-order modes observed along the fibre must arise from mode conversion due to imperfections in the interface, bending of the fibre or scattering in the core, due to either fundamental Rayleigh scattering or gross inhomogeneities.

Experiment: A plane-polarised helium–neon laser operating in the TEM_{00} mode at 0·633 μm was used to excite centrally, and at normal incidence, a liquid-core optical fibre[8] consisting of hexachlorobuta-1, 3-diene in tubing* having a bore of 57 μm. For this combination, $n_1 = 1{\cdot}551$ and $n_2 = 1{\cdot}485$, so that $v = 125$. The waist of the Gaussian beam was located at the entry face to the fibre, but, with the lenses available, the ideal launching conditions were not achieved, and, in the experiment, $w_0/r = 0{\cdot}86$. Even so, the predicted launching efficiencies were 89% for the HE_{11} mode and only 1·3% for the HE_{12} mode.

For these launching conditions, and lengths of a few metres, the output pattern was found to comprise mainly the HE_{11} mode with a fainter surrounding ring due to HE_{12} and higher modes, as shown in Fig. 2A(i). The photograph is rather overexposed to show the higher modes, resulting in severe saturation of the central spot. A corresponding scan using a *p-i-n* photodiode across the far-field pattern is shown in Fig. 2A(ii). The relative mode content may be judged from the fact that the central intensity is more than ten times that in adjacent peaks, and, furthermore, the intensity distribution in the central spot is close to Gaussian. The angle at which the first minimum occurs also corresponds to that of the HE_{11} mode.

For the above measurement, a lens of 10 cm focal length was used, which was then changed to microscope objective lenses of magnifying power ×10 and ×20, to mismatch the input beam and set up higher-order modes. The resulting far-field patterns are shown in Figs. 2A(iii) and 2A(iv), respectively, and confirm that the transmitted radiation consists primarily of HE_{1m} modes, despite the fact that the effect of mode conversion should be greater with very divergent beams.

The principal maximum in the radiation pattern of a mode is contained within an angle θ, which is given theoretically as:

$$\theta = \sin^{-1}\frac{U_m}{2\pi_r/\lambda} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

In Fig. 2B are plotted values of θ from eqn. 2 for various modes, together with experimental results obtained from angular-intensity scans such as that shown in Fig. 2A(ii). Despite the fact that one might expect the patterns to be affected by superposition of the subsidiary maxima of the various modes, the agreement betweem the predicted and the measured angles is good.

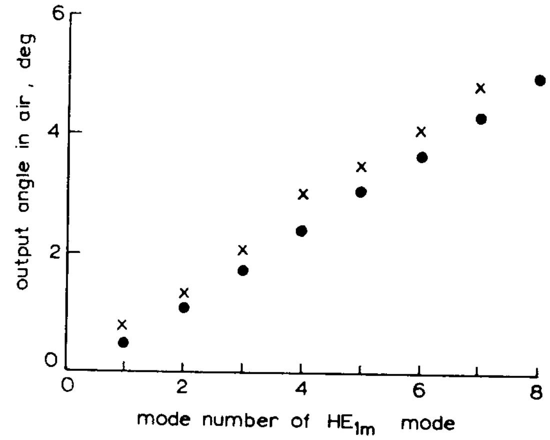

Fig. 2B *Comparison of theoretical and experimental values of characteristic mode angles in air, for HE_{1m} modes*
● theoretical
× experimental

Conclusions: Identifiable mode patterns have previously been observed[10] in multimode fibres over lengths of a centimetre or so and we have now greatly extended this length. The results indicate that, in the fibres used, the amount of mode conversion due to wall imperfections is negligible, and it is expected that effectively single-mode operation will be possible over much longer lengths. Hitherto, it has not been possible to compare theoretical predictions of mode conversion arising from curvature of the fibre with experiment, because of the overriding effect of mode scattering due to inhomogeneities. This comparison can now be made and will be reported elsewhere.

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