PARALLEL-BEAM EXCITATION METHOD FOR ESTIMATING REFRACTIVE-INDEX PROFILES IN OPTICAL FIBRES

Indexing terms: Fibre optics, Optical waveguides, Refractive index

A theoretical model is developed that demonstrates the presence of a ring in the far-field pattern when a graded-index fibre is excited by a collimated beam, incident at a given radius from the core centre. The angular position of tnis ring can be used to obtain an estimate of the fibre refractive-index profile, provided a correction for tne finite beam spot size is applied.

Introduction: In a recent publication,[1] a method of index-profile determination is described based on injecting an almost-parallel beam from a laser into the core of an optical fibre at a given radius. After about 1 m of fibre the output pattern in the far field is observed to exhibit a ring of peak intensity at angle θ_c to the axial direction. It is suggested that the corresponding angle θ_0 *inside* the fibre (i.e. $n_1 \sin\theta_0 = \sin\theta_c$) is related to the index profile $n(r)$ by the equation

$$n_1 \cos\theta_0 = n(r_0) \qquad (1)$$

where r_0 is the radius at which the input beam is injected and n_1 is the index at core centre. The authors of Reference 1 offer no explanation for the existence of the ring, but they have successfully employed eqn. 1 to determine fibre refractive-index profiles. These compare favourably with results obtained using the near-field scanning method[2] (n.f.s.), although it is indicated that it is not necessary to correct the latter for the presence of leaky modes.[3]

The purpose of the present contribution is

(*a*) to develop a ray-optical model that demonstrates the ring phenomenon and supplies a proof of eqn. 1

(*b*) to note that the index profile deduced from eqn. 1 is an overestimate, the error being similar to that caused by the presence of leaky modes in the n.f.s. technique

(*c*) to evaluate the method experimentally.

Theory: Consider the distribution $F(\beta)$ of rays in the fibre excited by a highly collimated input beam. $F(\beta)d\beta$ is defined as the power in rays with propagation constants in the range β to $\beta + d\beta$; β is the axial invariant[4] $n(r)\cos\theta$, where θ is the angle the ray makes with the fibre axis (z-axis). Under the excitation condition described, the rays launched will be almost meridional. In practice, the small amount of power launched into skew rays is sufficient to establish azimuthal symmetry after a short distance, typically less than 1 m. If $P(\beta, r)$ is the power flux in range r to $r + dr$, then:

$$P(\beta, r) = \frac{F(\beta)}{z_a(\beta)} \frac{dz}{dr} = \frac{F(\beta)}{z_a(\beta)} \left[\frac{n^2(r)}{\beta^2} - 1\right]^{-\frac{1}{2}} \qquad (2)$$

where $z_a(\beta)$ is half the ray periodic distance. Consider for simplicity a parabolic-index fibre having a core radius a and relative index difference Δ at the core centre:

$$n^2(r) = n_1^2\left[1 - 2\Delta\left(\frac{r}{a}\right)^2\right] \quad r \leqslant a \qquad (3)$$

In this case $z_a(\beta) = a\beta\pi/[2n_1(2\Delta)^{\frac{1}{2}}]$. Since there is a unique relationship between θ and r for fixed z, the angular distribution per unit solid angle $A(\beta, \theta)$ is given by:

$$A(\beta, \theta) = \frac{P(\beta, r)}{2\pi \sin\theta} \left|\frac{dr}{d\theta}\right| = \frac{\beta F(\beta)}{\pi^2 \sin\theta \cos\theta} [n_1^2 \cos^2\theta - \beta^2]^{-\frac{1}{2}} \qquad (4)$$

where eqns. 2 and 3 have been used. Eqn. 4 is valid for $\theta < \cos^{-1}(\beta/n_1)$; $A(\beta, \theta) = 0$ elsewhere. The total angular distribution $J(\theta)$ is found by summing contributions from all rays:

$$J(\theta) = \int_{\beta_{min}}^{\beta_{max}} A(\beta, \theta) d\beta \qquad (5)$$

If the input beam has a spot radius of δ, then $\beta_{min} = n(r_0 + \delta)$ and $\beta_{max} = min\{n(r_0 - \delta), n_1 \cos\theta\}$. The distribution $F(\beta)$ depends on the intensity profile of the input beam. For the purpose of illustration we take the simple case of a uniform distribution in β, i.e. $F(\beta) = 1$ for $n(r_0 - \delta) > \beta > n(r_0 + \delta)$, and $F(\beta) = 0$ otherwise (note that this distribution is unnormalised). From eqn. 5, the output distribution $J(\theta)$ is

$$J(\theta) = \begin{cases} \dfrac{1}{\pi^2 \sin\theta\cos\theta} \{[n_1^2 \cos^2\theta - n^2(r_0+\delta)]^{\frac{1}{2}} - [n_1^2\cos^2\theta - n^2(r_0-\delta)]^{\frac{1}{2}}\} \\ \text{for } \theta \leqslant \cos^{-1}[n(r_0-\delta)/n_1] \\ \dfrac{1}{\pi^2 \sin\theta\cos\theta} [n_1^2 \cos^2\theta - n^2(r_0+\delta)]^{\frac{1}{2}} \\ \text{for } \cos^{-1}[n(r_0-\delta)/n_1] \leqslant \theta \leqslant \cos^{-1}[n(r_0+\delta)/n_1] \end{cases} \qquad (6)$$

We see that the far field is described in general by cosec 2θ for small θ, but that it exhibits a subsidiary maximum at angle θ_0, given by

$$n_1 \cos\theta_0 = n(r_0 - \delta) \qquad (7)$$

This relationship is similar to that given in eqn. 1 but contains a correction δ that results from the finite size of the uniformly illuminated spot. Other more refined choices of input distribution lead to a similar effect, the correction required being in general intermediate between 0 and δ. An example calculated using an illuminating spot having a parabolic intensity distribution in β is illustrated in Fig. 1. The Figure shows the far-field distribution for a normalised spot size $\delta/a = 0{\cdot}1$, positioned at three different radii on the core of a parabolic-index fibre having $n_0 = 1{\cdot}5$ and $\Delta = 0{\cdot}005$. The expected positions of the rings using eqn. 1 are marked on the curves by arrows; it can be seen that the actual ring positions are appreciably different and occur at smaller output angles.

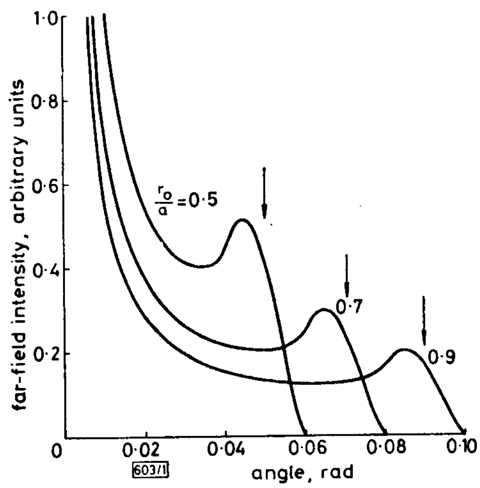

Fig. 1 *Far-field angular intensity distribution computed for various radial positions r_0/a of the exciting beam*

The curves are calculated for a spot of normalised size $\delta/a = 0{\cdot}1$ having an intensity profile giving a parabolic distribution in β. Arrows mark positions of maxima expected from eqn. 1

Thus refractive-index profiles inferred directly from the angle of the local maxima in the far-field patterns are subject to an error that consistently overestimates the true profile and, as in the n.f.s. technique, a correction factor is required to yield the true profile.

Experiment: A preliminary experiment indicated that excitation by a coherent laser beam results in a considerable degree of modal interference within the far field, thus tending to mask the position of the ring pattern. To overcome this difficulty a collimated filtered beam from a xenon-arc lamp was employed, apertured to give a spot size of 10 μm when focused onto the fibre endface. The fibre used had a core size of 63 μm, a close-to-parabolic index profile and a numerical aperture of 0·184. Representative results obtained by scanning the output from a 1 m length with a photodiode are shown in Fig. 2 for three positions of the input spot on the

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fibre core. The locations of the subsidiary maxima are marked on the Figure, and it is seen that the general shape of the curves is similar to that calculated in Fig. 1. Furthermore, results from a series of experiments indicate that eqn. 7 fits the known index data more accurately than does eqn. 1, although it was found that the experimental uncertainty caused by the ill-defined positions of the rings could in itself contribute an error of similar magnitude. It would appear from these experiments, therefore, that the method is unlikely to yield refractive-index data of accuracy comparable to that obtainable by other techniques.

Conclusions: A simple ray-optical model has been developed that demonstrates the presence of a ring in the far-field pattern when the fibre is excited with a near-parallel beam. The theory provides a relationship between the angular position of the ring and the value of the local refractive index at the launch radius. When used to obtain fibre refractive-index profiles, the method is subject to an inaccuracy as a result of the finite size of the exciting spot. The error is similar to that caused by the presence of leaky modes in the n.f.s. technique and consequently the results obtained will tend to agree with uncorrected near-field intensity plots. Experimental observations confirm this effect, but indicate that it is difficult to obtain accurate index data owing to the uncertainty in specifying the positions of the rings.

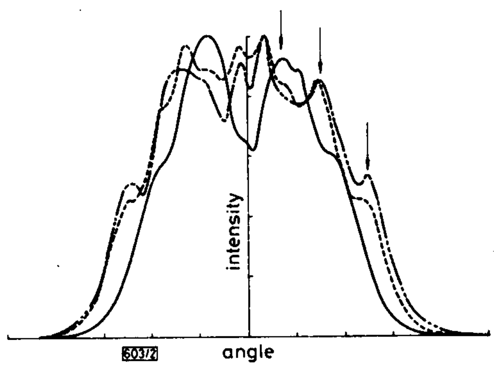

Fig. 2 *Experimental far-field intensity distributions for a graded-index fibre with $\alpha \approx 2$, core diameter $= 63\mu m$ and n.a. $= 0 \cdot 184$*

Curves are shown for various normalised r/a and were taken at a wavelength of $0 \cdot 83 \mu m$. Arrows mark positions of rings

———— $r_0/a = 0 \cdot 4$
– – – – – $r_0/a = 0 \cdot 6$
— – – — $r_0/a = 0 \cdot 8$

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