Determination of optical fiber refractive index profiles by a near-field scanning technique

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A simple and rapid method is described for determining the refractive index profile of an optical fiber by observation of the near-field intensity distribution. It is shown that in many cases the presence of tunnelling leaky modes is unavoidable and that these cause a length-dependent error in the measurement. A correction factor is developed which may be applied to the measured intensity profile once the fiber length, core diameter, and numerical aperture are known. Examples are given of measurements made on both step and graded-index fibers.

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Optical fibers having a smooth gradation of refractive index from a maximum on axis to a constant lower value in the cladding can exhibit very low pulse dispersion. Theoretical considerations[1,2] show that an optimum near-parabolic index profile exists for which the transit time of all modes is very nearly equalized, resulting in a considerable increase in bandwidth. However, the index grading must be accurately controlled, and whereas this can be achieved by using the chemical vapor deposition technique,[3] a need exists for a simple and rapid method of index profile determination. Existing methods[4,5] either require lengthy sample preparation or have yet to demonstrate sufficient precision to be of value in correcting profile inaccuracies by adjustment of the manufacturing process.

The near-field scanning technique to be described here provides a simple and rapid method for obtaining reproducible and detailed refractive index profile measurements. A short length of fiber is illuminated with an incoherent source, and the index profile is determined by observation of the light-intensity variation across the fiber output face. The profile obtained directly in this way may be suitable for many applications; however, for accurate determinations it is necessary to take into account the presence of tunnelling leaky modes. These modes contribute additional power to the observed near-field intensity distribution, resulting in an error in the inferred refractive index profile. The magnitude of this error decreases with fiber length as the leaky modes attenuate, but may still be significant after 100 m. We show here that a length-dependent correction factor can be calculated and employed to effectively eliminate this inaccuracy.

Gloge and Marcatili[1] have shown that a close resemblance exists between the near-field intensity distribution and the refractive index profile of a fiber in which all bound modes are equally excited, and this fact has already been used[6] to obtain a qualitative indication of the index profile of several fibers. Before quantitative measurements can be made, however, it is worth considering the factors which may influence the near-field intensity distribution in practical fibers. Principally these are (i) differential mode attenuation by absorption and scattering, (ii) mode conversion effects, and (iii) the presence of leaky modes. The first two may be largely eliminated in all but the worst fibers by using a relatively short length. However, for many index profiles, particularly near-parabolic, it is impossible to avoid launching leaky modes with even an apertured Lambertian source, since these modes are all contained within the angular limits of the numerical aperture.[7] Since 25% of the power launched from an incoherent source into a parabolic index fiber is contained within tunnelling modes,[8] a considerable departure from the predicted intensity profile occurs, and a length dependence is observed as these modes decay. The loss of the tunnelling modes varies from near zero for the least leaky to a large value for the most leaky, and hence the intensity profile will be influenced largely by those modes just below cutoff. By summation of the power remaining in all modes, it is possible to calculate the near-field intensity as a function of length. A correction factor may then be developed which can be applied to a given length of fiber to convert the observed intensity distribution into the refractive index profile. Thus the refractive index $n(r)$ at radius r can be related to the near-field intensity $P(r)$ by

$$\frac{n(r)-n_2}{n(0)-n_2} \simeq \frac{n^2(r)-n_2^2}{n^2(0)-n_2^2} = \frac{P(r)}{P(0)}\frac{1}{C(r,z)}, \tag{1}$$

where n_2 is the cladding refractive index and $n(0)$ and $P(0)$ are the refractive index and intensity at the core center, respectively. The correction factor $C(r, z)$ is calculated by summing the Lambertian source distribution (having a cosine angular dependence of intensity) over all angles of incidence θ and projected angles ϕ,[7] using a suitable weighting factor to allow for the attenuation of a ray.

$$C(r,z) = \frac{4}{\pi[n^2(r)-n_2^2]}\int_0^{\pi/2} d\phi \int_0^{\pi/2} \sin\theta \cos\theta \exp\left(\frac{-\alpha(\theta,\phi)z}{a}\right) d\theta, \tag{2}$$

where $\alpha(\theta, \phi)$ is the attenuation of the mode associated with rays launched at angles (θ, ϕ), z is the fiber length, and a is the core radius. The θ integral in Eq. (2) may be split into three angular acceptance regions[7] delineating bound, tunnelling, and refracted rays. The attenuation coefficient $\alpha(\theta, \phi)$ of a ray launched into the bound ray region is taken as zero, that of a refracted ray infinite, and that of the leaky rays remains to be calculated, but will vary between 0 and ∞. We see that after an infinite length of fiber, Eq. (2) reduces to $C(r, \infty) = 1$ as anticipated, since only bound modes remain. In addition, $C(r, z) \to [1-(r/a)^2]^{-1/2}$ in the limit $z \to 0$, as derived previously for the case when all leaky modes are present unattenuated.[7]

The detailed computation of the losses suffered by leaky rays in graded index fibers will not be presented here. For a step-index fiber, the attenuation coefficients may be evaluated exactly from the known electromagnetic fields. However, we note that for the purpose of evaluating Eq. (2) for a graded-index fiber, the attenuation may be calculated explicitly to a reasonable degree of accuracy by use of the zeroth-order WKB approximation. As a result of these calculations a simplified approximate expression has been derived for the correction factor, and it is hoped to present this at a later date. Fortunately it is found that $C(r, z)$ does not vary greatly with the form of the index profile, and furthermore can be normalized to the fiber length, core radius, and numerical aperture.

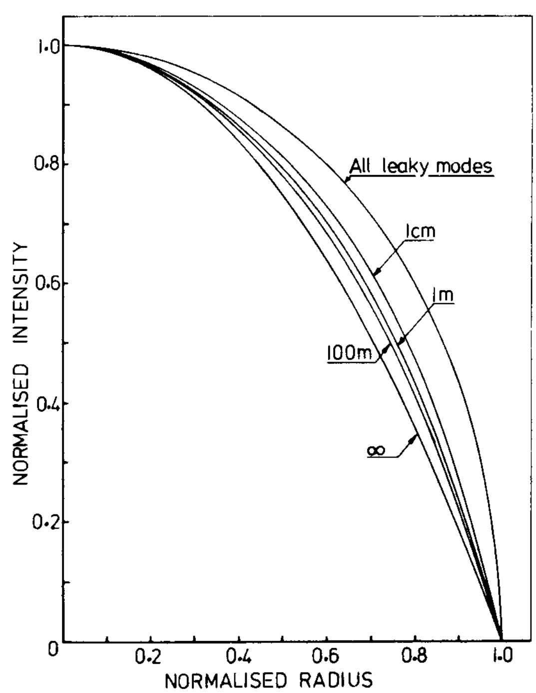

FIG. 1. Calculated near-field intensity distribution for a parabolic-index fiber having a numerical aperture of 0.2 and a core radius of 40 μm. The curves are plotted for lengths of 1 cm, 1 m, 100 m, and ∞. The curve for infinite length is equivalent to the index profile. Also shown is the curve calculated assuming all leaky modes are present unattenuated.

An indication of the length dependence of the intensity profile to be expected in practice is shown in Fig. 1, where the calculated distribution is plotted as a function of length for a typical parabolic-index fiber having a numerical aperture of 0.2 and a core radius of 40 μm. As shown by the difference between the curve for all leaky modes and that for 1 cm, many of the tunnelling modes are lost within a short distance from the source. However, the less-leaky modes are extremely persistent and cause significant error even after a length of 100 m. For this fiber a length of well over 1 km would be required before the direct measurement would give the index profile with negligible error, although after this length other propagation effects would in practice influence the result. Curves calculated for fiber having either a larger numerical aperture or core diameter converge more slowly to resemble the index profile since the tunnelling modes have lower loss.

The above theory applies to fibers in which all fiber modes are equally excited, and in practice this requires a Lambertian source such as a tungsten filament lamp or an LED, although it should be noted that many commercially available LEDs are far from perfect Lambertian emitters. Figure 2 shows the experimental arrangement. The incoherent source is either focussed onto the end of the fiber in the case of the lamp or is butted directly up to the fiber when using an LED. A magnified image of the fiber output face is displayed in the plane of a small-active-area (250 μm diameter) PIN photodiode which is arranged to scan the field transversely. Amplification is by a phase-sensitive detection system and the intensity profile is plotted directly onto an xy recorder. The photodiode and x axis of the recorder are controlled by means of stepper-motor drives and the relationship between step length and photodiode area gives the system a 1% spatial resolution. The fiber is kept as straight as possible to avoid radiation effects and is typically less than 1 m long. Optically flat end faces are obtained by transversely scratching and breaking the fiber under tension.

In order to test the accuracy of the technique and the validity of the calculated near-field correction factors, the intensity distribution was measured for two fibers having known refractive index profiles, one a parabolic-index fiber and the other a step-index fiber. Figure 3 shows the uncorrected intensity profile obtained from a 35 cm length of Selfoc. For comparison, the figure also shows the index profile obtained by observation of the interference fringe spacing in a 110-μm-thick cross-

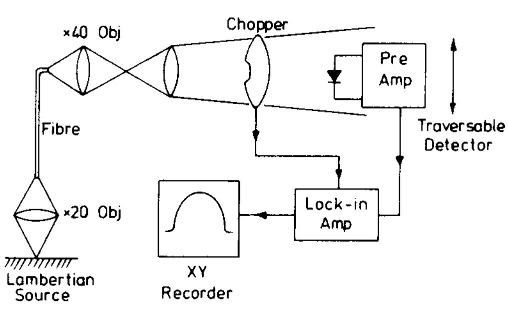

FIG. 2. Experimental apparatus.

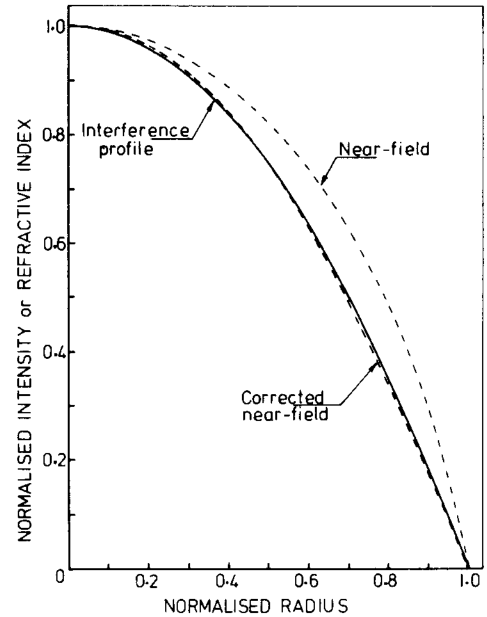

FIG. 3. Measured intensity distribution (upper dashed curve) and corrected intensity distribution (lower dashed curve) for a parabolic-index fiber compared with the index profile determined by an interference method. Length, 35 cm; numerical aperature, 0.43; core radius, 51 μm; wavelength, 0.8 μm.

sectional slice of the fiber. Although the effect is somewhat emphasised by the high numerical aperture of this fiber (0.43), it can be seen that the tunnelling rays cause a marked difference between the two curves. This error, however, is reduced to a negligible value by application of the correction factor, calculated as outlined earlier.

Figure 4 shows the results obtained when the measured intensity profile in a short length of step-index fiber is corrected. In this case good agreement with the known index profile is obtained up to a normalized radius of 0.8, as evidenced by the flatness of the corrected curve. However, some rounding of the curve occurs at a greater radius, and this is believed to be a result of the very high cladding loss in this fiber sample rather than an excessively large correction factor.

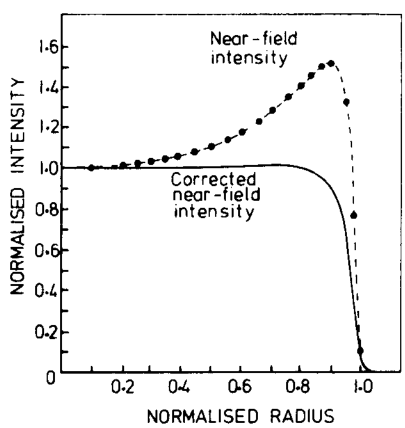

FIG. 4. Measured intensity distribution (upper dashed curve) and corrected intensity distribution (lower solid curve) for a step-index fiber. Numerical aperture, 0.26; core radius, 45 μm; length, 30 cm; wavelength, 0.93 μm.

The near-field scanning technique provides a rapid and convenient means of index profile determination. The method is attractive as it requires little specimen preparation and relatively simple equipment. In general, the plots contain considerably more fine detail than do those obtained by the interference fringe counting technique, and this is particularly useful when analyzing fibers made by the CVD process.

A correction factor which incorporates the length dependence of the intensity profile is required to allow for the existence of tunnelling leaky modes. The magnitude of this factor is greatest for a large normalized frequency or for short fiber lengths, and is significant in most practical cases. It is hoped to present detailed calculations of the normalized correction factors in a future publication.

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