INDEX PROFILE DETERMINATION IN GRADED INDEX FIBRES

D.N.Payne, F.M.E.Sladen and M.J.Adams

Introduction

Current interest in optical fibres having near parabolic refractive index distribution has emphasised the need for an accurate and simple means of determining the index profile, both in the laboratory and in production. Theoretical considerations show[1] that an optimum profile exists for which the transit time of all modes is very nearly equalised, and a considerable increase in bandwidth results. The index variation however must be controlled with great precision, and although it seems possible to achieve this by means of the chemical vapour deposition technique, a method has yet to be found by which the profile may be quickly and accurately measured. Existing methods[2,3,4] are either time consuming in that they require tedious preparation of the fibre samples, or do not possess sufficient accuracy to be of practical value.

By observation of the near field intensity distribution of a fibre excited by an incoherent source, we show that it is possible to obtain accurate, reproducible and detailed refractive index data, provided a correction is applied to allow for the presence of tunnelling leaky rays. The method requires very little sample preparation, is simple to set up and gives the complete profile within a few minutes. Furthermore measurements may readily be made at several different wavelengths.

Theory

It has been shown by Gloge and Marcatili[1] that in a fibre with all modes equally excited, a close resemblance exists between the near field intensity distribution and the refractive index profile. This fact has already been used[5,6] to obtain a qualitative indication of the index profiles of several different fibres. However, in order to apply the near field scanning technique to accurate quantitative determinations, it is necessary to take into account the propagation characteristics of practical fibres. In particular mode conversion, differential mode attenuation, and the existence of leaky rays can cause considerable departures from the predicted near field distribution. Short lengths of fibre may be used so as to largely eliminate the first two factors, but this emphasises the errors produced by the presence of leaky rays.

Fortunately however it is possible to extend the theory of reference 1 to include the leaky rays and hence to develop a correction factor for the near field intensity profile. By this means it can be shown[7] that the intensity P(r) at a radius r on the fibre end face is given by

$$\frac{P(r)}{P(0)} = \frac{n(r)^2 - n_2^2}{n(0)^2 - n_2^2} \cdot \frac{1}{\sqrt{1-(\frac{r}{a})^2}} \qquad \ldots (1)$$

where P(0) = intensity at fibre centre, n(r)= refractive index at radius r, n(0)= refractive index at fibre centre, n_2= refractive index of cladding and a=core radius.

Department of Electronics, University of Southampton, Southampton , U.K.

The above result is identical to that derived in reference 1, apart from the factor $\frac{1}{\sqrt{1-(r/a)^2}}$ which must be included for observations on short lengths of fibre, when all leaky rays are present. The observed near field intensity does not therefore truly represent the refractive index profile, but must be corrected by a factor which becomes larger as we progress outwards from the fibre centre. The correction factor may be applied to any circularly symmetric index profile, and may be employed equally well with both step index and parabolic index fibres. It does not however take into account the preferential loss of the leaky rays, so that in the case of a step index fibre of more than a few millimetres long the rapid radiation of some of these rays may result in a significant error in the measured profile.

Experiment

Equation (1) is applicable only to fibres in which all modes are excited equally. Experimentally this can be achieved by using an incoherent source such as an LED or a tungsten filament lamp. Fig.1 shows the experimental arrangement. The incoherent source is either focussed on the end of the fibre or is butted as close to the fibre as possible. A magnified image of the fibre output face is formed in the plane of a PIN photodiode which is arranged to scan the field transversely. The intensity profile is plotted directly onto an X-Y recorder. The fibre is kept as straight as possible to avoid leakage effects, and is typically less than one metre long. Optically flat end faces are obtained by scratching and breaking the fibre under tension.

Results

Fig.2(a) shows an uncorrected near-field intensity plot obtained from a 102μm diameter fibre of very nearly parabolic index profile. For comparison the figure also shows the index profile obtained by observation of the interference fringe spacing in a 110μm thick cross-sectional slice of the fibre. The presence of tunnelling leaky rays causes a marked difference between the two curves and this clearly demonstrates the need for a correction factor. As a further indication of the errors introduced by leaky rays, the intensity profile of a step index fibre is shown in fig.2(b) and may be compared with the known profile. In agreement with equation (1) the curves become increasingly divergent with distance from the fibre centre.

The effect of the correction factor on the near field intensity plot is shown in fig.3. The corrected and uncorrected plots are shown on a logarithmic scale so that the slope α (the parameter used in reference 1 to describe the index profile) may be determined. The corrected value of $\alpha=1.962$ is very close to the figure of $\alpha=1.957$ determined by the interference method, whereas the uncorrected plot yields $\alpha=2.117$, an error of 10%. A perfect parabola has $\alpha=2$.

Conclusions

The near field scanning method can be used on short lengths of fibre to determine the index profile, provided a correction factor is incorporated to allow for the presence of leaky rays. The correction factor may be applied to a fibre of any circularly symmetric index profile, although it can be shown that greater errors will occur for fibres with near step index profiles owing to the loss of some highly leaky rays. The method is attractive as it requires little specimen preparation and relatively simple equipment.

Although the present work is directed towards the determination of refractive index profiles, it serves to emphasise the importance of leaky rays, particularly in graded-index fibres. Whereas it is possible to avoid launching leaky rays in step index fibres by limiting the angular spread of the source so as not to excite rays lying outside the fibre numerical aperture, this is not so for a parabolic index fibre since all leaky rays are contained within the angular limits of the numerical aperture.

References

1. Gloge,D. and Marcatili,E.A.J.:"Multimode theory of graded-core fibres" B.S.T.J. 52 (1973) p.1563.
2. Martin,W.E.:"Refractive index profile measurements of diffused optical waveguides", Applied Optics 13 (1974) p.2112.
3(a) Eickhoff,W. and Weidel,E.:"Measuring method for the refractive index profile of optical glass fibres", Optical and Quantum Electronics 7 (1975) p.109.
(b) Ikeda,M., Tateda, M., Yashikiyo,H.:"Refractive index profile of a graded index fibre: Measurement by a reflection method", Applied Optics 14 (1975).
4. Marcuse,D. and Presby,H.M.:"Light scattering from optical fibres with arbitrary refractive index profiles",J.Opt.Soc.America 65 (1975) p.367.
5. Burrus,C.A., Chinnock,E.L., Gloge,D., Holden,W.S., Li ,T., Standley, R.D. and Keck,D.B.:"Pulse dispersion and refractive index profiles of some low-noise multimode fibers",Proc.IEEE 61 (1973) p.1498.
6. Burrus,C.A. and Standley,R.D.:"Viewing refractive-index profiles and small-scale inhomogeneities in glass optical fibers: Some techniques" Applied Optics 13 (1974) p.2365.
7. Adams,M.J., Payne,D.N. and Sladen,F.M.E.:"Leaky ray analysis of optical fibres with near-parabolic refractive index" submitted for publication.

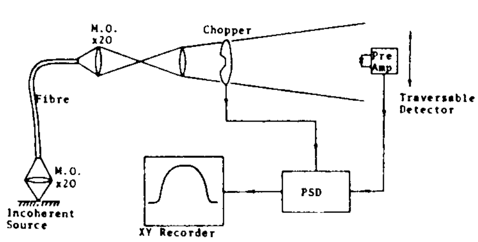

Fig. 1 Experimental Apparatus

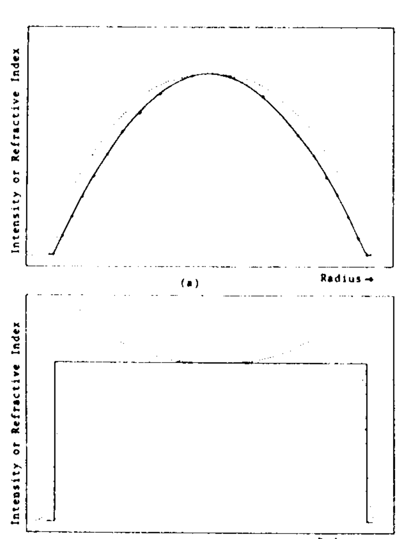

Fig. 2 Measured near field intensity (dotted) compared with the refractive index profile for (a) a near parabolic index fibre, and (b) a step index fibre.

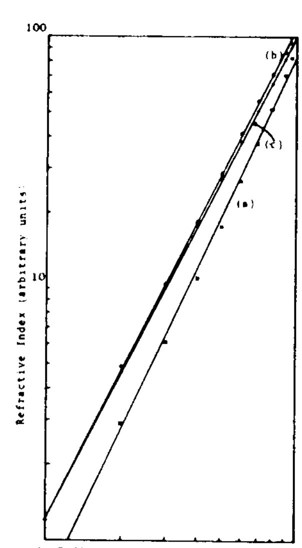

Fig. 3 Refractive index plots of a near parabolic index fibre determined by (a) an uncorrected near field intensity scan (b) a corrected near field intensity scan, (c) an interference method.