MODE SHIFT AT BENDS IN SINGLE-MODE FIBRES

Indexing term: Optical fibres

The predicted oscillatory field deformation at the onset of a bend in a single-mode fibre, together with the steady-state beam shift, have been confirmed experimentally.

Introduction: One of the important problems to be considered in the application of single-mode optical fibres to long-distance transmission is the loss due to radiation at bends. A wide variety of theoretical techniques have been used in attempts to predict bend loss, all of which initially had in common the assumption that the modal fields of the curved fibre remain identical with those of the straight fibre and that the rate of energy loss is constant around the bend. However, the agreement between such theoretical predictions and experimental measurements is unsatisfactory.

Experimentally, it has been recently shown[1] that the radiation emitted at the beginning of a bend is not uniform, but occurs preferentially in certain directions, giving the appearance of discrete divergent rays. With increasing distance along the curved fibre, the beams progressively broaden and the radiation gradually becomes more uniform and characteristic of a stable mode. This was the first practical demonstration of a transition region at the beginning of a bend. On the theoretical side, the modal fields of the curved fibre have been calculated[2] numerically by solving an approximate wave equation by using a double Fourier-Bessel expansion. The modes of the curved fibre have also been derived[3] analytically from the same equation with a perturbation method. At the same time, the question of nonuniform loss was considered by including a contribution due to coupling between the guided modes of the straight fibre and the radiation field at the beginning and end of the curved section. However, the uniform-loss term to which this was added was again found from the undeformed modes of the straight fibre.

More recently, an approximate technique based on the coupling of bound and leaky modes has been used.[4] This approach, by allowing coupling from the radiation field back to the guided field, provides an explanation for the discrete beams of radiation observed experimentally at the entrance to a sharp bend and predicts a periodic shift in the position of maximum power along the curved fibre. We present here (*a*) experimental results confirming the predicted fluctuating beam shift at the beginning of a bend and (*b*) a comparison of experimental and theoretical determinations of the steady-state beamshift in a continuously curved fibre.

Mode oscillation at discontinuities in curvature: A simple technique has been devised for making qualitative observations of the mode shift. The single-mode fibre investigated was made by homogeneous chemical-vapour deposition and had a dip in refractive index at the centre of the core. The output end was carefully cleaved and cemented to one edge of the curved side of a semicylindrical plastics former of the desired radius. By rotating the former, the length of bend, of fixed radius, was varied while the bend radius could be changed by using formers of different size. The fibre was excited by a Gaussian beam from a helium-neon laser and the output near-field pattern was imaged by a lens and recorded with a scanned-diode array.

It was found that the dip in the core profile produced a small drop in intensity in the near-field pattern. As expected, the depression was centrally situated in the field pattern when the fibre was straight (see distributions labelled $\theta = 28°$ and $40°$ in Fig. 1), but seemed to vary its position as the end portion of the fibre was curved, at constant radius, over progressively longer lengths. In fact, of course, the profile dip remained stationary while the mode pattern in the core moved relative to the axis. Thus, at the positions $\theta = 30°$, $34°$ and $38°$, the mode shifts steadily to the left of the dip, having a maximum displacement at $\theta = 34°$, and returns to the centre at $\theta = 40°$. The radius of curvature in this case was 15 mm, so that the periodic length of the oscillation is $15\,(12\pi/180) = 3$ mm. This movement of the 'mode' energy distribution is consistent with the ray emission and is in accordance with the mode-coupling theory.[4]

Steady-state beam shift: The method described above is simple and convenient for making qualitative observations of beam shift, since slight movements ($\sim 1\ \mu m$) of the fibre output end are not troublesome. However, the presence of a dip obscures the position of the energy maximum and must be avoided in making quantitative measurements. Thus, to measure the equilibrium beam shift, a fibre was selected which did not have a refractive-index depression in the core. The output end was firmly fixed in position on a cylindrical former and the near-field pattern was imaged on a photodiode array, with the fibre held in a straight configuration. A length of the output portion of the fibre was then coiled around the former and the shift in the position of maximum intensity was noted.

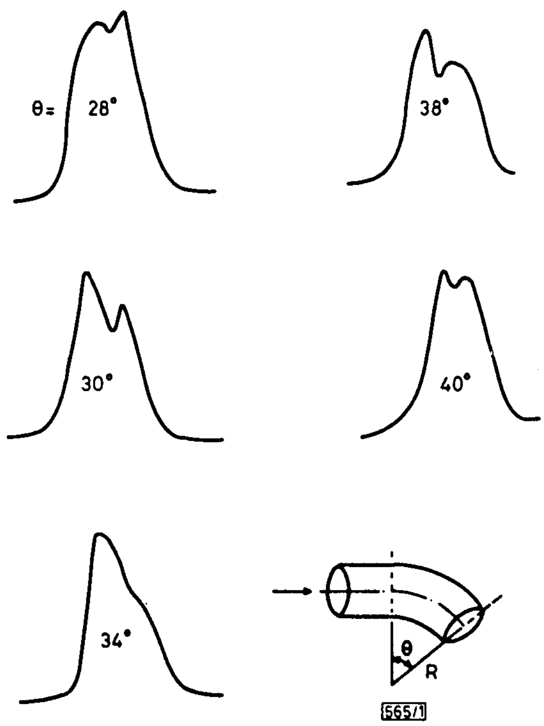

Fig. 1 *Near-field intensity distributions in curved single-mode fibre of n.a. 0·6, core radius 4 μm, cladding/core-diameter ratio 13·8 and bend radius 15 mm*

The linear distance along the curved fibre, z, is given in terms of the angular distance θ by $z = 15\pi\theta/180$ mm; the centre of curvature is to the right in each case

The experiment was then repeated with cylinders of various diameters. In each case the curved portion was made longer than that of the transition region where mode conversion and mode oscillation occur.

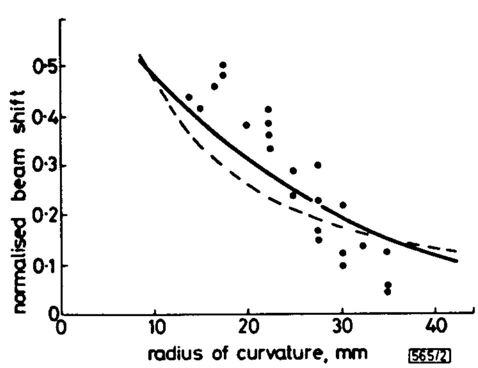

Fig. 2 *Equilibrium beam shift, as fraction of core radius, in single-mode fibre described in Fig. 1 as function of (constant) radius of curvature*

The points are measured; the broken and solid curves are derived from the theories given in References 3 and 4, respectively.

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The measured beam shift, normalised to the core radius, is shown as the experimental points in Fig. 2 for radii of curvature between 10 and 40 mm. The scatter in the results is due to the small displacements involved and the discontinuous response of the photodiode array, which makes the detection of the maximum point difficult. Nevertheless, the beam shift is clearly evident and it increases at smaller radii of curvature, as might be expected. The theoretical curves are deduced from the results of Miyagi and Yip[3] and from our theory[4] based on the coupling of bound and leaky modes. Considering the experimental difficulties, the agreement between theory and experiment is reasonable.

Discussion: The presence of a transition region at the junction of straight and curved sections of a single-mode fibre, where mode-conversion effects occur, has now been firmly established. The theoretical prediction of an oscillatory transient in the position of maximum mode energy, caused by coupling between the fundamental core mode and the leaky core and cladding modes, has been confirmed experimentally. We have also observed, for the first time, the steady-state shift in mode energy which occurs in a continuously curved fibre.

Measurement[5,6] of the variation in power carried by the core with distance along the curved fibre provides further evidence of the forward and backward coupling[4,7] between modes. Thus there are regions where the core power remains constant, or even increases, with distance as a result of power returning to the core from leaky or cladding modes. The same process gives rise to the emission of 'rays' from the transition region, as noted[1,4] earlier. Further, a better agreement between theoretical and experimental values of bend loss is obtained[5] when transition effects are taken into consideration. Clearly, therefore, the transition region and related mode conversion must be taken into account in any practical application of single-mode fibres.

It is interesting to note that most of the effects described here have also been observed[7] in the step-index multimode fibre.

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