Selective Excitation of Graded-Index Multimode Fibres Resulting in Annular Near Field Patterns

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A practical method, stemming from a purely theoretical analysis, for the selective excitation of multimode graded index fibres is described. The objective of such an excitation is to create annular near field patterns at the fibre output. The method uses an offset tilted beam and is intended for a mode group multiplexing system since the selective excitation of a mode group will yield a spatially distinguishable near field pattern. The analysis is based on both the modal and geometrical description of light propagation in the fibre.

1 Introduction

The selective excitation of multimode fibres (MMFs) has been used for the investigation of characteristics such as the differential mode attenuation and the differential mode delay. In these applications the spatial intensity distribution on the rear facet of the fibre is of no particular interest. This is not the case for a method referred to as mode group diversity multiplexing which deploys different groups of modes as independent communication channels [1]. The method is based on the selective excitation of different mode groups, the spatial filtering of the near field pattern and on signal processing at the receiver side to remove the crosstalk between the channels. Each launched mode group should result in a distinguishable intensity pattern at the fibre output. It is thus of great interest to find a practical way of selectively launching mode groups which result in annular near field patterns with the least possible radial spreading and which consist of as few modes as possible. In this way the number of potential communication channels can be increased.

In the following analysis the effect of mode mixing is not taken into account. The consequence of mode mixing is the radial expansion of the annular near field pattern. The stronger the effect of mode mixing, i.e. the closer is the fibre length to the equilibrium length, the fewer communication channels can be supported by the mode group diversity multiplexing technique. In this case the near field pattern is mostly determined by the effect of mode mixing rather than the launching conditions and therefore the latter do not need to be as precise as described here.

The results presented in this paper are often obtained by taking into account a parabolic refractive index profile since this is one of the few profiles with an analytical solution and is nearly the profile in dispersion-optimized fibres. However deviations from this profile are also examined.

2 Light propagation in graded-index multimode fibres

Light propagation in MMFs is more accurately described by using the Maxwell equations and applying the proper boundary conditions. The result is a set of modes each representing a different field distribution in the fibre and propagating with a specific propagation constant. A method for launching one LP mode makes use of a rather complicated mask based on its field distribution [2], [3]. It is very difficult in practice to use this method to launch simultaneously selected modes each excited by a different optical source as required in a mode group diversity multiplexing system.

However, if that would be the case, LP modes with radial mode number equal to one should be employed since their annular patterns show the least radial spreading.

A commonly used method for the analysis of graded-index MMFs is the WKBJ approach. The zeroth order WKBJ approximation gives the same results as the geometric optics approach based on the eikonal equation [4], [5]. The latter treats the light as rays and thus provides a simple, straightforward connection of the ray launching conditions and the tubular volume in the fibre where the ray is bound, or in field terms where oscillating and not evanescent fields exist. This volume is defined by two cylindrical (of circular cross section) surfaces known as caustic surfaces (fig. 1).

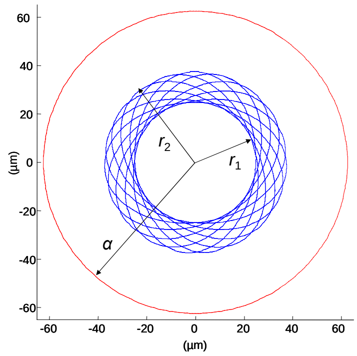

Fig. 1 Ray path projection on a plane vertical to the fibre axis; r_1, r_2 are the radii of the caustic surfaces. A perfluorinated (PF) polymer MMF was considered with core radius α=62.5 μm. Its refractive index profile is given by (1) with q=1.6.

3 Modelling of a light beam

In order to excite selectively an MMF an offset tilted beam is used. This means that a group of modes is excited since the mode patterns are symmetric to the fibre axis and consequently there cannot be a field matching between the input beam pattern and one mode pattern. Only in the case of zero offset it is possible to excite just the fundamental mode.

A Gaussian beam will be considered and its axis will be treated as a light ray, referred to as central ray. The beam is characterized by its waist w and it is launched under specific conditions which are defined by three parameters with respect to the central ray as illustrated in fig. 2. These are the radial offset r_0 (distance of the intersection point between the ray path and the fibre front facet from the fibre axis) and the two angles θ and ψ. Another parameter that has to be set when launching the light in the fibre is the position of the beam waist with respect to the fibre front facet.

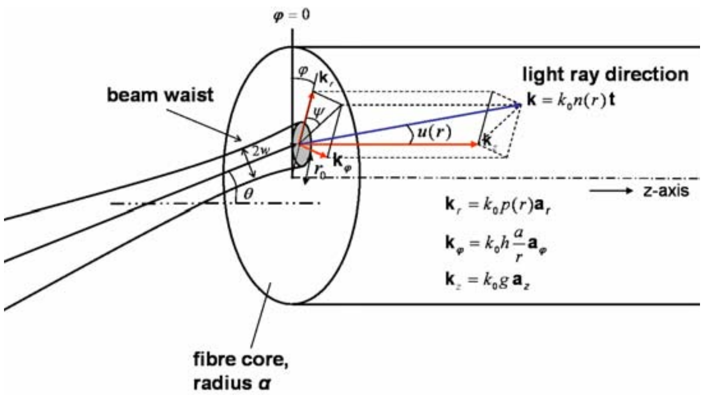

Fig. 2 Beam launching and ray propagation in MMFs; k_0 is the wave number in free space and the other parameters are explained in the text.

4 Optimization of the launching conditions

Considering the case of power law profiles where

$$n^2(r) = \begin{cases} n_0^2\left[1-2\Delta\left(\dfrac{r}{a}\right)^q\right], & 0 \le r \le a \\ n_0^2(1-2\Delta) = n_1^2, & r > a \end{cases} \quad \text{and} \quad \Delta = \frac{n_0^2 - n_1^2}{2n_0^2} \tag{1}$$

it can be shown [5] that a light ray path in a MMF is described by the two following differential equations

$$\frac{\mathrm{d}r}{\mathrm{d}z}=\frac{p(r)}{g} \text{ and } \frac{\mathrm{d}\varphi}{\mathrm{d}z}=\frac{ha}{r^2 g} \tag{2}$$

In the above formulas α is the radius of the fibre core, $p(r)=\pm[n^2(r)-g^2-h^2(\alpha/r)^2]^{½}$ and $g=n(r)\cos\theta(r)$, $h=n(r)\sin\theta(r)\sin\psi(r)r/\alpha$ are dimensionless constants which are called invariants.

As it can be seen in fig. 2 the radial component of the wave vector is proportional to $p(r)$. Oscillating fields can therefore exist in a tubular volume where $p^2(r)\geqslant 0 \Rightarrow p(r)\in\mathbb{R}$. Equation $p(r)=0$ defines the radii of the caustic surfaces that together with the front and rear facets of the fibre form the tubular volume. Since annular patterns with the least possible radial spreading are desired, launching parameters (r_0, θ, ψ) that result in helical rays will be pinpointed. In this case the radial coordinate of the ray path is constant and the radii of the two caustic surfaces coincide.

Where the ray trajectory adjoins with a caustic surface, $\psi=\pi/2$. For helical rays this is the case for every point along their path, i.e. $\psi=\pi/2\ \forall z$. Consequently $\psi=\pi/2$ at z=0. For every radial offset r_0 there is a unique θ_0 that results in a helical ray. For $\theta<\theta_0$, r_0 is equal to the radius of the outer caustic surface (r_2 in fig. 1) and for $\theta>\theta_0$, r_0 is equal to the radius of the inner caustic surface (r_1 in fig. 1). In the case of parabolic index profile (q=2) equations (2) have an analytical solution [6]. The radii of the caustic surfaces [6], [1] and the optimal (θ_0, r_0) pairs that result in helical rays are then calculated analytically. It can be easily shown (by equating the radii of the two caustic surfaces and setting $\psi=\pi/2$) that

$$\theta_0(r_0)=\sin^{-1}\left(\frac{r_0 NA}{an(r_0)}\right) \tag{3}$$

where $NA=\sqrt{n_0^2-n_1^2}$ is the central numerical aperture of the fibre.

The following diagram (fig. 3) depicts the optimal (θ_0, r_0) pairs for the cases of refractive index profile with q=1.5, 2, 2.5. In all three cases the numerical solution of equations (2) is involved and for the case of the parabolic profile the results are also calculated analytically. A fibre with 125 μm core diameter, NA=0.171 and n_0=1.355 was considered. These parameters are typical for PF polymer optical fibres.

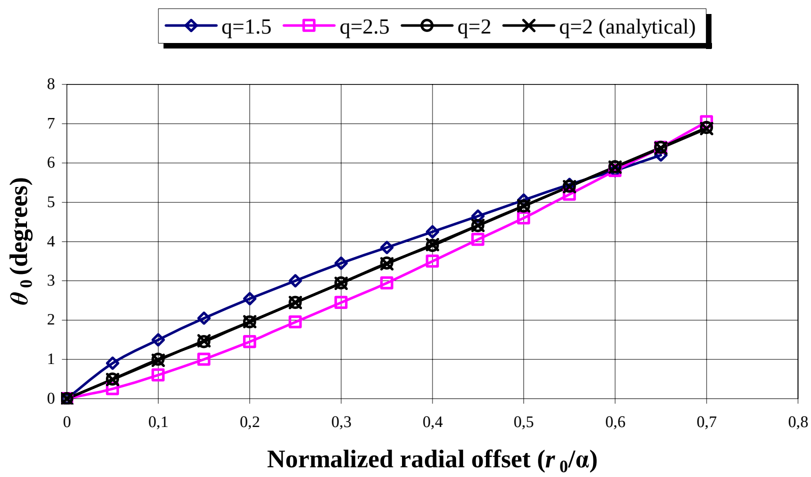

Fig. 3 Optimal (θ_0, r_0) pairs which result in helical rays for three cases of power law refractive index profiles (q=1.5, 2, 2.5) for a PF polymer graded index MMF.

For radial offsets larger than ~0.7α there is no θ_0 within the local numerical aperture. This means that launching the light in a way that could correspond to a helical ray (e.g. by using (3)) would result in a leaky or radiated ray. It should be mentioned that only discrete combinations of r_0, θ and ψ are supported by the MMF [7], depicting the discrete character of the modes. This means that the curves in fig. 3 may only serve as a guide in finding experimentally the (r_0, θ, ψ) combinations that result in annular near field patterns with the least possible thickness.

The ray approach has been used for optimizing the parameters r_0, θ and ψ since it provides a simple and straightforward model for relating the input (launching conditions) with the output (annular pattern). However a light beam cannot be described by a single ray. A field analysis for the case of parabolic index fibres [8] indicates that for exciting as few modes as possible using a Gaussian beam, the beam waist must be located on the fibre front facet and its width w should be

$$w = Cw_0 \text{ where } w_0 = \sqrt{\frac{2a}{k_0 NA}}$$

and it is a width associated with the fundamental mode. The constant C depends on the radial offset and the suggested compromise is $C \simeq 0.6$ which is nearly optimal for the excitation of higher order modes (r_0>~0.3α) and still retains almost the 80% of the power in the fundamental mode when r_0=0. In the case of a PF polymer optical fibre w_0=9.94 µm and thus w=0.6w_0 $\Rightarrow$ w=5.96 µm at 850 nm wavelength.

5 Conclusions

A method for the selective excitation of graded-index multimode fibres using an offset tilted beam was described. The method is meant for a mode group diversity multiplexing system and consists of optimal launching conditions with respect to the system requirements. It is based on a theoretical analysis which takes into account the modal as well as the geometrical description of light propagation in graded index multimode fibres.

6 Acknowledgement

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7 References

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