Mode coupling in plastic optical fibres of high and low numerical apertures

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ABSTRACT

We present here an experimental method to estimate mode coupling strength in plastic optical fibres (POFs), based on the changes in fibre output power pattern with mode coupling. The disk pattern found for the equilibrium mode power distribution changes to a ring pattern when mode coupling is incomplete, which can be applied to obtain the coupling coefficient of a fibre. Following this approach we have compared the mode coupling properties of plastic optical fibres of the same material polymethylmetacrylate (PMMA), but different numerical aperture (NA) in order to assess the extent of mode coupling contribution to the bandwidth increase found for fibres with low numerical apertures. Our results show significantly higher coupling in fibres with a high numerical aperture, suggesting that dispersion be determined by numerical aperture rather than by coupling strength.

INTRODUCTION

Plastic optical fibres (POFs) are being considered for high-performance fibre links at very short distances because their ductility, light weight and ease of connection as compared to those of glass optical fibres in spite of their narrower bandwidths. Low numerical aperture (NA) POFs show wider bandwidths than high NA POFs and therefore, the former are better suited to meet the ever increasing demands for low-cost high-bandwidth communications in short and medium-distance applications. Pulse broadening in multimode fibres is mainly due to modal dispersion and also chromatic dispersion out of the zero dispersion wavelegth. In PMMA based POFs, chromatic dispersion is around 0.3 ns/nm·Km at 650 nm and modal dispersion seems to be related mainly to the NA of the fibre, in such a way that low NA POFs present higher bandwidths than high NA POFs [1]. Nevertheless, it has been shown that strong mode coupling (power transfer from one mode to another) is present in step index POFs reducing modal dispersion, making it comparable to chromatic dispersion, and leading to a square-root dependence of bandwidth with fibre length instead of the expected linear rate. On the other hand, this strong mode-coupling present in POFs significantly changes output-field properties and degrade beam quality with possible consequences for power delivery and sensory systems. Therefore, it is necessary to have effective means of obtaining the rate of mode coupling.

A method to estimate coupling strength was first proposed by Gambling et al. for glass optical fibres and has been applied later to POF by other authors [2-4]. The method is based on changes in the fibre output pattern due to mode coupling. Thus, the pattern of the fibre output power is a disk for fibres longer than the coupling length for which the equilibrium mode distribution is reached. For shorter lengths, when light is launched into the fibre at small angles, a disk is also found, but if the launch angle increases, the patterns flatten until they look like a ring indicating a feeble mode coupling. The launch angle for which the disk to ring transition occurs, known as the transition angle θ_t, is related to mode coupling strength and can be used to estimate it by modelling its increase with fibre length. Garito et al. and Arrue et al. scanned the far-field output power distribution of the fibre obtained under different launching conditions and followed Gloge's power flow equation to estimate the coupling coefficient [3-5]. We have followed a similar approach with the main difference that we register directly an image of the output power distribution using a CCD camera, which is faster and more direct than the far-field angular scans. This procedure is described with detail in the next section. Then, we present the results for both high and low NA PMMA fibres and a summary of the conclusions.

METHODS

Our procedure to determine the transition angle for different fibre lengths is based on the analysis of a set of images of the near-field intensity registered with a CCD camera at a range of launch angles. The experimental system consisted in an opto-mechanical set-up and a computer controlled CCD camera. The source was a He-Ne laser (633nm) launched directly into the front end of the fibre, which was mounted onto a rotating stage. The output intensity was directly imaged on the CCD as shown in Figure 1.

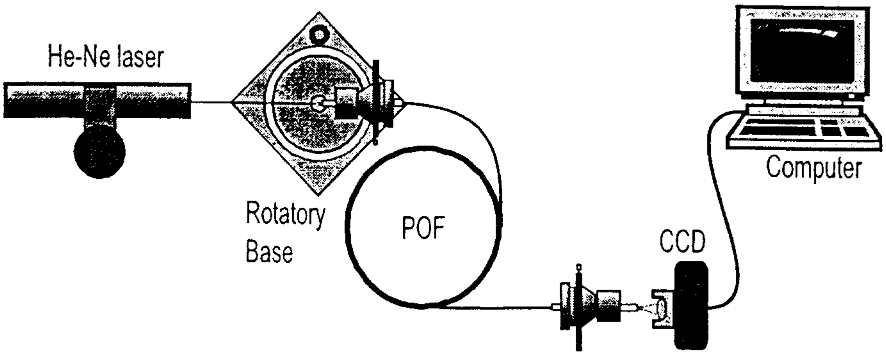

Figure 1: Experimental set-up used to obtain the power distribution images.

For a given fibre, the experimental procedure was as follows: First, a fibre between 20-30 m long was placed around a 18 cm diameter reel to avoid small curvatures that can bias the results increasing the transition angle [4]. The polished fibre ends were mounted on specifically designed chucks, and the launch end was carefully centred in the rotating stage. Then, launch angle was varied in one-degree steps, simultaneously recording the images. Once the angle scan was completed, a determined length of the fibre was cut from the further end. Then, the whole procedure was repeated to obtain a set of images like those shown in Figure 2. These near-field power distributions show the same behaviour than the far-field patterns, as shown in the work of Djordjevic et al., whose simulation results show a good agreement with our measured patterns [6]. The images were subsequently processed and their radial profiles extracted and analysed to determine which image shows the pattern change from disk to ring. The input angle corresponding to this image is the transition angle.

To relate these measurements with the coupling coefficient, we have followed Gloge's power flow equation to describe the changes in optical power caused both by attenuation and power transfer between neighbouring modes. Power transfer is described by the mode conversion constant *D,* which is related to a coupling coefficient that describes random perturbations inherent to the material caused by intrinsic and

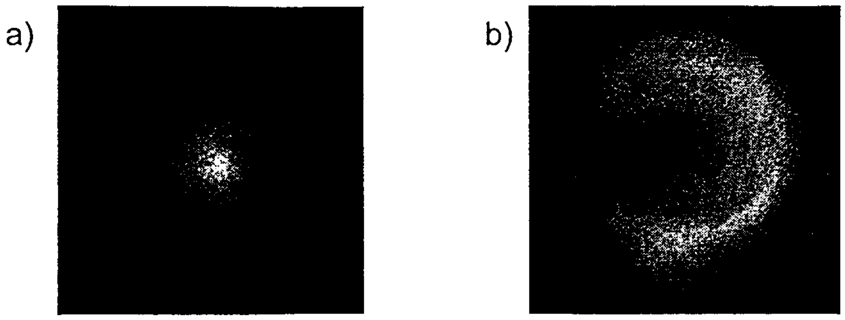

Figure 2: Images for a HNA fibre of 10m. a) Input angle of 0° showing the disk pattern typical of complete mode coupling. b) Input angle of 25° shows the ring pattern obtained for feeble coupling.

extrinsic variations. From Gloge's equation a log-log relation between transition angle (θ_t) and fibre length (z) can be derived to obtain D as follows [3-4,6]:

$$\log(\theta_t) = \frac{1}{2}\log(z) + \log\left(2D^{1/2}\right)$$

RESULTS

The fibres used in our experiments were PMMA based, step-index profile POFs, with a diameter of 1mm, and numerical apertures of 0.47 (HNA) and 0.32 (LNA). The transition angle in radians versus fibre length in metres was measured for several fibres of each type, as is shown in log-log coordinates in Figure 3. Data were fitted to straight lines obtaining slopes close to 0.5 (0.52 ± 0.02 for HNA POF and 0.51 ± 0.02 for LNA POF). Obtained values of D ($8.7\cdot10^{-4} \pm 1.2\cdot10^{-4}$ radians^2/m for HNA and $2.82\cdot10^{-4} \pm 3.5\cdot10^{-5}$ radians^2/m for LNA) show that mode coupling is significantly higher for the fibre with a high numerical aperture. Data published by Garito et al. for a SI-POF with NA of 0.51 is also plotted in Figure 3 as a mean of comparison with our results [3]. From the Figure 3, in spite of the different POF samples used in the experiments, a good agreement for HNA fibres can be observed. The value for the low NA fibre presents significantly lower D, implying a weaker mode coupling for this fibre type.

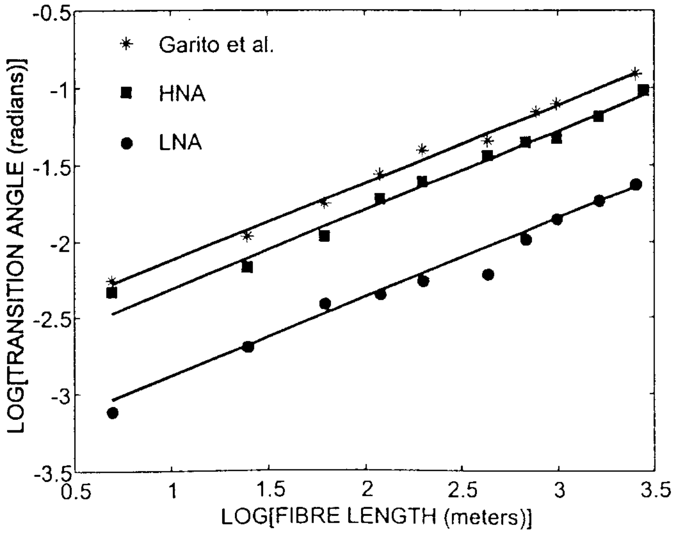

Figure 3: The figure shows the data obtained by Garito et al. for a HNA fibre (crosses), and our data for the HNA fibre (squares), and for the LNA fibre (circles).

In addition, we observed that both high and low NA fibres submitted either to stress or curvatures show shallower slopes and yield D values more than one order of magnitude higher than those found at normal conditions. Gambling et al. found an increase in D for liquid core fibres submitted to transverse pressure, while Arrúe et al. found that D is higher for small curvature radii [2,4]. These findings suggest that macro-defects, curvatures, pressure, etc. will enhance power transfer between neighbouring modes.

CONCLUSIONS

In this work, we have developed a straightforward method to measure the mode conversion constant (D) of plastic optic fibres, which is susceptible to be automated using a motor-driven rotation stage to vary the launch angle. Using this method, we have estimated the value of D for high and low numerical aperture plastic fibres of the same material. We found significantly lower D values for low numerical aperture POFs than for higher numerical aperture POFs, which indicates weaker mode coupling for low NA fibres. Moreover, our results show a good agreement with Gloge's model and also with previous works [2-4]. In addition, we have observed that an extensive use of the fibres (curvatures, pressure) causes an increase in D, which suggest a higher power transfer between modes.

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