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Bent induced refractive index profile variation and mode field distribution of step-index multimode optical fiber

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ABSTRACT

The effect of bending of step-index optical fiber on its refractive index profile and the mode field distribution were investigated. An enhanced slab model is suggested in this investigation. A qualitative study has been done on a bent step-index optical fiber. A very small radius of bending curvature (R) has been reached, practically R is 9.25 mm. In this case a dramatic change of the refractive index profile has been observed with an induced birefringence. The refractive index profile is recovered from the interferograms which were generated by Mach–Zehnder interferometer. The interferogram has been analyzed using advanced image analyses software. We have proposed another approach to calculate the refractive index profile of bent optical fiber. In this approach the fiber is divided into layers and slabs, simultaneously. The induced refractive index profile variation of the bent optical fiber, for parallel and perpendicular components of the light beam, is calculated considering the refraction of the light beam traversing the fiber. The mode field distribution and mode numbers in these two directions of polarizations are determined for both straight and bent fibers.

1. Introduction

Originally, optical fiber is used in optical telecommunications and data transfer [1]. Bending an optical fiber in the field of communication has a certain limitation which causes a signal loss. This limitation is related to the fiber's radius of curvature [2,3]. An intense research in the field of sensors and their behavior under stress and high temperature is currently underway. These sensors are able to monitor the variation of the measured physical parameter to have a better optimizing the on-line experimental parameters. Most of them are based on fibre bending [4]. This is why it is important to study, extensively, the refractive index variation due to bending of optical fibre [5,6].

The interferometric based methods are used as accurate and nondestructive tools to find the refractive index of fibrous materials [5–8].

The bending leads to an increase and a decrease of the refractive index of the compressed and elongated parts of a fiber, respectively. This has been demonstrated by Tai et al. [9]. Their study could be applied for all plastic and glass fibers. The beam propagating method has been used to evaluate the macro-bending loss for optical fibers as a function of bending radius [2,3].

The isotropic plastic optical fiber becomes a uniaxial fiber as a result of mechanical bending. The mechanical bending leads to induced birefringence, which is proportional to the distance measured from the neutral line [10]. The induced birefringence is related to the mechanical strain for the bent fiber cladding [11].

The effect of the mechanically induced residual stress on the refractive index of the single mode optical fiber has been investigated [12]. The birefringence was being negative for the elongation stress [12,13].

In recent papers [5,6], a theoretical model was proposed to determine the refractive index profile of bent single mode optical fibers, taking into account the refraction of the incident light beam by the fiber. This model is based on dividing the cross section into a large number of slabs with a constant refractive index. An enhancement on the accuracy has been achieved, using automated Fizeau interferometer and phase shift digital holography [5,6]. In addition, digital holographic interferometric phase shifting based on this model is used to determine the optical parameters of bent optical fiber with enhanced accuracy [6,14].

In the present work, another step forward has been done, taking into consideration that the beam transverses two layers (cladding–core) of step-index multimode bent optical fiber, which is divided to slabs. The modified model is suggested to consider the path of the beam when traversing slabs; these slabs could contain the cladding or cladding–core areas. In cladding–core area, core refractive index is recovered with knowledge of cladding refractive index given by the aid of strain-birefringence relation.

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Mach–Zehnder interferometer is used to generate the interferograms of the step-index bent optical fiber in two polarization states of the incident beam. The extracted optical phase differences, due to the mechanical bending of step-index multimode optical fiber in conjunction with the enhanced model, is used to calculate the full refractive index profile of the bent optical fiber.

It is interesting to use the obtained refractive index profile for determining the values of mode numbers and mode field distributions of the bent optical fiber. Analytical and numerical determinations of the mode field distribution have been presented for an integrated-optical waveguides [15–17]. The number of modes and propagation coefficients are calculated, for the investigated bent optical fiber, based on the experimentally obtained refractive index profile, using the method described in Ref. [18]. In the used method, the experimentally data of refractive index profile were fitted using a suitable function, in order to extract the required parameters. These parameters have been inserted in prepared software to get analytically the number of modes and propagation coefficients.

2. Theory

2.1. Refractive index profile of bent step-index optical fiber

Optical fibers are affected by mechanical processes such as bending; they convert from an isotropic state to an anisotropic state which leads to the appearance of birefringence. The polarization direction of the used laser beam is either vibrates parallel to the fiber axis ($n^{\parallel}$) or vibrates perpendicular to the axis ($n^{\perp}$). It is much easier to divide the bent optical fiber into two parts around the fiber axis. The first part is the compressed area which chose to vary along the positive direction of the x-axis. The other part, which is stretched, varies along the negative direction of the x-axis, see (Fig. 1). Considering a fiber consists of two separate regions, each region is divided into slabs of equal thickness (a). The first region of slabs (A) is located between the fiber radius (r_f) and the core radius (r_c) which has been divided into k slabs. The thickness of each slab, in this region, is given by

$$a=\frac{r_f-r_c}{k} \quad (1)$$

The second region of slabs (B) is located between the fiber center and the core radius (r_c), and have the same thickness (a).

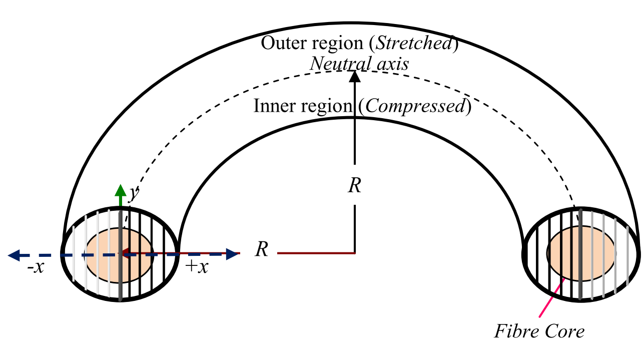

Fig. 1. A schematic diagram of the bent optical fiber.

The number of slabs M is given by

$$M=\frac{kr_c}{r_f-r_c} \quad (2)$$

Using this model, we calculate the refractive index profile of a bent fiber in two steps. In the first step, the ray tracing of laser beam in region (A) is considered, (see Fig. 2). Suppose the incident ray falls at the center of the jth slab at distance (d_j) from the original axis. This distance can be calculated by

$$d_j=r_f-\left(j-\frac{1}{2}\right)a \quad (3)$$

where, j is the order of slab, for the first layer $j=1$ at the fiber surface, and the incident angle is θ_{oj} which is given by

$$\theta_{oj}=\sin^{-1}\left(\frac{d_j}{r_f}\right) \quad (4)$$

In this case the refraction angle θ_{1j} is given by

$$\theta_{1j}=\sin^{-1}\left(\frac{n_L d_j}{n_{Aj} r_f}\right) \quad (5)$$

where, n_{Aj} is the refractive index of the jth slab in region (A). This ray exits the jth slab at a distance x_j' from the origin axis:

$$x_j'=r_f \sin\varphi_j \quad (6)$$

where φ_j is given by

$$\varphi_j=2\theta_{1j}-\theta_{oj} \quad (7)$$

Hence, we can calculate the optical path difference (OPD) as follows:

$$\text{OPD}=n_{Aj}L_{Aj}-n_L L_{oj} \quad (8)$$

where L_{oj} and L_{Aj} are the optical path lengths inside the liquid and the jth slab in region (A), respectively. From the geometry of (Fig. 2)

$$L_{oj}=\sqrt{{r_f}^2-{d_j}^2}+\sqrt{{r_f}^2-x_j'2} \quad (9)$$

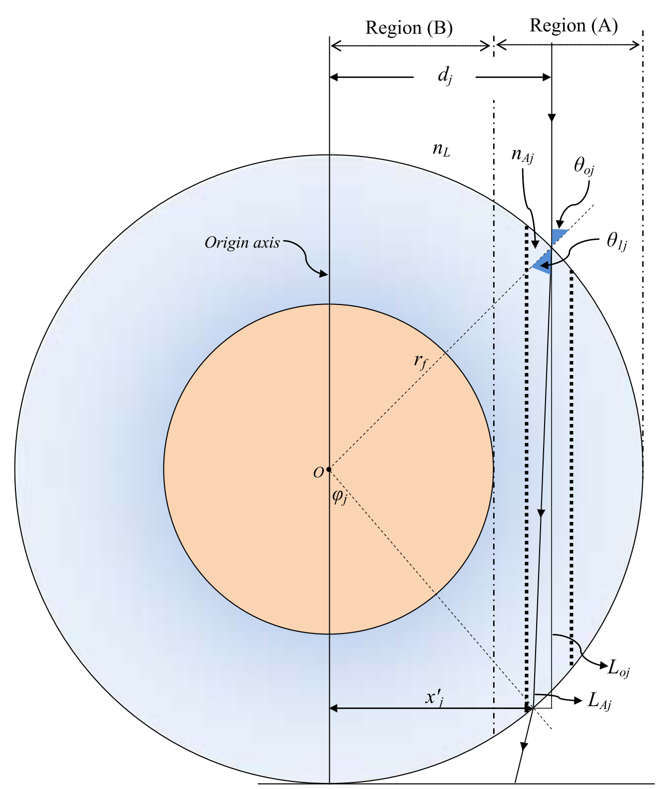

Fig. 2. The optical ray path across a slab in region (A).