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Controlled generation of different orbital angular momentum states in a hybrid optical fiber

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ABSTRACT

A new kind of hybrid optical fiber for different orbital angular momentum (OAM) states generation is proposed and investigated by simulation. The hybrid fiber is composed of three main regions: the core, the cladding and the bow-tie-shaped stress-applying zones (SAZs). The SAZs are symmetrically distributed on both sides of the core and filled with piezoelectric material PZT-5H which would generate radial mechanical movement when subjected to an electric field. The strain applied by the SAZs introduces anisotropic variation of the material permittivity which affect the propagation of the guided modes along the fiber core. The OAM modes of $|l| = 1, 2, 3$ can be generated by setting the appropriate electric potential applied in the SAZs. This fiber-based structure and electric control design enable the generation and adjustment of OAM states with the merits of accuracy, compactness and practicality, which would have potential application in OAM optical fiber communication systems and other systems utilizing OAM light.

1. Introduction

It has long been known that the spin angular momentum (SAM) of optical field is manifested as circular polarization, which has only two values of $\pm\hbar$ (Plank's constant divided by 2π) per photon [1,2]. In 1992, it was recognized that light beams with a helical phase structure described by $\exp(il\varphi)$ possess an orbital angular momentum (OAM) of $l\hbar$ per photon, where φ is the azimuthal angle and l is an integer counting the number of intertwined helices [3]. Since then, OAM light has been found as a useful tool in a variety of applications, such as optical manipulation [4], quantum communications [5] and super-resolution imaging [6]. In particular, OAM modes with different l values form a large orthonormal set of functions that can be used for encoding information. It provides an additional degree of freedom for data transmission. Recently, OAM beams have been applied in optical communication to increase the channel capacity and the spectral efficiency of communication systems [7,8].

In order to satisfy the needs of various applications, various techniques have been proposed and demonstrated for efficiently generating optical beams carrying OAM. In free space, OAM states can be generated by spiral phase plate [9], diffractive phase holograms [10], metamaterials-based phase plates [11], cylindrical lens pairs [12], q-plates [13], silicon integrated devices [14] and so on. Meanwhile, due to the advantages of long-distance/large-capacity transmission for optical communication systems, the fiber-based generation techniques are also developing rapidly. Several methods to generate OAM beams in fiber have been proposed, such as twisted special fibers [15–17], micro-bend fiber gratings [18], novel compact OAM couplers [19], helical gratings [20], and the all-fiber OAM mode converter [21]. However, the aforementioned fiber based generation methods are hard to realize tunable OAM modes generation, which brings difficulty to the development of highly capacity and integrated all-fiber OAM communication system.

In this paper, a new kind of hybrid optical fiber for different OAM states generation is proposed and investigated by simulation. The hybrid fiber is composed of a multimode core and a pair of bow-tie-shaped stress-applying zones (SAZs) in the fiber cladding. The SAZs are symmetrically distributed on both sides of the core. The cladding material is pure silica. The SAZs are filled with piezoelectric material which would generate mechanical movement when subjected to an electric field. By adjusting the electric potential applied in the SAZs, different OAM states can be generated at the output terminal of the hybrid fiber.

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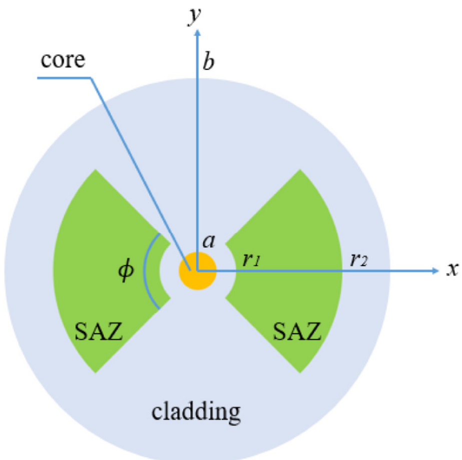

Fig. 1. Cross-section of the designed hybrid fiber for OAM generation. The radii of the core, the cladding, and the inner and the outer sides of the SAZs are a, b, r_1 and r_2, respectively. The circumferential angle of the SAZs is ϕ.

2. Fiber structure design

The cross-section of the hybrid fiber is shown in Fig. 1. This fiber is composed of three main regions: the core, the cladding and the bow-tie-shaped SAZs. The SAZs are symmetrically distributed on both sides of the core. The geometric parameters of this hybrid fiber structure include the core radius a, the cladding radius b, the circumferential angle of the SAZs, ϕ, and the inner and outer radii of the SAZs, r_1 and r_2, respectively.

The cladding material is pure silica. The SAZs are filled with piezoelectric material which would generate mechanical movement when subjected to an electric field. Metallic coatings deposited on the inner and the outer sides of the SAZs are used as electrodes. It is suggested that the piezoelectric material in the SAZs is polarized radially, so that the axial symmetry of the structure is maintained in the process of deformation. Electric potential U applied to the electrodes creates strain which leads to the nanoscale deformation of the fiber shape. In addition, the strain introduces anisotropic variation of the material permittivity. Both phenomena affect the propagation of the guided modes along the fiber.

The high order vector modes in optical fiber could be classified as HE, EH, TE, and TM modes. Each mixed mode (HE or EH) has two degenerate orthogonal modes (even and odd modes). In an ideal circular-core optical fiber, these two modes propagate with the same phase velocity. However, the hybrid fiber with electric potential is not perfectly circularly symmetric. The two modes propagate with different phase and group velocities. A phase difference will appear and accumulate between the two orthogonal modes. By adjusting the fiber length and electric potential appropriately, the two orthogonal modes can achieve a ±90° phase difference at the end of the hybrid fiber. And then the fiber OAM modes can be obtained by the coherent combination of the two degenerate orthogonal components of the same vector mode with ±90° phase difference (i.e. $\mathrm{OAM}^{\pm}_{\pm l,m} = \mathrm{HE}^{even}_{l+1,m} \pm i\mathrm{HE}^{odd}_{l+1,m}$, $\mathrm{OAM}^{\mp}_{\pm l,m} = \mathrm{EH}^{even}_{l-1,m} \pm i\mathrm{EH}^{odd}_{l-1,m}$). Moreover, by employing a multimode fiber which supports more numbers of modes and using appropriate electric potential, the proposed hybrid fiber can be used for generating higher-order OAM modes. The detailed calculations and analysis are described in the next section.

3. Numerical results and discussion

The geometric parameters of this proposed hybrid fiber are considered to be such that $a = 6.25$ μm, $b = 62.5$ μm, $r_1 = 12.5$ μm, $r_2 = 47$ μm, $\phi = 90°$. The length of the hybrid fiber is 10 cm. The refractive index of

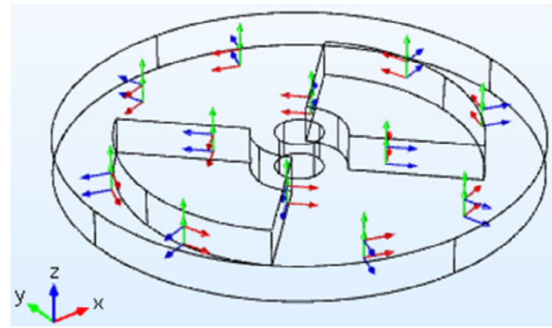

Fig. 2. Arrow plot depicting the user-defined cylindrical coordinate system used to set up the poling direction in PZT-5H.

the cladding and the core are 1.444 and 1.4592 at 1550 nm, respectively. The piezoelectric material in the SAZs is PZT-5H, which is a transversely isotropic material. Such a material has the same properties in one plane (isotropic behavior) and different properties in the direction normal to this plane.

In the core, the general linear stress-optical relation can be written, using tensor notation, as $\Delta n_{ij} = -B_{ijkl}S_{kl}$. Where $\Delta n_{ij} = n_{ij} - n_0 I_{ij}$, n_{ij} is the refractive index tensor, n_0 is the refractive index for a stress-free material, I_{ij} is the identity tensor, B_{ijkl} is the stress-optical tensor, and S_{kl} is the stress tensor. Because n_{ij} and S_{kl} are both symmetric, $B_{ijkl} = B_{jikl}$ and $B_{ijkl} = B_{ijlk}$. Therefore, this model includes only two independent parameters, B_1 and B_2 which are the first and second stress optical coefficient, respectively. The stress-optical relation then can be simplified as following [22]:

$$\begin{bmatrix}\Delta n_x\\ \Delta n_y\\ \Delta n_z\end{bmatrix} = -\begin{bmatrix}B_1 & B_2 & B_2\\ B_2 & B_1 & B_2\\ B_2 & B_2 & B_1\end{bmatrix}\begin{bmatrix}S_x\\ S_y\\ S_z\end{bmatrix} \tag{1}$$

where $n_x = n_{11}$, $n_y = n_{22}$, $n_z = n_{33}$, $S_x = S_{11}$, $S_y = S_{22}$, and $S_z = S_{33}$.

According to photo-elastic effect, the relation between the induced refractive index and the principle stress in x, y, and z axis direction can be written as:

$$n_x = n_0 - B_1 S_x - B_2\left(S_y + S_z\right) \tag{2}$$

$$n_y = n_0 - B_1 S_y - B_2\left(S_z + S_x\right) \tag{3}$$

$$n_z = n_0 - B_1 S_z - B_2\left(S_x + S_y\right). \tag{4}$$

A commercial finite element simulation software (COMSOL Multiphysics) is employed to investigate the effective refractive index of modes and stress distribution in hybrid fiber. In COMSOL Multiphysics, the poling direction of most piezoelectric materials is assumed to be z-polarized. This also means that if the piezo material properties assigned to a user-defined orthogonal coordinate system with unit vectors x_1, x_2, and x_3, then the piezo can be considered to be poled along the x_3 direction. Therefore, a user-defined cylindrical coordinate system (as shown in Fig. 2), where x_3 is aligned along the radial direction of the fiber, is created in the SAZs by the following relationship

$$\begin{bmatrix}x_1\\ x_2\\ x_3\end{bmatrix} = \begin{bmatrix}\varphi\\ z\\ r\end{bmatrix} = \begin{bmatrix}-\sin\left(\mathrm{atan}\left(\frac{y}{x}\right)\right) & \cos\left(\mathrm{atan}\left(\frac{y}{x}\right)\right) & 0\\ 0 & 0 & 1\\ \cos\left(\mathrm{atan}\left(\frac{y}{x}\right)\right) & \sin\left(\mathrm{atan}\left(\frac{y}{x}\right)\right) & 0\end{bmatrix}\begin{bmatrix}x\\ y\\ z\end{bmatrix}. \tag{5}$$

This setting will ensure that the PZT-5H in the SAZs is polarized radially. The displacement field and stress distribution of the bow-tie hybrid fiber are first studied. Suppose that the electric potential applied to the PZT-5H is $U = 100$ V. The total displacement of the PZT-5H due to the radial electric field is displayed as shown in Fig. 3(a). The maximum displacement occurs at the inner side of the SAZs, which is about 14 nm. The nanoscale deformation of the SAZs will introduce stress to the core. Fig. 3(b) shows the von Mises stress distribution of the