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Polarization rotator based on liquid crystal infiltrated tellurite photonic crystal fiber

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ABSTRACT

By employing the liquid crystal refractive index changes induced by applied electric field, a novel polarization rotator with low crosstalk and shorter length of rotation has been proposed and theoretically analyzed. The mode field distribution, birefringence of the fiber fundamental mode and the influence on birefringence of some parameters are simulated by full-vector finite element method. The results demonstrate that the polarization axis of the guided mode is determined by the rotation angle. When temperature is increased from 15 °C to 45 °C, the birefringence of tellurite photonic crystal fiber filled with liquid crystal gradually decreases. At the wavelength of 1.55 μm, the polarization angle of 45°, this kind of the polarization rotator have low crosstalk and shorter length of rotation. These distinguished features ensure its important applications in the integrated optical systems.

1. Introduction

Photonic crystal fiber (PCFs) constitute a special class of optical fibers [1,2], which possess numerous unusual properties such as high birefringence [3], wide single-mode wavelength [4], bend-loss edge at short wavelength [5,6], extremely large [7] or small [8] effective-core-area at single-mode region, and anomalous group-velocity dispersion at visible and near-infrared wavelengths [9,10]. Some specific properties of PCF, such as propagation and polarization properties can be easily manipulated through filling oil, polymer, or liquid crystal into their air holes. Liquid crystal (LC), an anisotropic fluid is defined as a material exhibiting some structural order even in the fluidic state. They can flow like ordinary isotropic fluids, but the rheological properties are more complex. The local orientation of LC can be described by a unit vector parallel to the direction of the average orientation of the molecules, which can be aligned by adopting proper boundary conditions to achieve a macroscopic alignment. With applying a static electric field the director's orientation can be controlled, since the liquid crystal molecules tend to align their axes along the applied external field. The main features of the LC-PCFs are that it combines the fiber properties and the variable anisotropy of LC materials. Due to the large birefringence ($\Delta n = n_e - n_o$) in infrared region, liquid crystal finds potential applications in dynamic scene projector, laser beam steering, millimeter-wave electronic phase shifter, and tunable band-gap photonic crystal fiber [11,12].

Tellurite glasses are transparent in the mid-infrared range, and have a higher n_2 than silica glass by at least one order of magnitude. Tellurite glasses have been successfully used for the development of PCFs [13,14]. Polarization rotators can be used to control the polarization states in the communication systems such as polarization switches and polarization modulators [15]. Polarization rotators based on a PCF filled with liquid crystal has been experimentally achieved. Moreover, a highly tunable polarization rotator based on soft glass liquid crystal filled PCF is proposed in [16]. In this paper, a polarization rotator based liquid crystal filled tellurite PCFs is proposed and studied. By infiltrating selectively nematic liquid crystal and adjusting the structure parameter of tellurite PCFs, a high birefringence can be achieved, which leads to a significant difference of the coupling lengths for the x- and y-polarization. The simulation results have the potential applications in optical fiber devices and optical fiber communications fields.

2. Formulations

Starting from the raw materials, high quality tellurite tubes are prepared and subsequently drawn to rods and capillaries. These are then stacked to form the desired preform, which is finally pulled

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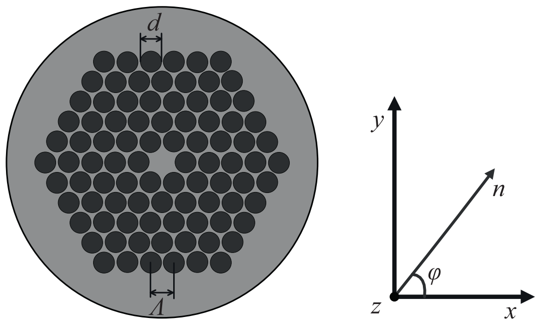

Fig. 1. Structure of the triangular lattice tellurite PCF filled with LC inclusion. The shaded region is infiltrated with liquid crystal. The right indicates the director of a nematic liquid crystal.

to tellurite PCFs. Fig. 1 shows a triangular lattice tellurite PCF filled with LC inclusion, where Λ is the pitch of the adjacent LC inclusion or air hole, d is the diameter of nine LC inclusions. The background material is TeO_2–ZnO–Li_2O–Bi_2O_3, and the refractive index of tellurite n_t is given by the Sellmeier equation

$$n_t^2(\lambda) = 1 + \sum_{i=1}^{l} \frac{A_i \lambda^2}{\lambda^2 - L_l^2} \quad (1)$$

where $A_1 = 1.67189$, $A_2 = 1.34862$, $A_3 = 0.62186$, ${L_1}^2 = 0.00046656\ \mu m^2$, ${L_2}^2 = 0.057460884\ \mu m^2$, and ${L_3}^2 = 46.72542736\ \mu m^2$ [17].

The LC inclusion has two types of refractive indices. One is the ordinary refractive index, and the other is the extraordinary refractive index. Light waves with electric fields perpendicular (or parallel) to the director of LC have ordinary (or extraordinary) refractive indices [18,19]. When the electric field is transverse direction (in x–y plane), the refractive index tensor takes the form of

$$n_r = \begin{bmatrix} n_{xx} & n_{xy} & 0 \\ n_{yx} & n_{yy} & 0 \\ 0 & 0 & n_{zz} \end{bmatrix} \quad (2)$$

where

$$\begin{aligned} n_{xx}(r) &= \left[n_e^2(r)\cos^2\varphi + n_o^2(r)\sin^2\varphi\right]^{1/2} \\ n_{xy}(r) &= n_{yx}(r) = \left[n_e^2(r)\cos\varphi\sin\varphi - n_o^2(r)\cos\varphi\sin\varphi\right]^{1/2} \\ n_{yy}(r) &= \left[n_o^2(r)\cos^2\varphi + n_e^2(r)\sin^2\varphi\right]^{1/2} \\ n_{zz}(r) &= n_o(r) \end{aligned} \quad (3)$$

where φ is the rotation angle of the director of LC. $\boldsymbol{n} = (\cos\varphi, \sin\varphi)$ is the director of LC, as shown in Fig. 1.

The LC inclusion is E7 liquid–crystal mixture, whose refractive indices are mainly determined by the molecular structures, wavelength, and temperature. In infrared region, the refractive index of E7 is given by the extend Cauchy model

$$\begin{aligned} n_e(\lambda) &\cong A_e + \frac{B_e}{\lambda^2} + \frac{C_e}{\lambda^4} \\ n_o(\lambda) &\cong A_o + \frac{B_o}{\lambda^2} + \frac{C_o}{\lambda^4} \end{aligned} \quad (4)$$

where n_e is the extraordinary refractive index and n_o the ordinary refractive index; $A_e = 1.7055$, $B_e = 0.0087\ \mu m^2$, $C_e = 0.0028\ \mu m^4$, $A_o = 1.5006$, $B_o = 0.0065\ \mu m^2$, and $C_o = 0.0004\ \mu m^4$ at temperature 15 °C; $A_e = 1.6933$, $B_e = 0.0078\ \mu m^2$, $C_e = 0.0028\ \mu m^4$, $A_o = 1.4994$, $B_o = 0.0070\ \mu m^2$, and $C_o = 0.0004\ \mu m^4$ at temperature 25 °C; $A_e = 1.\ 6761$, $B_e = 0.0091\ \mu m^2$, $C_e = 0.0025\ \mu m^4$, $A_o = 1.4987$, $B_o = 0.0071\ \mu m^2$, and $C_o = 0.0004\ \mu m^4$ at temperature 35 °C; $A_e = 1.6565$, $B_e = 0.0083\ \mu m^2$, $C_e = 0.0024\ \mu m^4$, $A_o = 1.5018$, $B_o = 0.0068\ \mu m^2$, and $C_o = 0.0006\ \mu m^4$ at temperature 45 °C.

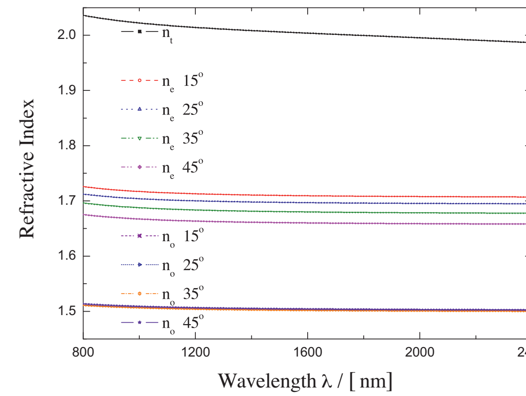

Fig. 2. The refractive index of the tellurite n_t, the ordinary refractive index n_o, and the extraordinary refractive index n_e of E7 liquid–crystal mixture.

The refractive index of the tellurite n_t material, n_e and n_o of the E7 liquid–crystal mixture at different temperature are shown in Fig. 2. It is revealed that n_t is higher than n_e and n_o, which guarantees light guiding in the tellurite PCF filled with LC inclusion is the modified total internal reflection response for light trapping within the high index core. It is also revealed from Fig. 2 that the n_e change with varying temperature.

3. Simulation results

3.1. Analysis method

A full-vector finite element method with the perfectly matched layer boundary conditions is used to analyze the birefringence and the nonlinear coefficient of tellurite PCF filled with LC inclusion [20,21].

Starting with Maxwell's curl equations, the vector equation for the electricfield vector $\boldsymbol{E}$ can be derived as:

$$\left(\nabla_i^2 + k_0^2 n_i^2 - \beta^2\right) E = 0 \quad (5)$$

where the subscript i is section number, $k_0 = 2\pi/\lambda$ is the wave number in the vacuum, λ is operation wavelength [22].

The curvilinear hybrid edge/nodal elements based on linear tangential and quadratic normal vector basis functions are adopted to realize the computational window divisions and perfectly matched layer is incorporated as the boundary condition to absorb waves out of the computational window. Applying the finite element procedure to equation (5), the following eigenvalue equation

$$[A]\left\{H\right\} = n_{\mathrm{eff}}^2 [B] \left\{H\right\} \quad (6)$$

is obtained. Where $[A]$ and $[B]$ are the global finite element matrices. The eigenvector $\{H\}$ and the eigenvalue n_{eff}^2 provide, respectively, the full vector magnetic field distribution on the cross section of PCF and the effective index of the mode.

The birefringence B, beat length L_B can be obtained using the following equations [19]

$$B(\lambda) = n_{\mathrm{eff}}^s(\lambda) - n_{\mathrm{eff}}^f(\lambda) \quad (7)$$

$$L_B(\lambda) = \frac{\lambda}{n_{\mathrm{eff}}^s(\lambda) - n_{\mathrm{eff}}^f(\lambda)} = \frac{\lambda}{B(\lambda)} \quad (8)$$

where λ is the wavelength, $n_{\mathrm{eff}}^s(\lambda)$ and $n_{\mathrm{eff}}^f(\lambda)$ are the real part of model indices (effective indices) of the two orthogonal polarization states corresponding to the slow and fast axis, respectively.