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Properties analysis of tellurite photonic crystal fiber filled with nematic liquid crystal

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ABSTRACT

We theoretically investigate the modes, birefringence, dispersion, confinement loss, nonlinear coefficient and the temperature properties of tellurite photonic crystal fiber filled with nematic liquid crystal. The birefringence caused by the high index difference between ordinary and extraordinary refractive indices of nematic liquid crystal makes it possible for single-mode single-polarization guiding. The influence of rotation angle of the director of liquid crystal on the modal properties is also demonstrated. The results demonstrate that the dispersion curve of tellurite photonic crystal fiber filled with nematic liquid crystal along fast axis is more flatten than that along slow axis the fast axis. The tellurite photonic crystal fiber filled with nematic liquid crystal has low confinement loss and high nonlinear coefficient. When temperature is increased from 15 °C to 45 °C, the birefringence of tellurite photonic crystal fiber filled with nematic liquid crystal gradually decreases and the dispersion along slow axis gradually becomes flat, which is very useful for making compact and diverse polarization-manipulating devices.

1. Introduction

Photonic crystal fiber (PCF) has attracted much attention for their complex microstructures in transverse plane and the flexible ability in designing various types of fibers [1,2]. Moreover, compared with conventional fibers, PCF has great potential in designing extraordinary characteristics of fibers, such as novel dispersion properties, single mode guidance over a wide spectral range, high birefringence, and high nonlinearity [3–5]. 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 [6–8].

Due to the large birefringence ($\Delta n = n_e - n_o$) in infrared region, nematic liquid crystal (NLC) finds potential applications in dynamic scene projector, laser beam steering, millimeter-wave electronic phase shifter, and tunable band-gap photonic crystal fiber [9–11]. NLC is an anisotropic material composed of rod-like molecules; in which the orientational order of the rod-like molecules lead to anisotropic optical properties [12]. The local orientation of NLC 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.

Tellurite glass extends the infrared transparency range, and has a higher n_2 than silica glass by at least one order of magnitude [13,14]. For silica-based PCF filled with NLC inclusion, the light guiding is photonic bandgap effect, which relies on the coherent backscattering of light into the core. However, light guiding in the tellurite PCF filled with NLC inclusion is the modified total internal reflection. In this paper, we theoretically analyze the properties of the tellurite PCF filled with NLC inclusion. By full-vector finite element method, the modes, birefringence, dispersion and the temperature properties of the tellurite PCF filled with NLC inclusion are investigated. The simulation results have the potential applications in nonlinear fiber optics and optical fiber sensing fields.

2. Formulations

Fig. 1 shows the cross section of the triangular lattice the tellurite PCF filled with NLC inclusion sandwiched between two electrodes, where d and Λ are the diameter of each NLC inclusion and the pitch

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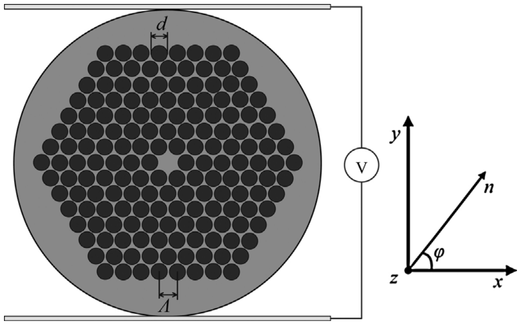

Fig. 1. Cross section of the triangular lattice the tellurite PCF filled with NLC inclusion sandwiched between two electrodes. The shaded region is infiltrated with liquid crystal. The right indicates the director of a nematic liquid crystal.

of the adjacent NLC inclusion, respectively. 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

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

where $A_1 = 1.67189$, $A_2 = 1.34862$, $A_3 = 0.62186$, ${L_1}^2 = 0.00046656$, ${L_2}^2 = 0.057460884$, and ${L_3}^2 = 46.72542736$ [15].

The NLC inclusion has two types of refractive indices. One is the ordinary refractive index n_o, and the other is the extraordinary refractive index n_e. Light waves with electric fields perpendicular (or parallel) to the director of NLC have ordinary (or extraordinary) refractive indices [16,17]. When the electric field is transverse direction (in x–y plane), the refractive index tensor takes the form of

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

where

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

where φ is the rotation angle of the director of NLC and it can be controlled by the external static electric field. $\boldsymbol{n} = (\cos\varphi, \sin\varphi)$ is the director of NLC, as shown in Fig. 1.

For properties analysing, we assume the rotation angle of the director φ as 0 or $\pi/2$, which gives rise to a simplification of $n_r = \text{diag}[n_e\ n_o\ n_o]$ for $\varphi = 0$, and $n_r = \text{diag}[n_o\ n_e\ n_o]$ for $\varphi = \pi/2$.

The NLC 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 [12]

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

where $A_e = 1.7055$, $B_e = 0.0087$, $C_e = 0.0028$, $A_o = 1.5006$, $B_o = 0.0065$, and $C_o = 0.0004$ at temperature 15 °C; $A_e = 1.6933$, $B_e = 0.0078$, $C_e = 0.0028$, $A_o = 1.4994$, $B_o = 0.0070$, and $C_o = 0.0004$ at temperature 25 °C; $A_e = 1.\ 6761$, $B_e = 0.0091$, $C_e = 0.0025$, $A_o = 1.4987$, $B_o = 0.0071$, and $C_o = 0.0004$ at temperature 35 °C; $A_e = 1.6565$, $B_e = 0.0083$, $C_e = 0.0024$, $A_o = 1.5018$, $B_o = 0.0068$, and $C_o = 0.0006$ at temperature 45 °C.

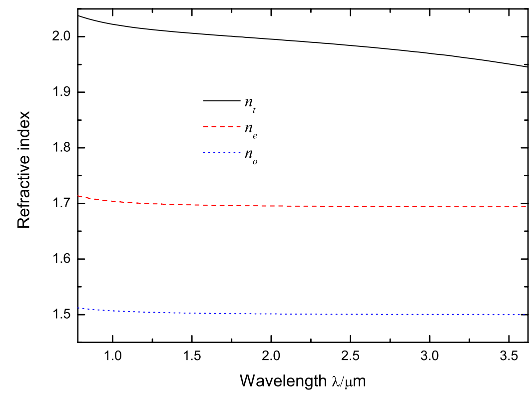

Fig. 2. The refractive index of the tellurite n_t, the ordinary refractive index n_o, and the extraordinary refractive index n_e of E7 liquid–crystal mixture.

Fig. 2 shows 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 at temperature 25 °C. It can be seen that the refractive index of the tellurite n_t is bigger than the ordinary refractive index n_o and the extraordinary refractive index n_e. Although the ordinary refractive index n_o and the extraordinary refractive index n_e of E7 liquid–crystal mixture change with varying temperature, they are always less than the refractive index of the background materials. So light guiding in the tellurite PCF filled with NLC inclusion is the modified total internal reflection response for light trapping within the core.

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 dispersion properties of the tellurite PCF filled with NLC inclusion.

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

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

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

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 [18,19]. Applying the finite element procedure to Eq. (5), the following eigenvalue equation

$$[A]\left\{H\right\} = n_{\text{eff}}^2 [B]\left\{H\right\} \tag{6}$$

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 degree of modal birefringence B of PCF is defined by

$$B = n_{\text{eff}}^s - n_{\text{eff}}^f \tag{7}$$

where n_{eff}^s and n_{eff}^f are model indices (effective indices) of the two orthogonal polarization states corresponding to the slow and fast axis, respectively.