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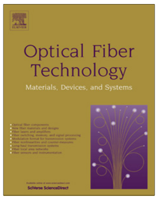

Regular Articles

Thermal tunability of photonic bandgaps in liquid crystal filled polymer photonic crystal fiber

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ABSTRACT

A highly tunable bandgap-guiding polymer photonic crystal fiber is designed by infiltrating the cladding air holes with liquid crystal 5CB. Structural parameter dependence and thermal tunability of the photonic bandgaps, mode properties and confinement losses of the designed fiber are investigated. Bandgaps red shift as the temperature goes up. Average thermal tuning sensitivity of 30.9 nm/°C and 20.6 nm/°C is achieved around room temperature for the first and second photonic bandgap, respectively. Our results provide theoretical references for applications of polymer photonic crystal fiber in sensing and tunable fiber-optic devices.

1. Introduction

Photonic crystal fibers (PCFs), with a periodic microstructure of air holes running along the axial direction in the cladding, have received particular interest due to their novel structure and properties [1]. The presence of the microstructured air holes around the fiber core allows more degrees of freedom in design than conventional fiber design [2–4]. Furthermore, an index guiding PCF can be converted to a photonic bandgap (PBG) guiding PCF by filling the cladding air holes with high-index materials, such as high-index fluids or Liquid Crystals (LCs), which was firstly demonstrated in Ref. [5]. The attractive properties of nematic LCs, i.e. high thermal, electrical and magnetic tunability, make them more suitable for filling material of tunable devices. LC-PCF based tunable fiber devices, such as threshold switching, tunable birefringence controller and tunable filter, were reported in [6,7] and references therein. The effects of LC alignment on bandgap formation and polarization dependent guiding were theoretically investigated by Sun et al. [8] and Ren et al. [9], respectively. However, most work to date concentrates on LC filled silica PCFs.

In recent years, polymer photonic crystal fibers (pPCFs) [10] have attracted much attention on account of the lower processing temperature, variety of processing methods and polymer materials compared with silica PCFs. Yuan et al. demonstrated for the first time the photonic bandgap effect and the thermal tunability of bandgaps in pPCFs filled with two kinds of nematic LCs, E7 ($T_c = 58$ °C) and MDA-00-1444 ($T_c = 98.5$ °C), respectively [11]. However, the insertion losses were higher than those of LC filled silica PCFs as their designed LC pPCFs has only three rings of air holes. Hu et al. analyzed thermal influence on the bandgap properties of silica PCF filled with LC of 5CB type [12]. But material dispersion of 5CB was neglected, which could cause discrepancy with experiments, especially at short wavelength region.

In this paper, a thermally tunable bandgap guiding pPCF is designed by infiltrating the cladding air holes with 5CB (4-cyano-4-n-pentylbiphenyl), which has lower clearing temperature ($T_c = 35.3$ °C) and larger temperature gradient of the ordinary refractive index (dn_0/dT) at room temperature compared with E7 and MDA-00-1444 [11]. Structural dependence and thermal tunability of the PBGs, mode properties and confinement loss of the designed LC-filled pPCF (LC-pPCF) are studied by using the powerful full-vector finite element method (FEM) [13].

2. LC-pPCF design

2.1. Fiber structure design

Cross-section of the designed LC-pPCF is shown in Fig. 1. We construct the fiber cladding by arranging circular holes (with hole diameter d) in triangular lattice pattern (with lattice constant Λ) in the background of Polymethyl methacrylate (PMMA). The cladding

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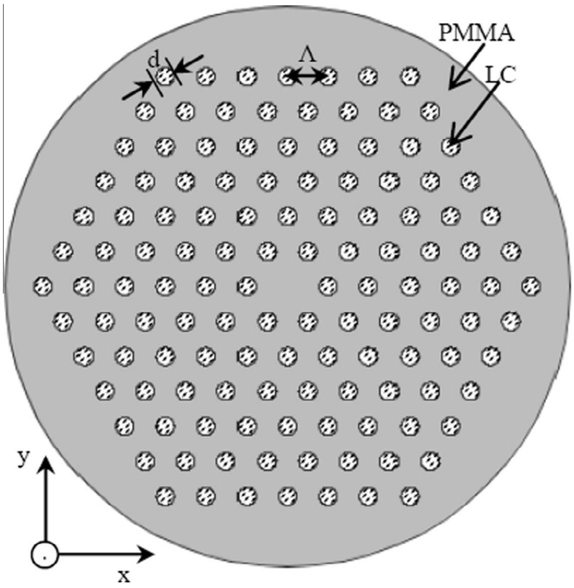

Fig. 1. Cross section of the LC-pPCF.

holes are infiltrated with LC of 5CB type. As 5CB has higher refractive indices [14–16] ($n_o = 1.5361$, $n_e = 1.7124$ at 589 nm, 25.4 °C) than PMMA ($n = 1.49$), the effective index of fiber cladding is higher than that of the core area. Propagation mechanism of the designed LC-pPCF fiber is based on PBG effect. However, pPCF without LC filling guides light with improved total internal reflection (TIR) effect, abbreviated as TIR-pPCF.

Several factors should be considered to design the suitable fiber structural parameters. Firstly, hole diameter to pitch ratio (d/Λ) should be less than 0.45 in order to obtain endlessly single-mode behavior for the unfilled TIR-PCF [17]. Secondly, position of the effective PBG should be in consistent with the low loss window of core material [10,11]. Structural parameter dependence of the PBG position and its scaling property will be discussed in Section 3.1. Thirdly, more than three rings of cladding holes filled with high-index material are necessary for better mode confinement, especially for the low refractive index contrast solid core photonic bandgap fibers [18]. Six rings of cladding holes are necessary to obtain confinement loss less than 0.01 dB/m for the designed LC-pPCF (see Section 3.4).

In our previous papers, a series of theoretical and experimental investigations have been carried out for the fabrication and application of pPCFs [19–21]. Both high-index solid filled [20] and high-index liquid [21] filled pPCFs with 13 rings of air holes arranged in triangular lattice have been fabricated by the extrusion-stretching techniques as reported in Ref. [22]. The relatively simple architecture of the designed LC-pPCF in this paper will be fabricated by the same method in our consequent researches.

2.2. Refractive indices of LC

Thermally tunable PCFs (devices) utilize the thermal-induced refractive index change of nematic LCs. Thermal tunability of the LC-PCF is mainly determined by the dn_0/dT of the LC [11]. Tuning sensitivity is increasing with temperature approaching the clearing temperature of LC, due to an increasing temperature gradient of n_o. For thermally tunable LC-PCFs with resistive or optical pump-induced heating, it is desirable to have a high tuning sensitivity at approximately room temperature in order to decrease the power consumption and ease handling and packaging [6].

The commercial LC of 5CB type, well-known for its simple structure, is selected as the filling material of our designed LC-pPCF due to its nematic property (within 22.0–35.3 °C), low T_c and large dn_0/dT around room temperature [23]. Besides, the wavelength- and temperature-dependent refractive indices for the 5CB have been widely studied, providing us both reliable experimental data and theoretical models [14–16].

The variation of refractive indices with temperature for 5CB is shown in Fig. 2. The wavelength- and temperature-dependence of refractive indices can be expressed by the extended Cauchy equation [15], which can be extrapolated to infrared [16]:

$$n_{o/e}(T,\lambda) = A_{o/e}(T) + \frac{B_{o/e}(T)}{\lambda^2} + \frac{C_{o/e}(T)}{\lambda^4} \tag{1}$$

where $A_{o/e}$, $B_{o/e}$, and $C_{o/e}$ are the Cauchy coefficients of 5CB. These parameters used in the simulation are taken from Ref. [15]. For convenience, they are listed in Table 1.

Experimental results of Yuan et al. [11] and Alkeskjold et al. [24] show that the director of LC filled in the cladding holes PCF is parallel to the fiber axis when temperature is below T_c without external electric (or magnetic) static field across the fiber. Dielectric tensor of the nematic LC takes the form $\varepsilon_{LC} = \mathrm{diag}(n_o^2, n_o^2, n_e^2)$. The ordinary indices n_o of LC predominantly determine the spectral features, and the x- and y-polarized fundamental modes are degenerate [8,9]. This kind of LC alignment can theoretically be exhibited under the influence of the appropriate homeotropic anchoring conditions.

3. Results and discussion

A systematic investigation of the PBGs and guided modes properties of the designed LC-pPCF is carried out by using the commercially available FEM solver COMSOL. In this simulation, the dielectric properties of LC are directly included through the extended Cauchy equation [15].

3.1. Structural parameter dependence of PBGs

PBGs of infinitely cladding structure (periodic triangular lattice of LC inclusions in a background of PMMA) are calculated and presented in Fig. 3 at $T = 25.1$ °C. For certain structural parameters, areas between the corresponding boundary lines represent PBGs. There exist two effective PBGs as the green shading regions shown. The horizontal core line corresponds to refractive index of PMMA. Fig. 3(a) shows PBGs for cladding structure with fixed $d/\Lambda = 0.44$

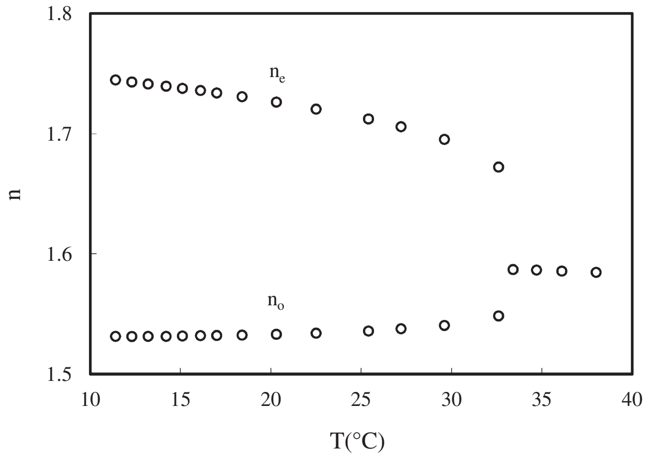

Fig. 2. Temperature dependent refractive indices of 5CB at 589 nm [14].