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A novel ultra-broadband single polarization single mode photonic crystal fiber

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ABSTRACT

The concept of employing a central hole infiltrated with nematic liquid crystal (NLC) and two additional air holes in the core region is exploited to obtain an ultra-broadband single polarization single mode photonic crystal fiber (SPSM-PCF). The effects of structural parameters on the SPSM operation are studied using the full-vectorial finite element method. Numerical results show that the proposed structure can attain the SPSM operation bandwidth of 1610 nm (from 1.51 to 3.12 μm) with confinement loss lower than 0.01 dB/km. The SPSM operation range can also be widely tuned to shorter wavelengths by adjusting the structure parameters. And meanwhile, a broad dispersion-flattened SPSM PCF is also obtained around the communication wavelength. Moreover, the dual-core SPSM PCF has also been investigated, enabling potential applications in the wavelength splitter of 1.31 and 1.55 μm bands at a short fiber length of 1.629 mm with SPSM operation.

1. Introduction

Photonic crystal fibers (PCFs) have been intensively studied due to their unique properties such as high birefringence, endlessly sing-mode operation, low confinement loss, ultra-flattened dispersion [1–3]. Among these features, polarization-maintaining (PM) PCFs can be easily achieved through exploiting the high birefringence property of the PCF, which are used for more extensive applications for the coherent optical communication systems and fiber sensor systems [4]. However, polarization cross talk and polarization mode dispersion will still exist and affect the stability of optical devices and transmission systems. To eliminate the adverse effects, single polarization single mode (SPSM) PCFs which guide only one polarization state of the fundamental mode have been presented [5,6], which are desirable for some polarization-sensitive applications such as optical gyroscopes, optical modulators, high-power fiber laser, and current sensors.

There are two design principles to realize SPSM PCFs. The first one is through index-matching coupling [7], which can eliminate the unwanted polarized mode through its resonance coupling to the cladding defect modes. One the other hand, the second one is through exploiting the asymmetry in the fiber core and/or cladding region to form a large effective index difference between x- and y-polarized fundamental modes, polarization cutoff occurs when the effective index for one polarization of the fundamental modes falls below that of the fundamental space-filling mode (FSM) [8]. The high birefringence is essential to realize SPSM operation, especially for the aforementioned second approach. Several kinds of SPSM PCF structures have been reported by many research groups. Saitoh et al. first proposed a SPSM operation with a confinement loss less than 0.1 dB/km from 1.48 to 1.6 μm based on a triangular lattice PCF with circular air-holes [5]. Much wider SPSM-PCF design can be achieved through exploiting elliptical air-holes and rectangular-lattice [9–12], however, the complicated arrangement make fabrication challenging. In addition, some liquids [13] or liquid crystals (LCs) [14] are also introduced in the silica based PCF to achieve SPSM operation, however, the bandwidths of SPSM operation in [13,14] are not enough large.

In this paper, we propose an ultra-broadband SPSM PCF structure with the core region containing a line array of two additional air holes and a NLC central hole. A selective filling technique has been successfully applied in the liquid crystal infiltration of the PCF holes [15]. The effects of the structure parameters on the SPSM operation are analyzed using the full-vectorial finite element method (FEM) [16]. The proposed PCF with only two different hole sizes can achieve a SPSM operation bandwidth of 1610 nm (from 1.51 to 3.12 μm) with confinement loss lower than 0.01 dB/km. The SPSM band can also be widely tuned to shorter wavelengths by varying the parameters of two additional air holes and a NLC central hole in the fiber core region. Also, the single polarization operation can be inverted with the rotation angle changing from 90° to 0° and a dispersion-flattened SPSM PCF is also achieved. Moreover, the dual-core SPSM PCF are further studied,

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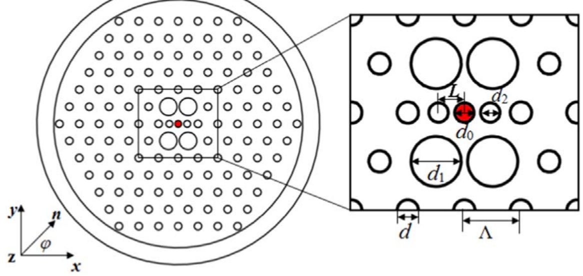

Fig. 1. Cross section of the proposed SPSM PCF.

which can be employed in wavelength splitting of 1.31 and 1.55 µm bands at a short fiber length of 1.639 mm with SPSM operation.

2. Model and theory

The cross section of the proposed broad SPSM PCF is shown in Fig. 1, where a red central hole of diameter d_0 is infiltrated with a NLC of type E7. Two identical air holes of diameter d_2 placed on the x-axis with a distance L from the NLC central hole are introduced in the fiber core region to tune the SPSM operation range. The cladding structure is composed of six layers of air holes in a hexagonal lattice, and the lattice constant of the structure is denoted by Λ. Four enlarged air holes near the fiber core with a normalized diameter as big as d_1/Λ=0.95 are used to produce a remarkable anisotropy. The diameter of the rest air holes in the cladding is denoted by d.

The background material is pure silica whose material dispersion is given by the Sellmeier equation [17]. The refractive indices of the NLC of type E7 anisotropic material considered in the proposed structure are characterized by ordinary index n_o and extraordinary index n_e, which can be modeled by the extend Cauchy equation from the visible to the infrared [18]. The n_o and n_e of the E7 material are calculated using the Cauchy models defined as [18].

$$n_e = A_e + B_e/\lambda^2 + C_e/\lambda^4 \quad (1)$$

$$n_o = A_o + B_o/\lambda^2 + C_o/\lambda^4 \quad (2)$$

where the Cauchy coefficients of A_e, B_e, C_e, A_o, B_o, and C_o are sensitive to the temperature of T. At T=25 °C, the Cauchy coefficients are A_e=1.6933, B_e=0.0078 µm^2, C_e=0.0028 µm^4, A_o=1.4994, B_o=0.007 µm^2, and C_o=0.0004 µm^4. The direction of the NLC can be controlled through the external static electric field, and the uniform alignment of the NLC director with constant rotation angle can be realized by the uniform external electric field line distribution on the fiber cross section as reported in [19,20]. When NLCs molecular are aligned along y-axis (φ=90°), the permittivity tensor ε_r of the E7 material has the diagonal of [n^2_o, n^2_e, n^2_o]; when they are aligned along x-axis (φ=0°), ε_r has the diagonal of [n^2_e, n^2_0, n^2_o] [21]. As reported by Li et al. [18] the birefringence ($\triangle n$=n_e-n_o) of E7 is increased slightly with the increasing of wavelength in the visible region, while in the near-infrared and mid-infrared region, the birefringence of E7 is approximately constant.

The FEM is used to accurately find complex propagation constants of the guided modes and analyze the guiding characteristics of the proposed PCF in the paper. An anisotropic Perfectly Matched Layer (PML) added in the outmost layer which is used for absorbing the radiation energy, a scatting boundary condition outside with PML region is used to reduce the reflections. The confinement loss can be evaluated by the following equation [12]

$$\alpha = 8.686 \times \frac{2\pi}{\lambda} \times \mathrm{Im}(n_{eff}) \times 10^9 \quad (3)$$

Where Im(n_{eff}) is the imaginary part of the effective indices. λ is the wavelength of light. The units of the confinement loss and the wavelength are dB/km and micrometer, respectively. The wavelength dependent refractive indices of optical material (silica) and the NLC are calculated using Sellmeier equation and Cauchy models respectively. Therefore, the material dispersion is directly included in the simulation. The dispersion (D) is derived from [3]

$$D = -\frac{\lambda}{c}\frac{d^2 Re\,[n_{eff}]}{d\lambda^2} \quad (4)$$

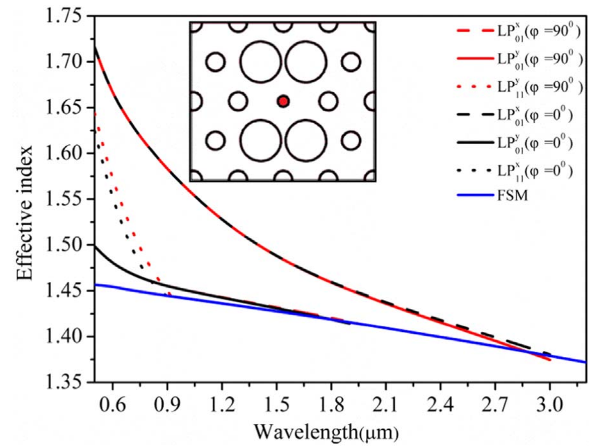

Fig. 2. The effective indices versus wavelength for the LP^x_{01}, $LP^y{}_{01}$ modes, the second-order modes, together with the FSM at φ=90° and φ=0°, respectively. The inset is a cross section of the proposed PCF with only one NLC central hole.

3. Design and optimization of SPSM-PCF

Initially, we consider the PCF with only one central NLC hole in the fiber core shown in an inset of Fig. 2. Fig. 2 shows the effective indices of the horizontally polarized (x-polarized) and vertically polarized (y-polarized) fundamental modes and the second-order mode as a function of wavelength for the PCF with Λ=3.5 µm, d=1.4 µm, d_1/Λ=0.95, d_0=0.8 µm, T=25 °C at φ=90° and φ=0°, respectively. The effective index of FSM is also displayed in Fig. 2, which is calculated by applying a unit cell of the periodic infinite cladding structure [8]. The x- and y-polarized FSMs are considered to be degenerate due to the sixfold symmetry of the cladding structure. The effective index of the second-order mode is also considered to confirm single mode operation. The numerical simulation shows that the x-polarized second-order ($LP^x{}_{11}$) and the y-polarized second-order ($LP^y{}_{11}$) modes have the highest effective index among all the higher order modes at φ=0°and φ=90°, respectively. As seen in Fig. 2, the cutoff wavelengths of the second order modes are shorter than those of two orthogonal fundamental modes. Therefore, the higher-order modes are not excited in this single polarization region. It is also evident from Fig. 2 that the effective index of the x-polarized fundamental ($LP^x{}_{01}$) mode is smaller than that of y-polarized fundamental ($LP^y{}_{01}$) mode due to the fact that ε_{xx} is smaller than ε_{yy} at φ=90°. Within the SPSM operation range from 1.95 to 2.95 µm, only the $LP^y{}_{01}$ mode is guided at φ=90°. Additionally, a broad SPSM operation range from 1.95 to 3 µm where only the $LP^x{}_{01}$ mode is guided at φ=0° as shown in Fig. 2. It can also be observed that the effective index of the $LP^x{}_{01}$ mode at φ=90° is almost the same as that of the $LP^y{}_{01}$ mode at φ=0°, and the effective index of the $LP^y{}_{01}$ mode at φ=90° is almost the same as that of the $LP^x{}_{01}$ mode at φ=0°. This is because ε_{xx} at φ=90° is equal to ε_{yy} at φ=0°. In addition, ε_{yy} at φ=90° is equal to ε_{xx} at φ=0°. Therefore, the PCF structure parameters have similar effect on the SPSM operation at φ=90°and φ=0° respectively. The infiltration of the NLC increases the birefringence between the two fundamental polarized modes and further broadens the bandwidth of the SPSM operation in the proposed design.

In order to tune the SPSM band to shorter wavelengths and further