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Broadband tunable single-mode single-polarization fiber

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ABSTRACT

Traditional single-mode single-polarization (SMSP) fibers are very difficult to produce and their working bandwidths are narrow. So a broadband tunable SMSP fiber device in this paper is designed. Using refractive index-matching coupling method, the fiber can achieve SMSP transmission from 1.25 μm to 1.6 μm. The adjusting range is about 350 nm. It is worth noting that its working wavelength covers 1310 nm and 1550 nm, which are two important communication windows. In addition, by adjusting the refractive index of the fillers, the device can realize the unique switch function, which has great significance for the establishment and application of optical fiber network.

1. Introduction

Birefringent photonic crystal fiber has been widely used in optical fiber sensing, precise optical measurement and optical fiber communication systems. Compared with the conventional birefringent fiber, it has higher mode birefringence, which is usually about 10^{-3} magnitude [1]. In a recent report, the mode birefringence of the fiber has already reached 0.05 [2]. The birefringence become bigger and bigger because of the structural parameters of photonic crystal fiber that are easy to be adjusted. By changing the size and the shape of the air holes or adding the asymmetric structure, it can realize the separation between two polarization modes. However, although the value of the birefringence is increased quickly, the polarization maintaining ability did not get corresponding improvement. Under the influence of polarization mode dispersion and polarization crosstalk, two polarization modes cannot be transmitted for a long distance. So far, the most effective way to solve this problem is to use SMSP fiber, which always transmits a kind of polarization mode in the optical fiber.

Actually, it is not very difficult to realize SMSP transmission in photonic crystal fiber. It is reported that only adjusting the structure of high birefringence fiber slightly can make the fiber achieve SMSP transmission at specific wavelengths. Usually, there are two methods: (1) one is based on varying the scale of the air holes and pitch between them [3,4] or changing the shape of the air holes [5] to make the two polarization modes have different cutoff wavelengths. Over the region between two cutoff values, only the high refractive index mode can be transmitted along this fiber core; (2) another method uses refractive index matching coupling method, which can suppress the unwanted polarization mode by introducing refractive index-matching cladding defect waveguides to achieve SPSM in high birefringent photonic crystal fiber (HB-PCF) [6,7]. Compared with the method (1), the fabrication process of the fiber becomes simple and does not damage the transverse structure of the fiber. So it is a hot research spot at now. Chen et al. [8] used this method to design a novel SMSP fiber (the fiber core is asymmetric structure) and made two polarization modes of incident light wave separate during transmission. So the two polarization modes have different dispersion curves. When the dispersion curve of one of the polarization mode intersects with that of the defect mode in the cladding, strong coupling effect will generate between them and the loss of corresponding mode increases rapidly. After some distance, the corresponding polarization mode will be eliminated.

Although there are some reports about SMSP transmission in optical fiber, the problem of narrow work bandwidth always exist. In particular, the SMSP fiber designed by the refractive index matching method can only work at a single wavelength. This reduces the application value of the device in optical networks. In order to solve these problems, using the electrical properties of liquid crystal (LC) molecules, a broadband tunable SMSP fiber device is designed here. The designed fiber can keep SMSP transmission in 350 nm bandwidth range. Especially, it also can be used as a switch in some special wavelength range, which is of

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great significance for the establishment of the optical fiber network.

2. The electrical properties of liquid crystal molecules

Nematic liquid crystal is a kind of anisotropic material, which consists of rod-shaped molecules in a certain order. The arrangement of the molecules centers has ordering. In the vertical direction, molecules arrange equally. But in other directions, they present no regularity. This makes that the physical constant (such as refractive index, magnetic susceptibility, electrical conductivity) in the long axis direction of molecular is different to that in the shot direction. In this paper, 5CB is selected as a filled material, which has less loss in communication band. So the absorption loss of the material can be ignored. The liquid crystal has two kinds of dielectric constants generally. One is the ordinary dielectric constant $\varepsilon_o = 2.27$, and the other is the extraordinary dielectric constant $\varepsilon_e = 2.89$. Light waves with electric fields perpendicular and parallel to the direction of the LC have ordinary and extraordinary refractive indices, respectively. When electric field is applied transversely, the dielectric constant tensor takes the form of [9,10]

$$\varepsilon_r = \begin{pmatrix} \varepsilon_{xx} & \varepsilon_{xy} & 0 \\ \varepsilon_{yx} & \varepsilon_{yy} & 0 \\ 0 & 0 & \varepsilon_{zz} \end{pmatrix} \tag{1}$$

$$\varepsilon_{xx} = \varepsilon_o \sin^2\phi + \varepsilon_e \cos^2\phi. \tag{2}$$

$$\varepsilon_{yy} = \varepsilon_e \sin^2\phi + \varepsilon_o \cos^2\phi. \tag{3}$$

$$\varepsilon_{xy} = \varepsilon_{yx} = [\varepsilon_e - \varepsilon_o]\sin\phi\cos\phi. \tag{4}$$

$$\varepsilon_{zz} = \varepsilon_o. \tag{5}$$

ϕ is the rotation angle of the LC molecules, which can be controlled by the external electric field. So, in order to adjust the refractive index of liquid crystal, we can add electrodes outside of the fiber. LC molecules are very sensitive to the change of external electric field. Even the small variant of electric field can change its rotation angle [11]. Fig. 1 shows the rotation angle of the LC molecules as a function of voltage. When there is no external electric field, the directions of LC molecules keep perpendicular to the electrodes. In order to ensure that, before filling LC to the fiber, the surfaces of the air holes need pretreatment. Usually, injecting some polyimide to the air holes is a method because it can be anchored to the LC molecules. As the photonic crystal fiber has a certain length, anchor effect on the LC molecules cannot make all of the LC molecules arrange in our desired direction. However, ϕ is a unit vector in the direction of the average orientation of the molecules. So the inconsistency has small influence on the calculation. In the following discussion, the alignment of the direction is assumed to be uniform within the holes for simplified calculation. With the voltage varying from low to high, the rotation angle increases quickly. While the voltage increases to a certain degree, the change of rotation angle trends to be flat. In this case, the direction of the LC molecules is parallel to the electrodes. So we can believe that the applied electric field can change the refractive index of liquid crystal.

3. The structure design of the fiber

Fig. 2 shows the structure of the designed SMSP fiber. Two symmetrical holes are added in the fiber core to separate the transmission modes and increase the birefringence effect. The diameter of large hole $d_1 = 5.52$ μm is slightly greater than that in the cladding $d_2 = 4.6$ μm. The other air holes have the same size with hole diameter $d_3 = 2.3$ μm and spacing $\Lambda = 4.6$ μm. In order to achieve the tuning function, the LC (refractive index range from 1.5 to 1.7) is injected to the defects in the cladding. On the outside of the fiber, there are two electrodes, which can provide applied electric field.

The refractive index of traditional quartz optical fiber is about 1.45, which has large gap to LC. It is difficult to meet the refractive index matching for the mode in the fiber core and in the defect. But with the improving of the manufacturing technology for optical fiber, a lot of special optical fibers appear. Mingling sulfur to pure silicon can effectively increase the refractive index of the fiber material, whose refractive index is 1.55. In addition, polymer materials also can be used to fabricate high refractive index fiber such as PMMA (the refractive index is 1.52) and PC (the refractive index is from 1.42 to 1.69).

In order to study the coupling mechanism of the SMSP fiber, the designed optical fiber can be regarded as a combination of a solid core fiber (SC-PCF) and a HB-PCF. Their structures are shown in Fig. 3(a) and (b). They have the same cladding and parameter with difference in fiber core.

Fig. 4 gives the mode dispersion curves in cladding defects and

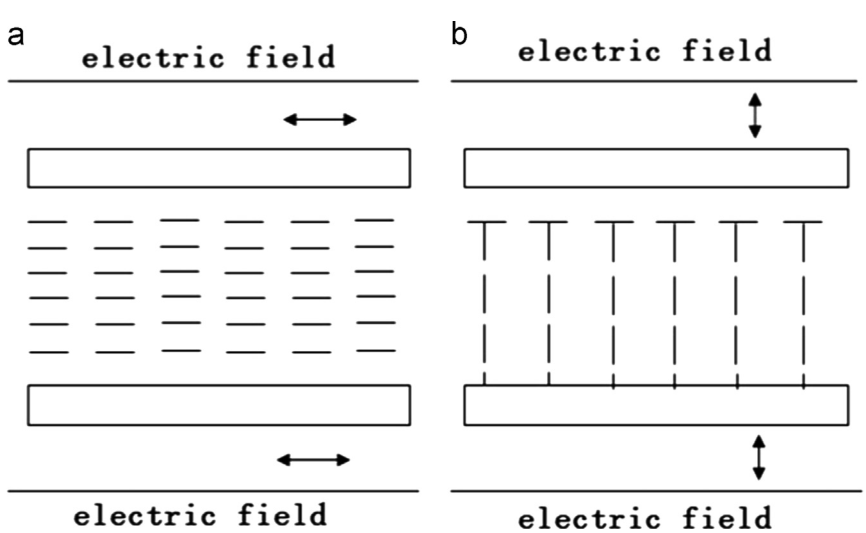

Fig. 1. The arrangement of LC molecules when (a) $\phi = 0°$ and (b) $\phi = 90°$.