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Voltage influence on propagation characteristics of liquid crystal photonic crystal fiber of terahertz wave

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This paper presents a novel structure of photonic crystal fiber (PCF). Using the finite element method, a new type of LC PCF terahertz waveguide by voltage modulation is designed which is based on that the holes of PCF filled with nematic LC 5CB. We use COMSOL and MATLAB to simulate and calculate the parameters of PCF of different structures under *THz* wave band. We made PCF have continuously tunable sensing properties without changing its structure. It provides great convenience for the practical application.

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1. Introduction

Since the periodic structure of refractive index of the PCF can control the motion of photons freely, it makes PCF possess many more attractive features than electron crystal materials. So it gives us a lot of room for designing and constructing. It injects a new impetus to the development and application of optical communication technology. PCF has become a big hot spot in photoelectron research in recent years [1]. *THz* wave is electromagnetic waves whose frequency is in the range of 0.1*THz*-10*THz,* locating between the microwave and infrared bands. There are overlap between long wavelength band and millimeter wave, between short wavelength band and infrared band. It is the link of macroscopic electronics and microscopic photonics for its special position. PCF applied in *THz* bands has many advantages such as easy preparation, because its size is in the millimeters magnitude [2-3].

In 2002, Bise, as well as other scientists, was the first to propose program and carry out the research. They tried to obtain photonic band gap (PBG) PCF by filling the total internal reflection PCF with the high refractive index materials [4-5]. The reaction of LC's refractive index to the change of the external electric field is more sensitive than others, so we can infiltrate the air holes of PCF with LC selectively. Then we adjust the parameters of PCF by changing the voltage of applied electric field [6].

2. Voltage characteristic of the LC refractive index

LC, also called the fourth state of substance, is an intermediate state between liquid and crystal. A liquid crystal has both the liquidity and the crystal-like orderliness. It likes liquid in terms of mechanical properties, while it also likes crystal in terms of optical properties. So we call it liquid crystal [7].

In this paper, we use nematic LC 5CB. We change the LC's refractive index by changing the external electric field. When there is no applied electric field, the LC molecules are similar to the uniaxial crystal. The direction of Z axis is consistent with the direction of LC molecular alignment, as shown in Fig. 1. At this point, it's equivalent that light spreads in the isotropic material, so the transmitted light is ordinary light and the refractive index of LC is n_o. When the applied voltage is greater than the threshold voltage, the LC molecules will begin to spin. The angle between the direction of LC molecules' long axis and the direction of PCF axis is θ, as shown in Fig. 2. It's similar as that light spreads in the anisotropic medium. In the process of voltage changing, the refractive index of the polarized light in X axis direction will keep unchanged. The refractive index of the polarized light in Y axis direction will change with the impressed voltage [8-9].

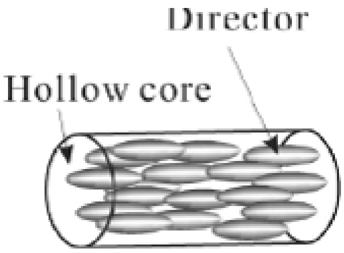

Fig.1. The orientation of the liquid crystal molecule, if E=0.

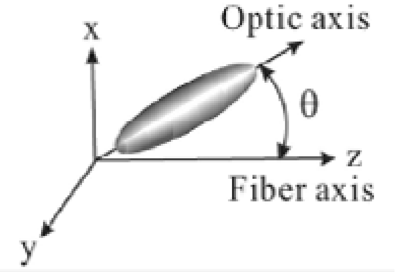

Fig.2. The orientation of the liquid crystal molecules, if E≠0.

The polarized refractive index of LC molecules in the direction along the X-axis and Y-axis can be obtained by the following formula:

$$n_x = n_0 \tag{1}$$

$$n_y = \left(\frac{sin^2\theta}{n_e{}^2} + \frac{cos^2\theta}{n_o{}^2}\right)^{-\frac{1}{2}} \tag{2}$$

The refractive index of extraordinary light and ordinary light of LC 5CB at 25°C are around 1.77 and 1.58 in the frequency range of 0.2*THz*–1.0 *THz*, respectively [10].

The θ is determined by:

$$\theta = \begin{cases} 0, E_{eff} \le E_c \\ \frac{\pi}{2} - 2\,tan^{-1}\left[exp\left(-\frac{E_{eff}-E_c}{30E_c}\right)\right], E_{eff} > E_c \end{cases} \tag{3}$$

The E_{eff} is the effective voltage, which interacts with LC molecules to control molecular sorting. E_c is the threshold voltage, which is only related to the LC molecules themself.

3. The results of numerical simulation and analysis

We use polyethylene as a material of PCF, which can be easily obtained. The refractive index of this material is 1.5. We choose the structure shown as Fig. 3. We fill the marked air holes with LC 5CB. The radius of the cladding holes are 0.3mm, 0.4mm, 0.5mm, 0.6mm respectively. The air hole spacing in the cladding is 1.25mm. The input frequency is 0.6*THz*.

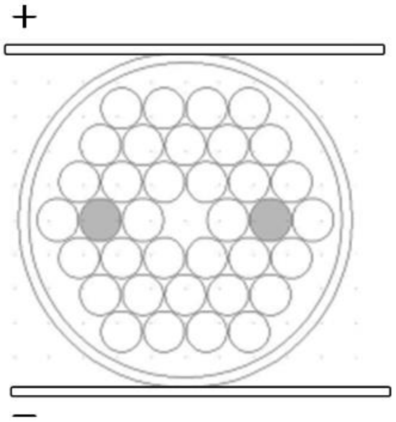

Fig.3. The nematic LC schematic diagram of filling.

3.1. Voltage characteristic of effective refractive index

The effective refractive index is an important parameter of PCF. It is closely related to other characteristics of the PCF such as dispersion. Using COMSOL Multiphysics, we can directly acquire PCF’s effective refractive index in different modes. Fig.4 shows the curve of the fundamental mode effective refractive index (n_{eff}) varying with impressed voltage.

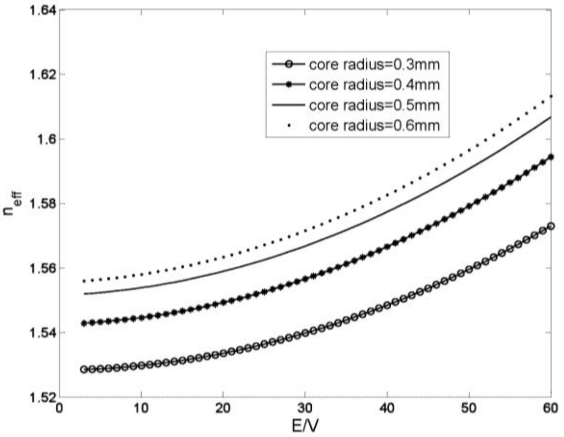

Fig.4. The basic mode effective index of different aperture radius changes with the voltage.

As Fig. 4 shows, at the same applied voltage, when the holes' center distance keep unchanged while the pore radius increases, n_{eff} increases more and more slowly. When the pore radius is constant, n_{eff} is proportional to the applied voltage. And the greater the voltage is, the faster the n_{eff} increases. At the same pore radius, n_{eff} becomes bigger when the applied voltage grows greater. Meanwhile, the n_{eff} of four different structures do not overlap nor intersect, and they almost have the same growth trend.

3.2. Voltage characteristic of normalized frequency

The normalized frequency of PCF has connection with the input frequency, the radius of the air holes, the core effective refractive index and the cladding effective refractive index. It is determined by the equation below:

$$V_{eff} = \frac{2\pi R}{\lambda}\left(n_{core}^2 - n_{clad}^2\right)^{\frac{1}{2}} \qquad (4)$$

In the equation, we define $V_{eff} < 2.55$ as the cut-off frequency of the second order mode. The normalized frequency of PCF filled with LC varies with the applied voltage. The curve is shown in Fig. 5.

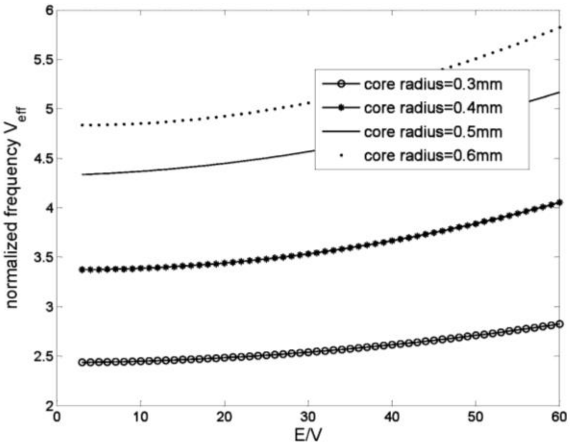

Fig.5 Normalized frequency of PCF filled with LC versus voltage for different structures.

It can be seen that the single-mode transmission can occur only when the radius of the air holes is 0.3mm.The normalized frequency increases with the voltage increasing. Under the same applied voltage, the bigger the radius of air holes is, the larger the normalized frequency will be. And the growth trend will become more apparent. Because index of cladding effective refractive changes slowly with the voltage changing; furthermore, the larger the radius of the air holes is, the changes of the cladding effective refractive index are less obvious .

3.3. Voltage characteristic of effective core area

Effective core area of the PCF filled with LC is controlled by PCF's structure and applied voltage. We can get a large variation range of effective core area by selectting applicable structure of PCF. The effective core area is defined as:

$$A_{eff} = \frac{\left[\iint |E(x,y)|^2 dxdy\right]^2}{\iint |E(x,y)|^4 dxdy} \qquad (5)$$

E(x, y) represents electric mode field distribution.

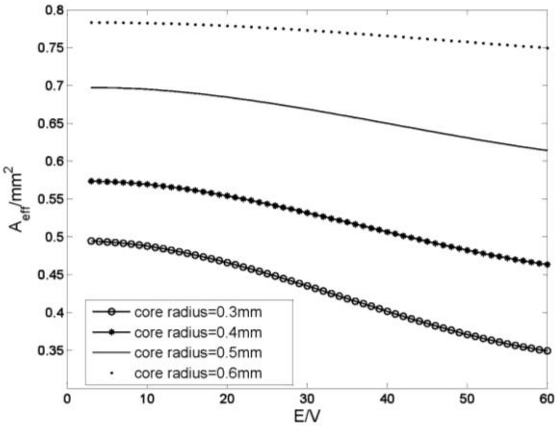

Fig.6. Effective mode area of PCF filled with LC versus voltage for different structures.

As shown above, when the applied voltage is fixed, the effective core area increases with the increase of air holes' radius. When air holes' radius is constant, the effective core area increases with the applied voltage decreasing. Meanwhile, the larger the radius of the air holes is, the effective core area of PCF is more stable, therefore, the value of nonlinear effects are more stable. We can choose appropriate structure parameters and applied voltage to control the size of the required effective core area. Thus we can improve the nonlinear and single-mode transmission characteristics of PCF.

3.4. Voltage characteristic of numerical aperture

NA is the important parameter which reflects the light gathering power of PCF. And it is defined by:

$$NA = \sin\theta_a =$$

$$\sin\left(\tan^{-1}\left(\frac{\lambda}{\pi\omega}\right)\right) \approx$$

$$\left(1 + \frac{\pi A_{eff}}{\lambda^2}\right)^{-\frac{1}{2}} \qquad (6)$$

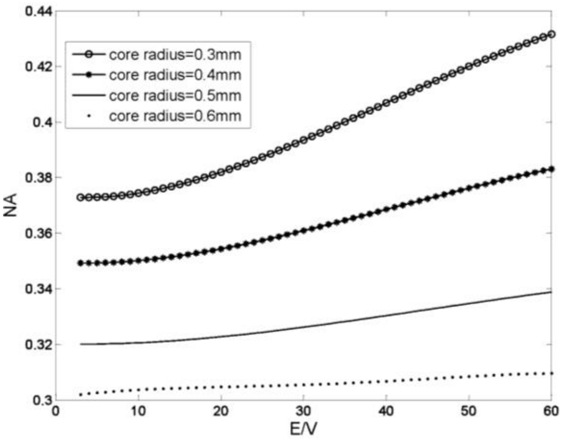

Fig.7. The numerical aperture of the different aperture radius along with the change of voltage.

Seen from Fig. 7, when radius of the air holes is fixed, the numerical aperture increases as the voltage growing. With the radius of air holes increasing, the numerical aperture will change more gradually. When the voltage is fixed, the numerical aperture reduces with the radius increasing. We can achieve the desired numerical aperture by designing different fiber structures and adjusting applied voltage on PCF.

3.5. Waveguide dispersion

Since the material dispersion of polyethylene waveguide is small, its effect on the total dispersion can be ignored. The total dispersion is only determined by the waveguide dispersion. Waveguide dispersion is an important parameter of the PCF, so controlling dispersion is very crucial for the transmission of signal. The fiber dispersion can be expressed as

$$D_\omega = \frac{d^2\beta}{d\omega^2} = \frac{1}{c}\left(2\frac{dn_{eff}}{d\omega} + \omega\frac{d^2n_{eff}}{d\omega^2}\right) \tag{7}$$

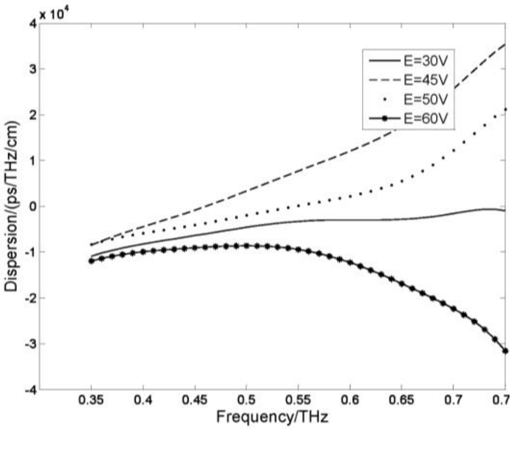

Fig. 8. The waveguide dispersion constants under different voltages.

According to the value of effective refractive index at different frequencies, we can get a dispersion constant curve at different temperature by fitting with MATLAB. Fig. 8 shows the curve of dispersion constant under diverse frequency in one structure. The air hole radius is 0.6mm.

As shown in Fig. 8, the frequency varies from 0.35*THz* to 0.7*THz*. The dispersion constant changes from negative to positive. At low frequencies, dispersion constant is almost unchanged. The smaller the applied voltage is, the more smoothly the curves change. When the applied voltage is lower than 50V, the dispersion zero-point will move to lower frequencies with the applied voltage increasing.

In this structure, we can get a large negative dispersion value. Moreover, when the applied voltage is 30V, a wide range of the nearly zero ultra-flattened dispersion is appeared. Verified by simulation, this feature also can be gained when the applied voltage is lower than 30V. This feature has a great advantage in practical applications. For example, the dispersion-flattened PCF will play a role in ultra-wide wavelength division multiplexing system in the future.

4. Conclusions

In this paper, we use COMSOL and MATLAB to do simulation. And we received the performance parameters of the PCF infiltrated by LC 5CB. These properties include effective refractive index, the normalized frequency, the effective core area, numerical aperture and waveguide dispersion. Results indicate that both single-mode transmission and nearly zero ultra-flattened dispersion can be achieved under the appropriate applied voltage and suitable structure. Moreover, stable nonlinear effect appears in the condition that the radius of air holes is big. It provides references to design voltage sensing terahertz waveguide device used for corresponding demands.

Acknowledgments

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