Thermal tunability and sensitivity of bandgap photonic crystal fiber of terahertz wave

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The production of filter combined terahertz with photonic crystal fiber is rare. Fill the nematic liquid crystal in the photonic crystal fiber air hole, photonic crystal optical fiber transmission mechanism was tuned by changing the nature of the liquid crystal. Liquid crystal refractive index change with temperature, so that the defect mode frequency will move. Based on this mechanism, threshold switching or filter can be designed. For the terahertz sensing characteristics in this article, mode field area and sensitivity become small as the wavelength increases.

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1. Introduction

In recent years, terahertz research attracted more and more attention to the world's countries [1]. Terahertz wave is the electromagnetic wave which frequency is between 0.1THz and 10 THz. There are overlap between short wavelength band and infrared band, between long wavelength band and millimeter wave. It is a link of macroscopic electronics and microscopic photonics for its special position. So it carries important practical and academic value [2].

The concept of Photonic Crystal Fiber (PCF) was proposed by ST. J. Russle et al in 1992 [3]. In 2003, the plastic PCF made by high density polyethylene is reported by Research Group of Pohang University of Science and Technology [4]. The characteristic of relatively low dispersive and low loss is demonstrated when it is used in terahertz wave band. A typical of photonic crystal fiber is constituted by the core and the cladding spatially periodic structure. The center can be seen as defects which are introduced in the two-dimensional photonic crystal. According to the core material and cladding different arrangement of the periodic structure, the PCF can achieve different optical transmission. And its transmission mechanism is determined by the relative refractive index of core and cladding. If the core refractive index is bigger than the cladding index, the wave transmit according to the nature of the total reflection (MTIR-PCF); Conversely, it spread depending on photonic crystal band theory (PBG-PCF).

Today, using the liquid crystal and photonic crystal as THz devices will have broad prospect of application [5-7]. However, at this moment, using liquid crystals and the photonic crystal fiber to design the THz filter is a new topic, there are many physical and technical issues need further study. We fill the polymer liquid crystal materials to the PCF air hole, on the one hand, it can change the transmission mechanism of photonic crystal fiber, on the other hand, it can also realize the tunable output of PCF through regulating the refractive index of liquid crystal by changing voltage or temperature [8].

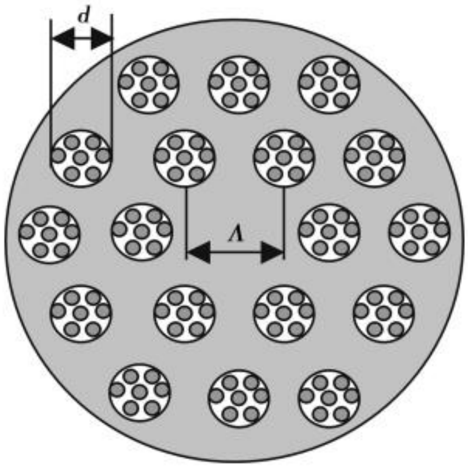

Fig. 1. Filled LC in the cladding of PCF.

In this article, the cladding of bandgap PCF is infiltrated with LC 5CB. Ru-Pin Pan [9] of National

Chiao Tung University has studied optical properties of nematic LC 5CB in terahertz frequency range, and demonstrate that 5CB exhibits a small absorption loss and a relatively strong birefringence effect in this frequency range. The experiment data indicates that the 5CB is viable for transporting terahertz wave. Temperature-dependent optical constants and birefringence of nematic LC 5CB in terahertz frequency range have obtained by using terahertz time-domain spectroscopy by Ru-Pin Pan et al in the year of 2008 [10]. In this paper, the tunable and sensing characteristics of the PCF mode field after being infiltrated with LC 5CB are analyzed by the finite element method (FEM)[11-12].

2. Temperature sensing characteristics

2.1. Arrow model

Transmission mechanism of solid-core PBG-PCF can be explained by arrow model [13-15]. In this model, the infiltrated holes are treated as isolated waveguides. Minima in the transmission spectrum occur for cutoff wavelengths of following modes propagated in one hole. The position of these minima can be calculated according to

$$\lambda_m = \frac{2d\sqrt{n_2^2 - n_1^2}}{m + 1/2} \tag{1}$$

Where λ_m (cutoff wavelength) is the wavelength corresponding to the minimum in the fiber's transmission spectrum, d is the diameter of the hole, m is a natural number, and n_1 and n_2 are the refractive indices of polyethylene and the LC filling the hole, respectively. And the temperature dependence of the refractive indices had been fitted [10]:

$$n = A \times (B - T_R)^C \tag{2}$$

So, we can draw the picture of λ_m as the changes with temperature (Fig. 2).

As the change of liquid crystal effective refractive index, the cutoff wavelength in PCF change correspondingly. When the ambient temperature changes, it will lead to the liquid crystal refractive index changes. So that, the change of the transmission spectrum is equal to the movement of the PCF bandgap.

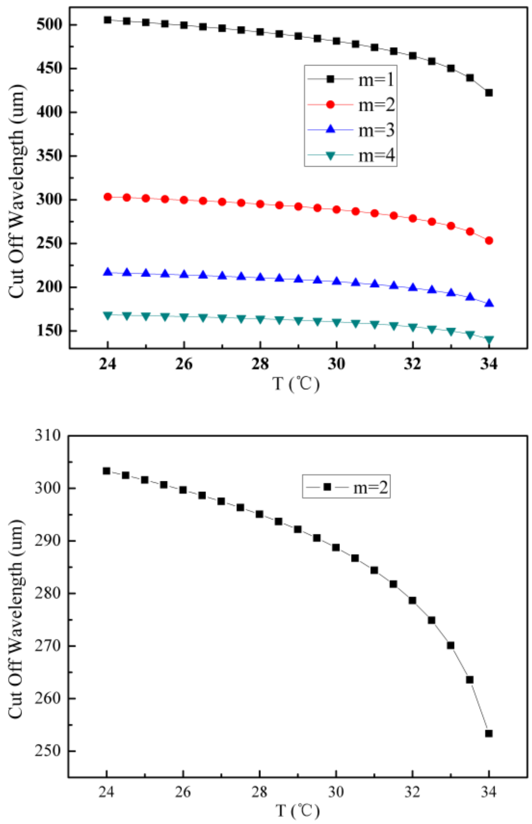

Fig. 2. (a)The cutoff wavelength at different m as the temperature changes. (b)At m=2.

It can be seen from Fig. 2 that the bandgap has blue shift with the increase of temperature. The higher of the temperature is, the cutoff wavelength variation with temperature more obvious is.

2.2. Temperature characteristics of effective core area

The effective core area is defined as:

$$A_{eff} = \frac{\left[\iint |E(x,y)|^2 dx\,dy\right]^2}{\iint |E(x,y)|^4 dx\,dy} \tag{3}$$

The effective core area of PCF filled with LC varies with outside temperature and different fiber structure. It impacts on nonlinear coefficient of the PCF. The relationship between the nonlinear coefficient and effective core area is:

$$\gamma = \frac{2\pi \cdot n_2}{\lambda A_{eff}} \tag{4}$$

Where n_2 is nonlinear coefficient of PCF.

We have received the curve of effective core area versus temperature for the wavelength is 355um, 350um and 345um, as shown in Fig. 3.

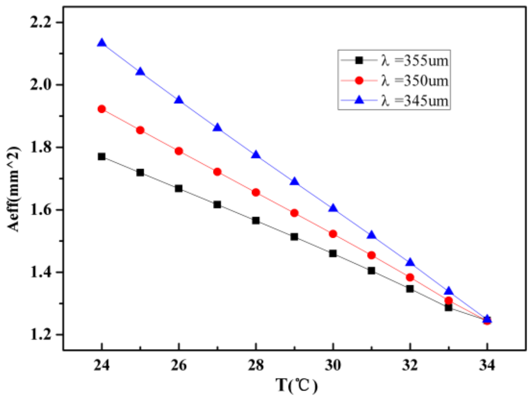

Fig. 3. Effective core area of PCF filled with LC versus temperature for different wavelength.

As seen from Fig. 3, the effective core area decreases linearly with the growth of temperature. And at the same temperature, effective core area is larger when the wavelength is smaller. We can select appropriate structure of PCF and working temperature according to the requirement of nonlinear coefficient in practice.

2.3. Confinement loss veruse temperature

We use loss characteristics to represent the transmission properties. Loss include the absorption loss and scattering loss, bending loss and confinement loss. Plastic optical fiber absorption loss is small, the dispersion and bending loss is negligible. Major loss is caused by confinement loss. Selecting 28 °C and ignoring the other losses, only considering the confinement loss, the transmission characteristics can be indicated by confinement loss. Confinement loss can be calculated using the comsol software, its expression is as follows:

$$L_1 = \frac{2\times\pi\times1000\times8.686\times\mathrm{Im}(n_{eff})}{\lambda}(dB/km) \qquad (5)$$

$\mathrm{Im}(n_{eff})$ represent the imaginary part of effective refractive index.

According to the (5) formula. We have received the curve of confinement loss versus temperature in the wavelength is 355um, 350um and 345um, as shown in Fig. 4.

We can see from Fig. 4, the confinement loss decreases with the growth of temperature. This is because that the LC refractive index become bigger with the decrease of temperature, which lead THz wave to be more likely to leak into the cladding.

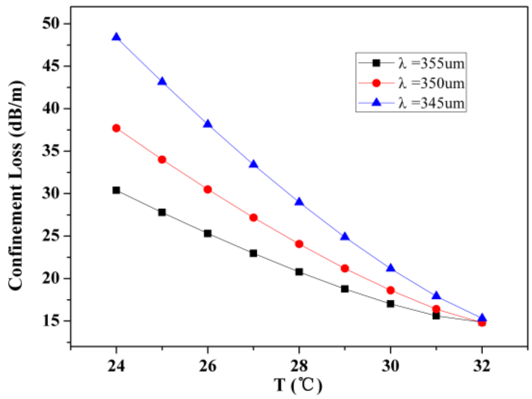

Fig. 4. Confinement loss versus temperature for different wavelength.

And at the same temperature, confinement loss is larger when the wavelength is smaller. Their curves of confinement loss versus temperature roughly meet the linear relationship. The slope of each curve is their sensitivity. 355um, 350um and 345um, correspond to their sensitivity is 1.98929dB/m/ °C, 2.90276dB/m/ °C and 4.17381dB/m/ °C. In certain range of THz wave, the higher of wavelength is, the sensitivity is lower.

3. Thermal tunability

3.1. Threshold switching

The refractive index of the liquid crystal 5CB changes with temperature changes. So, the loss will vary with temperature in specific wavelength band, just as Fig. 4. There are also some conditions that the change of the transmisson is not linear, it may suddenly become very big. And according to this phenomenon, we can design the terahertz switch.

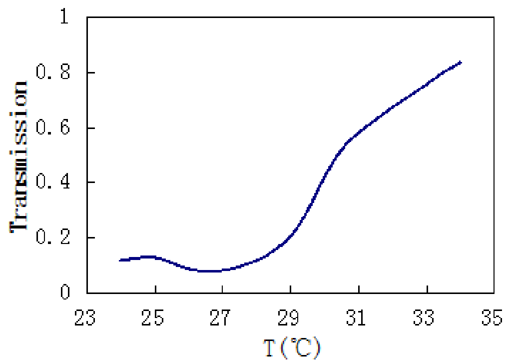

Fig. 5. The transmission versus temperature at 0.96THz.

As is shown in Fig. 5, we can put the 24 °C as a closed state, and 34 °C as a on state. It can also be designed as a temperature switch alarm. We can take 24 °C to 30 °C as a safe temperature, and as soon as the temperature exceeds 30 °C, the transmission exceeds a certain threshold, the alarm will ring.

3.2. Tunable filter

As is shown in Fig. 2, the cutoff wavelength versus temperature can reflect the variation of band. In the spectrum, transmission dips basically at the cutoff wavelengths. Because the refractive index of the liquid crystal changes with temperature, these spectral dips can be utilized for making tunable optical filters.

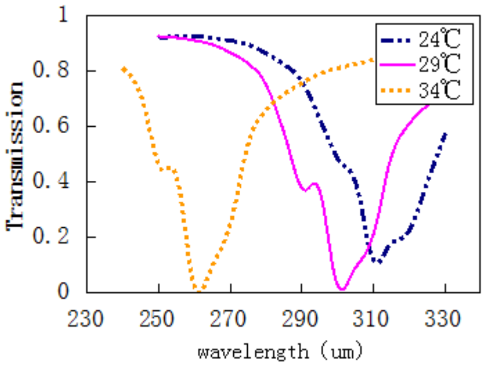

Fig. 6. Bandgap moves for different temperature.

It can be seen from the Fig. 6, the dips will move in the direction towards the shortwave when the temperature becomes higher. The higher the temperature is, the move is more obvious. This conclusion is consistent with the arrow model we mentioned before.

If we want to get filter band near 290um, according to the figure shown above, we can design in this way, just let the wave band first pass through the PCF at 34 ^{o}C, then pass through it at 24 ^{o}C. So that, we can get the wavelength at 290um nearly, and achieve the effect of filtering.

5. Conclusion

The FEM method is used to analyze temperature influence on effective refractive index, effective core area and confinement loss of terahertz wave PCF which is infiltrated LC 5CB. It is shown that the curve of confinement loss versus wavelength changes as temperature changes. Band has a blue shift when temperature rises, and it represent an obvious tunable filtering characteristics which can be used to design a temperature switch alarm and filter. For sensing properties, mode field area and sensitivity become small as the wavelength increases. It is helpful for designing communication devices and Sensors of THz band.

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