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

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Using the temperature sensitivity of refractive index of Liquid Crystal (LC), a new type of LC photonic crystal fiber (PCF) terahertz waveguide by temperature modulation is designed which is based on that the core of PCF is filled with nematic LC 5CB. The change of characteristics of modes of PCF with temperature under the conditions of different core radius is simulated. It is shown that there is no endless single mode. The waveguide dispersion of terahertz waveguide under the different temperature is simulated. It is shown that, the dispersion constant decreases with temperature increasing and the ultra-flattened dispersion is implemented.

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1. Introduction

In recent years, a research upsurge of terahertz wave has been raised among countries in the world with the development of terahertz wave generation technique[1]. Terahertz wave is the electromagnetic wave what frequency is between 0.1*THz* and 10*THz*. 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. So it carries important academic and practical value.

The concept of Photonic Crystal Fiber (PCF) was proposed by ST.J.Russle et al in 1992[2]. The plastic PCF made by high density polyethylene is reported by Research Group of Pohang University of Science and Technology in 2003[3]. The characteristic of low loss and relatively low dispersive is demonstrated when it is used in terahertz wave band. However the transmission characteristics cannot be changed if PCF has been produced. In Practical applications, transmission characteristics need to be adjusted according to specific needs. The parameters of dielectric constant, conductivity and refractive index of LC molecules are anisotropic and the parameters are easily affected by surrounding. So using the temperature sensitivity of refractive index of LC, the tunable devices of photonic crystal fiber can be manufactured if the air hole of PCF is filled with LC[4]. On the basis of that the refractive index of LC which is in the air hole varies with temperature, temperature information can be obtained through the change of transmission spectra[5]. So it can be applied to sensor which is based on PCF. Ru-Pin Pan[6] 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.

The structure parameter of the PCF for terahertz waveguide is in the magnitude of mm. Compared to the PCF which is in visible and infrared light, PCF used in terahertz waveguide is more easily to be prepared. The PCF used is hollow-core PCF. There have complex bandgap effect when the air holes are filled with LC. The realization of the bandgap light-guide mechanism carries a strict requirement with the structure of the PCF. However, a bandgap-guiding PCF can be converted to an initial index-guiding PCF by infiltrating the core with LC. In this paper, the temperature characteristic of the PCF mode field after being infiltrated with LC 5CB is analyzed by the finite element method (FEM).

2. Finite element method (FEM)

FEM is an algorithm that can solve mathematics and physics problems based on variational principle. PCF of any irregular section shape and refractive index under any combination material can be solved well by FEM which has higher calculation accuracy in analyzing mode field.
The vector wave equation of magnetic field vector can be obtained from Maxwell equations[7]:

$$\nabla \times \left(n^{-2} \nabla \times \overrightarrow{H} \right) - k_0^{\ 2} = 0 \qquad (1)$$

Where n is refractive index, k_0 is the free space wave vector. The del operator is defined as[8]:

$$\nabla = \vec{x}\alpha_x \frac{\partial}{\partial x} + \vec{y}\alpha_y \frac{\partial}{\partial y} + \vec{z}\alpha_z \frac{\partial}{\partial z} \quad (2)$$

Where $\vec{x}$、 $\vec{y}$ and $\vec{z}$ are the unit vector in the x, y and z direction respectively. α_x, α_y and α_z are the parameters of perfect matched layer imposed at the edges of the computer window. The incident wave will enter into the PML with reflectionless by adding PML outside the calculation region of PCF. The direction of light propagation is assumed to be along the z-axis, α_z will be set unity.

$$\alpha = 1 - j\frac{3\lambda\rho^2}{4\pi n W^3}\ln\left(\frac{1}{R_t}\right) \quad (3)$$

Where λ is the wavelength, W is the width of the PML. ρ is the distance between the PML and the edge of computational window. And R_t is the theoretical reflection between the PML and the edge of computational window.

Assuming that the transverse magnetic field, $\vec{H}_t$, is decomposed into slowly changed envelope, $\vec{h}_t$, and a rapid oscillating item, $\exp(-jn_0k_0z)$, a total wave equation of transverse magnetic field can be obtained by the equation (1) and using the conditions of $div\vec{H} = 0$. Applying Galerkin's method leads to:

$$[M]\frac{d^2\{h_t\}}{dz^2} - 2jn_0k_0[M]\frac{d\{h_t\}}{dz} + \left([K] - n_0{}^2k_0{}^2[M]\right)\{h_t\} = \{0\} \quad (4)$$

Where [M] and [K] are the global finite element matrix[8]. The effective index and field distribution of the l th mode are assumed to be n_{eff} and $\{h_{t,l}\}$ respectively. The eigen equation of the l th mode is given as follow:

$$[K]\{h_{t,l}\} = k_0{}^2 n_0{}^2 [M]\{h_{t,l}\} \quad (5)$$

$\{h_t\}$ converges to $\{h_{t,l}\}$ when the propagation steps are large enough, and the effective refractive index of the mode can be obtained by formula:

$$n^2_{eff,l,k} = \frac{\{h_t\}^*_k [K]_k \{h_t\}_k}{k_0^2 \{h_t\}^*_k [M]_k \{h_t\}_k} \quad (6)$$

3. Temperature characteristics of LC's refractive index

In this paper, the core of the PCF is filled with a nematic LC 5CB. The LC molecular is composed of rod-liked molecular which has large aspect ratio. The centroids of these rod-liked molecules distribute randomly, but they nearly keep parallelism in the direction of long axis. And the molecular has optical uniaxiality, in general, the direction of optical axis is consistent with the direction of long axis of molecule[9]. In this paper, the direction of long axis of the LC molecules which is used to fill the core of hollow-core PCF is along the direction of fiber axis, as shown in Fig.1. Take the optical axis direction as Z, fiber cross section as X-Y plane. The ordinary and extraordinary refractive index are denoted by n_o and n_e respectively, then $n_o = n_x = n_y, n_e = n_z$.

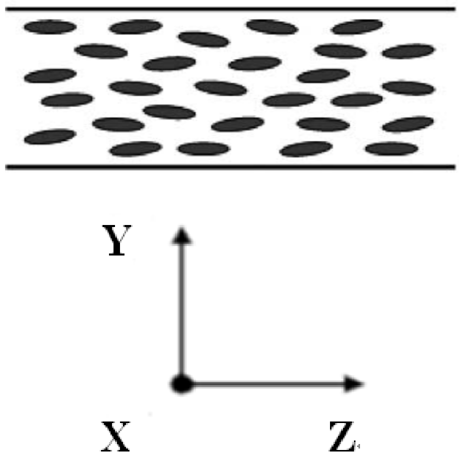


Fig.1 filled mode of LC in the core of PCF.

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]. 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 0.2–1.0 *THz*, respectively. And the temperature dependence of the refractive indices had been fitted:

$$n = A \times (B - T_R)^C \quad (7)$$

Where n is refractive index, T_R is the temperature difference between measured temperature and clearing point $(T - T_C)$. The fitting parameters A, B and C in different frequency range are also obtained[10].

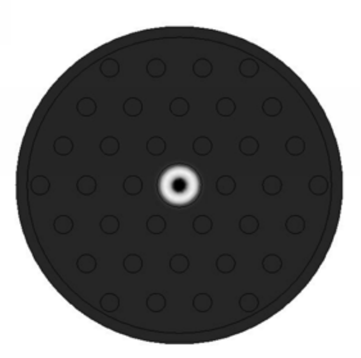
4. Temperature sensing characteristics

4.1Temperature characteristics of transmission mode

The effective normalized frequency of PCF filled with LC is:

$$V_{eff} = \frac{2\pi R}{\lambda}\left(n_{core}^2 - n_{clad}^2\right)^{1/2} \quad (8)$$

Where define $V_{eff} < 2.55$ as the cut-off frequency of second order mode. We use polyethylene, which can be easily got, as a material of PCF. The refractive index of this material is 1.5. Operating temperature range of LC is 25℃−34℃. LC will turn into isotropic phase when the temperature is higher than 34℃. The Core effective refractive index n_{core} and the cladding effective refractive index n_{clad} can be obtained through simulation by comsol. The intensity distribution of the core and the cladding mode is shown in Fig.2(a) and 2(b). The diameter of the cladding hole is 0.5*mm*, the air hole spacing in the cladding is 1.25*mm*.



(a)

(b)

Fig.2 Calculated intensity distribution of the PCF with R=0.6um (a) The fundamental core mode and (b) the cladding mode.

Fill the hollow- core with the LC 5CB.The curve of normalized frequency of PCF filled with LC versus temperature for different core radius is showed in Fig.3 by using FEM. The core radius is 0.4*mm*, 0.6*mm*, 0.8*mm* respectively, and the frequency is 0.625*THZ*.

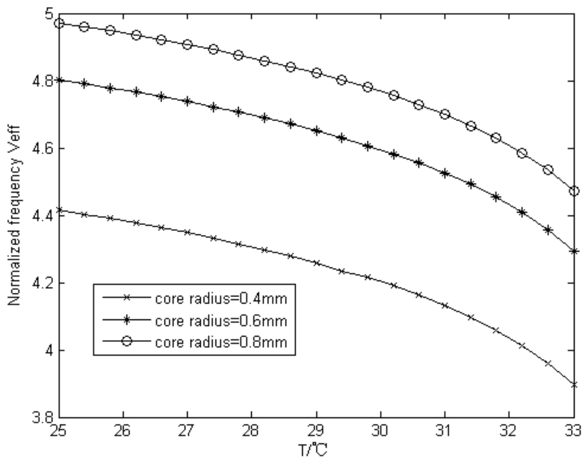


Fig.3 Normalized frequency of PCF filled with LC versus temperature for different core radius.

It can be seen that there is no single-mode transmission in the selected frequency. The normalized frequency decreases with the temperature rising. And at the same temperature, normalized frequency is larger when the core radius is bigger. This is caused by that the refractive index decreases with the growth of the temperature according to formula (7), while n_{core} decreases. However, from the simulation result, the effective refractive index of the cladding n_{clad} is almost keeping constant when the temperature changed. Moreover, according to formula (8), the single-mode transmission will be happened in long wavelength region. Therefore, the designed PCF in this paper has no endless single-mode characteristic. The single-mode transmission will be occurred in long-wavelength region at certain temperature.

4.2. Temperature characteristics of effective core area

The effective core area of PCF filled with LC varied with different fiber structure and outside temperature. The effective core area is defined as:

$$A_{eff} = \frac{\left[\iint \left|E(x,y)\right|^2 dxdy\right]^2}{\iint \left|E(x,y)\right|^4 dxdy} \quad (9)$$

The effective core area impacts on nonlinear coefficient of the PCF. The relationship between the nonlinear coefficient and effective core area is:

$$\gamma = \frac{2\pi \cdot n_2}{\lambda A_{eff}} \quad (10)$$

Where n_2 is nonlinear coefficient of PCF.

We have received the curve of effective core area versus temperature for the core radius is 0.4mm, 0.6mm and 0.8mm, as shown in Fig. 4.

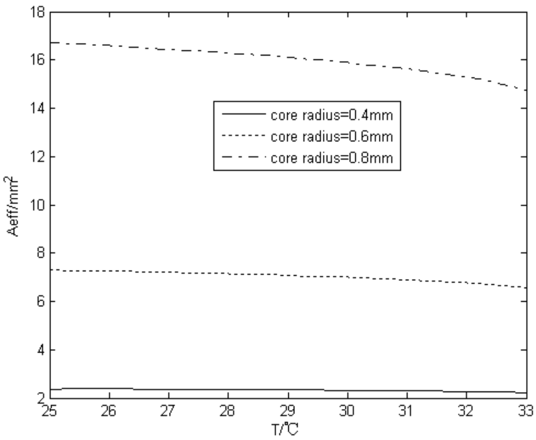


Fig.4 Effective core area of PCF filled with LC versus temperature for different core radius.

As seen from Fig.4, the effective core area decreases with the growth of temperature. The higher the temperature is, the effect for effective core area is greater. And at the same temperature, effective core area is larger when the core radius is greater. We can select appropriate structure of PCF and working temperature according to the requirement of nonlinear coefficient in practice.

4.3. Waveguide dispersion

Since the material dispersion of polyethylene waveguide is small, the effect for the total dispersion can be ignored. The total dispersion constant is only determined by the waveguide dispersion. The waveguide dispersion can be calculated by equation (11):

$$D_w = \frac{d^2\beta}{d\omega^2} = \frac{1}{c}\left(2\frac{dn_{eff}}{d\omega} + \omega\frac{d^2 n_{eff}}{d\omega^2}\right) \qquad (11)$$

According to the value of effective refractive index at the different frequencies, we can get a waveguide dispersion curve at different temperature by fitting with MATLAB, shown as in Fig.5. And the radius of the core is 0.8*mm*.

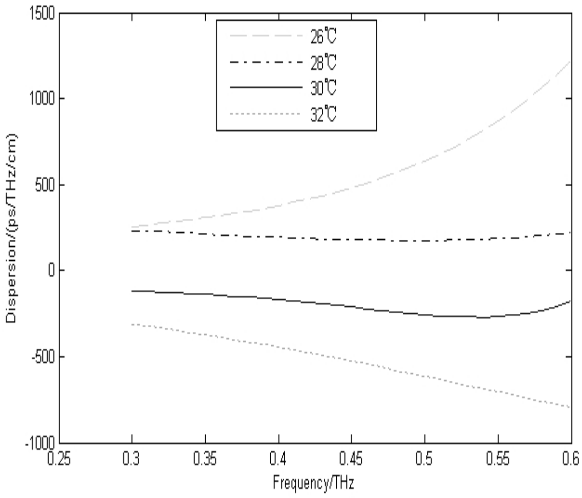


Fig.5 shows the waveguide dispersion constant at different temperature.

It can be seen that the dispersion constant changes from positive to negative. At the same temperature, the waveguide dispersion constant reduces with the growth of temperature. The dispersion constant increases with frequency rising at 26℃. While the range of dispersion has little change at 28℃. The ultra-flat dispersion is realized basically. The negative dispersion is appeared at 30℃. When the temperature reaches 32 ℃, the dispersion constant decreased further. Moreover, the dispersion constant decreases with frequency increasing. We can design the ultra-flat dispersion terahertz waveguide and achieve dispersion compensation by changing the temperature range in practical application.

5. Conclusion

The FEM method is used to analyze temperature influence on effective refractive index, effective core area and waveguide dispersion of terahertz wave PCF which is infiltrated LC 5CB. It is shown that the single-mode transmission will be occurred in long-wavelength region at certain temperature. And we can get the effective core area that we need by changing the structure and temperature. The dispersion constant changes at different temperature. Moreover, a wide range of ultra-flat dispersion is appeared. It is helpful for designing temperature sensing terahertz waveguide device.

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References

[1] W W Huang, Li B J, Progress on Terahertz Waveguide, Laser & Optoelectronics Progress **43**, 9 (2006)

[2] J.C.Knight, T. A. Birks, P. St. J. Russel, D. M. Atkin, Optics Letters, **21**, 1547（1996）

[3] H.Han, H. Park, M. Cho, J. Kim，I..Park, H.Lim, IEEE MT-S Digest, WE4C-3, 1075 (2006)

[4] Thomas Tanggaard Larsen, Anders Bjarklev, David Sparre Hermann, Jes Broeng, Express **11**, 2591(2003).

[5] Tomasz R. Wolinski, Aleksandra Czapla Sławomir Ertman, Marzena Tefelska, Andrzej W. Domanski, Jan Wójcik, Edward Nowinowski-Kruszelnicki, Roman Dabrowski, IEEE Transactions on Instrumentation and Measurement **57**, 1796(2008)

[6] Chao-Yuan Chen, Cho-Fan Hsieh, Yea-Feng Lin, Ru-Pin Pan, Xi-Cheng Zhang, Optics ExprESS **12,** 2630(2004)

[7] S.S.A. Obayya, B.M.A. Rahman and K.T.V. Grattan, IEE Proc.-Optoelectro, **152**, 241(2005)

[8] S. S. A. Obayya, B. M. A. Rahman, H. A. El-Mikati. Journal Lightwave Technology **18,** 409 (2000)
[9] P.G. de Gennes (translated by Sun Z M, Wang X J), physics of liquid crystal, (Volume1)Shanghai:Translation Publishing Company, p9 (in Chinese) (1990)
[10] Ru-Pin Pan,Cho-Fan Hsieh,Ci-Ling Pan and Chao-Yuan Chen, Journal Of Applied PhysiC, **103**, 093523, (2008).

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