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Characteristics of a liquid-crystal-filled composite lattice terahertz bandgap fiber☆

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ABSTRACT

A new type of terahertz fiber is presented based on composite lattice photonic crystal bandgap. The cladding is filled selectively with the nematic liquid crystal 5CB which is sensitive to the electric field. The terahertz wave can be modulated by using the electric field to control the orientation of liquid crystal molecules. The plane wave expansion method and the finite element method are employed to theoretically analyze bandgap characteristics, polarization characteristics, energy fraction and material absorption loss. The results show that this fiber structure can be used as tunable terahertz polarization controller.

1. Introduction

Terahertz refers to the electromagnetic wave with the frequency range from 0.1 to 10 THz, which exists between the microwave and infrared radiation in the electromagnetic spectrum. Due to the special spectrum position, terahertz wave combines the advantages of both microwave and infrared light, and possesses many superior properties such as perspective, security, and high spectral signal-to-noise ratio, and so on. It has been widely applied to spectral analysis, object imaging, medical diagnosis, radio astronomy, security detection, materials testing and wireless communication technology [1–6].

In recent years, with the in-depth research on terahertz waveguide, many high-performance terahertz waveguide structures have been proposed, such as bare metal wire waveguide [7], metal tube waveguide [8], sub-wavelength polymer fiber [9], hollow-core photonic crystal fiber [10], and porous fiber [11–14]. The research on terahertz functional devices based on waveguide structure, especially for the tunable filter, switching and polarization controller devices, has become a focus in the field of terahertz applications with the development of waveguide technology and the increasing demand of practical system.

In 2007, Li et al. [15] proposed the electrically controlled silicon photonic crystal terahertz switch in theory, since then utilizing photonic crystal to form terahertz functional devices has been widely concerned by the researchers. Ghattan et al. [16] experimentally realize the terahertz switch in two-dimensional photonic crystal by controlling the optical axis direction of liquid crystal (LC) with external electric field to change the transmission characteristics of terahertz wave. Zhang et al. [17] designed the wide-band terahertz tunable filter and switch with two-dimensional photonic crystal of different lattice structures by making use of the external magnetic field to control the liquid crystal. Guo et al. [18] presented the tunable terahertz filter and switch, which overcome the weaknesses of inconvenient control and narrow tuning range, by using magnetic photonic crystal that was filled with LC. However, there is a relatively large coupling loss for these terahertz functional devices mentioned above. Reyes [19] experimentally verified that the coupling loss was up to 5.8 dB for two-dimensional silicon photonic crystal. An ideal way to reduce coupling loss is to directly integrate the functional devices with waveguides or fibers.

Compared with the photonic crystal, it is easier to fabricate the terahertz functional devices based on the fiber structure. The research on the fiber functional devices is more common in visible and infrared band [20,21], but the relevant research is relatively few in the terahertz band. In 2009, Wu et al. [22] designed a terahertz switch based on the hollow Bragg fiber, and the coupling loss was significantly reduced, but the tunable bandwidth range was narrower and the extinction ratio was lower. In 2012, Hou et al. [23] presented a terahertz switch and polarization controller based on the solid-core photonic crystal fiber

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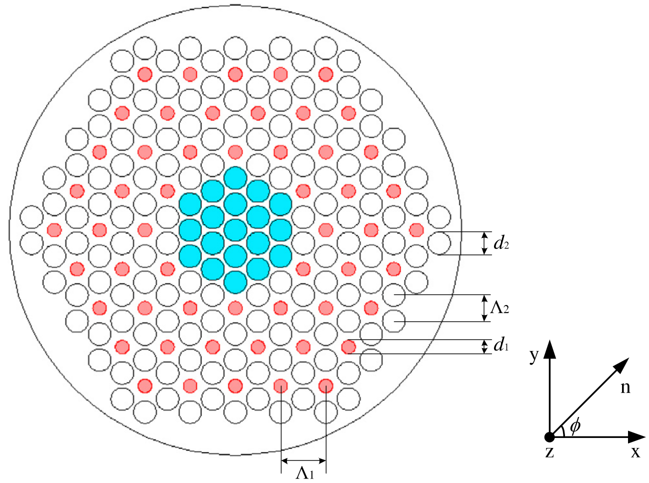

Fig. 1. The end face schematic diagram of terahertz composite lattice photonic crystal bandgap fiber. The right indicates the director of a nematic liquid crystal.

which filled with LC. For this device structure, terahertz wave was mainly transmitted in the base material, which resulted in a large transmission loss.

This paper presents a novel liquid-crystal-filled terahertz fiber based on the composite lattice photonic crystal bandgap. The cladding is filled selectively with the nematic LC 5CB which is sensitive to the electric field. The terahertz wave is modulated by using the electric field to control the refractive index which is depending on the orientation of the LC molecules. The results indicate that the bandgap fiber can be used as the tunable polarization controller. Moreover, the fiber core adopts a porous structure, so it can effectively reduce the transmission loss of fiber.

2. Fiber structure and methods

The end face geometry of the composite lattice photonic crystal bandgap fiber is shown in Fig. 1. The fiber is composed of high density polyethylene base material, composite lattice air hole cladding and the porous core, which include 19 air holes. In the cladding, the air holes pitch of the triangular lattice is $\Lambda_1 = 295$ μm, and the diameter of air hole is $d_1 = 0.33\Lambda_1$; the air holes pitch of the honeycomb lattice is $\Lambda_2 = \sqrt{3}\Lambda_1/3$, and the diameter of air hole is $d_2 = 0.55\Lambda_1$. In the core, the pitch and the diameter of air holes are consistent with the honeycomb lattice air holes in the cladding. The air holes of the triangular lattice are filled with the nematic LC 5CB. To align the orientation of the LC molecules to parallel to the optical axis direction of fiber in tests, the active agents are injected in the air hole to pre-process surfaces before the LCs are filled. The refractive index of base materials is 1.534 [24], the refractive index of air is 1, and the dielectric constant of LC 5CB for o-light (normal light) and e-light (non-normal light) are 2.34 and 3.06, respectively. The terahertz waves with electric fields perpendicular to the director of the LC has ordinary refractive indices, while the waves with electric fields parallel to the director has extraordinary refractive indices. When electric field is applied transversely, the dielectric constant tensor takes the form of [21,25]:

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

where

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

$$\varepsilon_{xy} = \varepsilon_{yx} = \left(\varepsilon_e - \varepsilon_o\right)\sin\phi\cos\phi \tag{3}$$

$$\varepsilon_{yy} = \varepsilon_o \cos^2\phi + \varepsilon_e \sin^2\phi \tag{4}$$

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

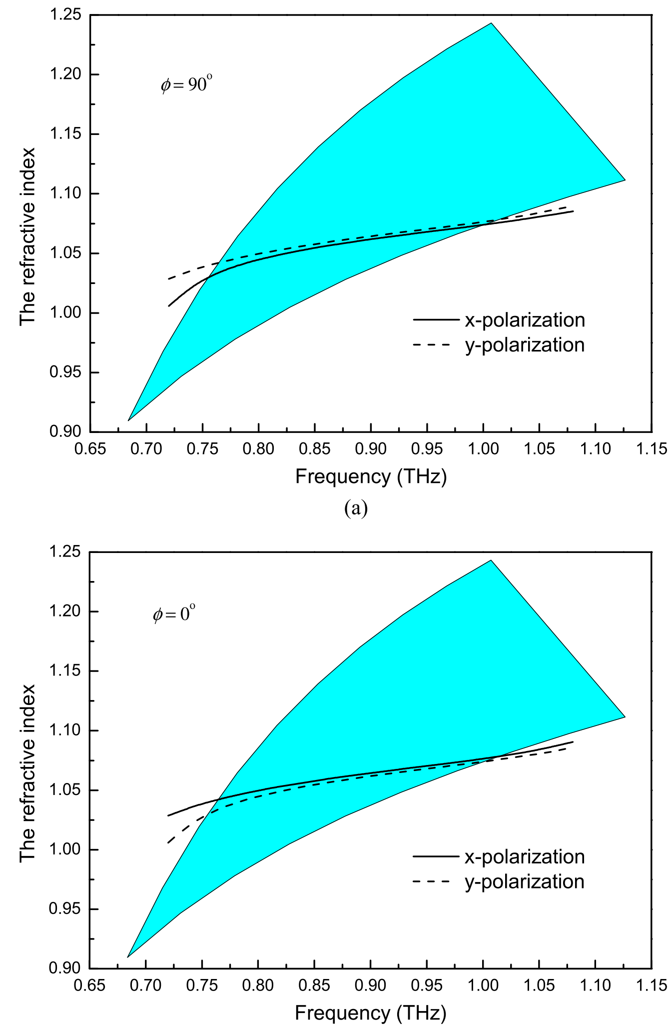

Fig. 2. The bandgap range of fiber and the effective refractive index of HE_{11x} mode, HE_{11y} mode for $\phi = 90°$ (a) and $\phi = 0°$ (b).

ϕ is the rotation angle of LCs director as shown in Fig. 1, which can be controlled by the external electric field. Due to the preprocessing of air holes, the direction of LC molecules is parallel to the optical axis of fiber in the absence of external electric field, while rotation angle $\phi = 90°$. The change of ϕ has little effect on the shape of the bandgap, however, it has affect mode properties [21,23].

For bandgap and mode field analysis, the plane wave expansion method and the finite element method are employed to solve a full-vectorial eigenvalue equation [26]:

$$\begin{pmatrix} P_{xx} & P_{xy} \\ P_{yx} & P_{yy} \end{pmatrix}\begin{pmatrix} E_x \\ E_y \end{pmatrix} = \beta^2 \begin{pmatrix} E_x \\ E_y \end{pmatrix} \tag{6}$$

where the differential operators are defined as:

$$P_{xx}E_x = \frac{\partial}{\partial x}\left[\frac{1}{\varepsilon_r}\frac{\partial\left(\varepsilon_r E_x\right)}{\partial x}\right] + \frac{\partial^2 E_x}{\partial y^2} + \varepsilon_r k^2 E_x \tag{7}$$

$$P_{yy}E_y = \frac{\partial^2 E_y}{\partial x^2} + \frac{\partial}{\partial y}\left[\frac{1}{\varepsilon_r}\frac{\partial\left(\varepsilon_r E_y\right)}{\partial y}\right] + \varepsilon_r k^2 E_y \tag{8}$$

$$P_{xy}E_y = \frac{\partial}{\partial x}\left[\frac{1}{\varepsilon_r}\frac{\partial\left(\varepsilon_r E_y\right)}{\partial y}\right] - \frac{\partial^2 E_y}{\partial x \partial y} \tag{9}$$

$$P_{yx}E_x = \frac{\partial}{\partial y}\left[\frac{1}{\varepsilon_r}\frac{\partial\left(\varepsilon_r E_x\right)}{\partial x}\right] - \frac{\partial^2 E_x}{\partial y \partial x} \tag{10}$$