Dependence of transmission spectra on director orientation in the photonic crystal with a liquid crystal layer*

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(Received 9 February 2012)

The transmission spectra of one-dimensional (1D) photonic crystals (PCs) with parallel and twisted nematic liquid crystals (LCs) as defect layers are discussed by 4 × 4 matrix method, respectively. The results show that the photonic band gap (PBG) mainly depends on the periodic arrays of dielectric composites. The orientation of director and the symmetry of the director configuration have important influence on the location and amplitude of defect modes. The location and amplitude of defect modes can be controlled conveniently by changing the orientation of director. The symmetry of the director configuration can help us understand the defect modes spectra.

Document code: A **Article ID:** 1673-1905(2012)04-0277-3

DOI 10.1007/s11801-012-1180-6

By introducing defects in the periodic dielectric structure, the allowed modes of electromagnetic waves can be created within band gaps, which are called as defect modes. This property is very interesting and applicable in tunable filters[1-4]. One-dimensional (1D) photonic crystals (PCs), which are similar to three-dimensional (3D) PCs, may have omnidirectional band gaps[5]. Because liquid crystals (LCs) have a wide range of optical transparency, high birefringence and high susceptibility to external parameters, many studies on PCs with an LC defect layer have been reported[6-12]. The present study aims to investigate the dependence of defect modes on director orientation in the PCs with parallel nematic (PN) LC and twisted nematic (TN) LC as defect layers. By comparing the defect modes spectra of PN LC and TN LC, we discover that the defect modes and band gap of PC depend on not only the effective index of the defect layer but also the director configuration. The symmetry of the director configuration and the relative orientation between the director and the polarized direction of incident light beam can help us understand the defect modes spectra. The results can help us analyze and select the suitable LC to design 1D PCs.

PCs with LC as defect layer can realize the electro-optical tuning by the electro-optical effect of LC. In this paper, we calculate the directors of PN LC and 90° TN LC using iterative finite-difference method[13,14] under strong anchoring condition. When the applied voltage is zero, the directors of PN LC parallel to the *x*-axis, the tilt angles (angles between directors and the *x*-*y* plane) of 90° TN LC directors are zero, and the twist angles (angles between directors and *x*-axis) of 90° TN LC directors vary gradually from 0° to 90° along *z*-axis[14]. The nematic E7 LC material is used in our calculation, and its parameters are $n_{//}$ = 1.71 and $n_{\perp}$ = 1.50. The structure, processing technique, electro-optical properties and director alignment of the nematic LC cell are well studied in Refs.[13,14], in which the relations between LC directors and external voltage are shown.

The schematic drawing of a 1D PC with an LC layer is depicted in Fig.1. Its structure is $(HL)^6$H-LC-$(HL)^6$H, where L and H represent the dielectric layers with the low and high refractive indices, respectively. Their refractive indices are n_L=1.465 (SiO_2) and n_H= 2.065 (TiO_2). Both optical thick-

Fig.1 Schematic diagram of a 1D PC with an LC layer

* This work has been supported by the National Natural Science Foundation of China (No.10805040), and the Talent Introduction Program of Henan University of Technology (No.2007BS041).

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nesses of them are $\lambda_0/4$, and λ_0=1.55 μm is the central wavelength of PBGs.

Since LCs are anisotropic optical materials, we analyze the transmission spectra of PCs using 4 × 4 matrix method[9,10,15,16]. Compared with 2 × 2 transfer matrix method, 4 × 4 matrix method has a lot of advantages. It can do well in anisotropic media as well as isotropic media, deal with the tangential components of the electric and magnetic field vectors simultaneously, analyze the transmission and reflection spectra of arbitrary polarization direction of incident light, etc. For convenience, we assume that the incident plane is in the *x*-*z* plane, the incident light beams are the normal ones, and both the input medium and output medium are the air.

Fig.2 depicts the transmission spectra of 0°, 30°, 60° and 90° linearly polarized light beams. Here the angles are between the *x*-axis and the polarized directions. The defect layer is the PN LC layer, and its thickness is 1 μm. We can see that there are two defect modes in the spectra. A light beam can be divided into the ordinary (o) ray and the extraordinary (e) ray in LC, and we could call them as the o mode and e mode, respectively. The intensities of them are related to the polarized direction. For example, the o mode is weaker than the e mode for 30° linearly polarized light, the o mode is stronger than the e mode for 60° linearly polarized light, and only one defect mode occurs for 0° and 90° linearly polarized light. It can be understood according to the principle of birefringence. Because only one eigenmode occurs for 0° and 90° linealy polarized light, we can analyze the transmission spectrum of an arbitrary polarized light beam by decomposing it along the two directions. Since the director configuration depends on the applied voltage, the wavelengths of the defect modes are also related to it.

As shown in Fig.2, below the threshold voltage of about 1 V, the transmission spectra remain unchanged. In the region of 1−3 V, the e mode shifts toward the shorter wavelength side as the applied voltage increases. In the region above 3 V, the peaks of the two modes merge into one, and the polarization sensitivity of the PC disappears. Additionally, the photonic band gap (PBG) is insensitive to the voltage, and the tunable range is 87 nm.

Fig.3 shows the transmission spectra of 45°, 75°, 105° and 135° linearly polarized light beams. Here, the defect layer is the 90° TN LC layer, and its thickness is 0.5 μm. We can see from Fig.3, there are also two defect modes in the transmission spectra, and the intensities of them are related to the polarized direction. Unlike the PC with the PN LC defect layer, only one defect mode occurs for the spectra of 45° and 135° linearly plarized light beams. The reason is related to the symmetry of the director configuration. The tilt angles and the twist angles of the directors are symmetric with respect to the center of the 90° TN LC layer along the *z*-axis direction whether the applied voltage is zero or not[13,14]. The possible defect modes are restricted by the symmetry of the director configuration and the relative orientation between the director and the polarized direction, when a light beam passes through the PC. Because of the symmetry and the twist of 90°, only one mode can occur for the 45° and 135° linearly polarized light beams. Combining Fig.3(b) and (c), we know that the two directions can be used as the basic directions to analyze the transmission spectrum of an arbitrary polarized light beam for the PC with a 90° TN LC layer, although the real process that a light beam passes though the PC is complicated. Additionally, as shown in Fig.3, similar to the PC with a PN LC layer, the transmission spectra remain unchanged below the threshold voltage of about 1 V, the e mode shifts toward the shorter wavelength side as the applied voltage increases in the region of 1− 2.5 V, and the peaks of two modes merge into one and the polarization sensitivity of the

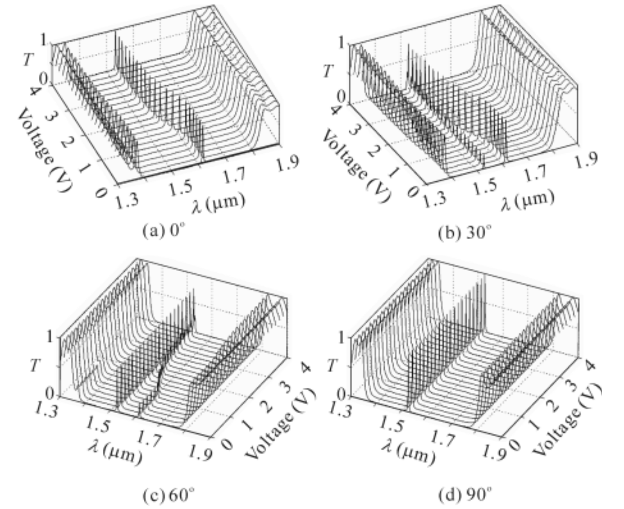

Fig.2 Transmission spectra of 0°, 30°, 60° and 90° linearly polarized light beams

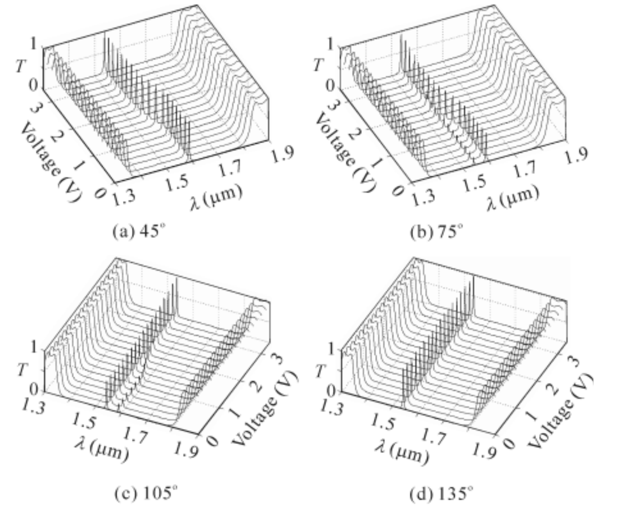

Fig.3 Transmission spectra of 45°, 75°, 105° and 135⁰ linearly polarized light beams

PC disappears in the region above 2.5 V. The PBG is also insensitive to the voltage, and the tunable range is 53 nm. By comparing the defect modes spectra of PN LC and TN LC, we can see that the defect modes and band gap of PC depend on not only the effective index of the defect layer but also the director configuration. The symmetry of the director configuration and the relative orientation between the director and the polarized direction of incident light beam have important influence on the defect modes. So we can meet our expected design requirement not only by changing the external voltages and the incident angles but also by the different director configurations of nematic LC, such as PN, TN and super-twisted nematic (STN) LCs.

In conclusion, PBGs mainly depend on the periodic arrays of dielectric composites. The defect layer and the director orientation have little influence on PBGs. So the location and the intensity of the defect mode can be adjusted by changing the director orientation of the LC layer. The effects of the director orientation on defect modes mainly cover two aspects: one is the configuration of directors, and the other is the relative orientation between the director and the polarized direction. In the practical application, the configuration of directors can be controlled by alignment layers or an external voltage. We can process nematic LC into PN LC, TN LC, STN LC by alignment layers, and further control the orientation of the directors by an external voltage. The relative orientation between the director and the polarized direction can be controlled by changing the polarized direction of the incident light, changing the incident angle, or rotating the PC axially. From Figs. 2 and 3, we can see that the location of defect modes mainly depends on the director configuration, and the amplitude of defect modes mainly depends on the relative orientation between the director and the polarized direction. So the defect modes can be adjusted exactly by electro-optical tuning combined with controlling the relative orientation between the director and the polarized direction.

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