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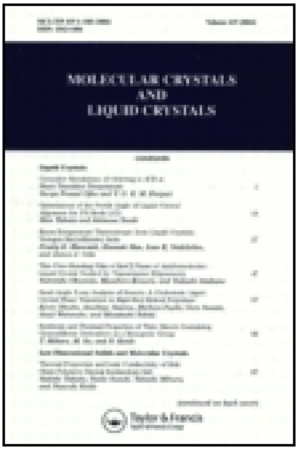

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Tunable Defect Mode in One-Dimensional Photonic Crystal with Liquid Crystal Defect Layer

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Electrical tuning of defect modes in a one-dimensional (1D) photonic crystal (PC) has been demonstrated using a ferroelectric liquid crystal (FLC) and a nematic liquid crystal (NLC) defect layers in the periodic structure. The transmission peak intensities for defect mode depends on the angle between LC molecular axis and polarization direction of the incident light. At defect mode wavelength, the 1D PC with LC defect layer transmits only the light with the polarization direction determined by the direction of extraordinary or ordinary optical axes in LC defect. Polarization direction of the light propargating through the 1D PC with in-plane NLC defect can be controlled based on field-induced in-plane realignment of NLC molecules.

Keywords: defect mode; photonic crystal; polarizer

INTRODUCTION

Photonic crystal (PC) having a three-dimensional (3D) ordered structure with a periodicity equivalent to optical wavelength has attracted considerable attention from both fundamental and practical points of view, because in such materials new concept such as a photonic band gap (PBG) has been theoretically predicted in which the existence of a certain energy range of photons is forbidden, and various applications

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of PCs have been proposed [1,2]. In particular, the study of a defect mode in PBG is one of the most attractive subjects since photons are localized. However a complete 3D PC with a periodicity equivalent to visible wavelength remains a technical challenge [3].

On the other hand, liquid crystals (LCs) have a large optical anisotropy and are sensitive to an external stress such as electric field. Therefore LCs have been a vital material in electrooptic devices at present. Based on such optical anisotropy and field sensitivity, a tunable PC has been proposed in opal or inverse opal infiltrated with LC [4–9]. Although opal and inverse opal are simple and inexpensive approaches to realize the 3D PC using self-organization of colloidal particles [10,11], the introduction of a defect into the 3D periodic structure is a problem that must be resolved.

Not only the 3D PC but also a one-dimensional (1D) PC is an attractive subject. Although the 1D PC does not have a complete PBG, there are plenty of applications using extraordinary dispersion of a photon and a localized photonic state in a stop band due to a defect layer. Recently, we have introduced a nematic LC (NLC) layer in a dielectric multilayer structure as a defect in a 1D PC, in which the wavelength of defect modes was controlled upon applying electric field based on the change in optical length of the defect layer caused by the field-induced molecular reorientation of the NLC [14]. Furthermore, the modulation of defect mode lasing [13,14] and the high speed electrooptic switching [15] by applying a low voltage has been demonstrated in the 1D PC containing NLC defect layer.

In this paper, we investigate electrooptic properties of defect modes of 1D PC containing a ferroelectric LC (FLC) and a NLC as defect layers. In addition, we demonstrate a novel technique to electrically rotate the polarization direction of the propagating light based on the tunable defect mode in a dielectric multilayer as 1D PC with in-plane switchable NLC defect layer.

EXPERIMENTAL

A schematic view of 1D PCs with a FLC defect or an in-plane NLC defect is shown in Figure 1. A dielectric multilayer as 1D PC consists of an alternating stack of SiO_2 and TiO_2 layers deposited on a glass substrate. The number of SiO_2-TiO_2 pairs on each substrate is five and the center wavelength of the photonic band is adjusted to be 600 nm by setting the optical thickness of both SiO_2 and TiO_2 to be one-quarter of 600 nm. The refractive indices of SiO_2 and TiO_2 are 1.46 and 2.35, respectively, and the thickness of SiO_2 and TiO_2 layers are 103 and 64 nm, respectively. In order to introduce the defect layer,

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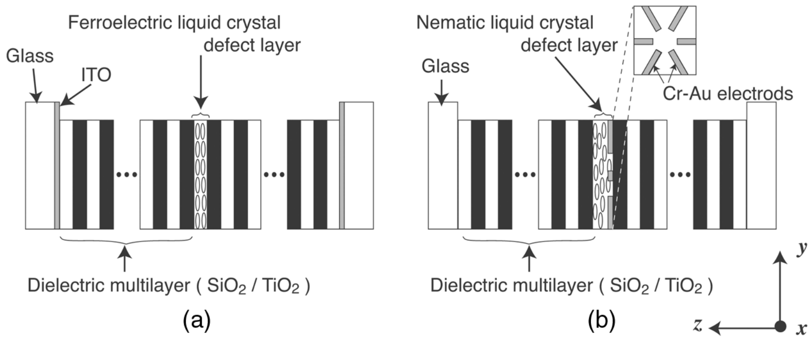

FIGURE 1 A schematic view of the one-dimensional (1-D) photonic crystal (PC) containing (a) a ferroelectric liquid crystal (FLC) defect layer or (b) a in-plane switchable nematic liquid crystal (NLC) defect layer.

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FLC (Chisso, CS1029) or NLC (Merck, E44) are sandwiched between two dielectric multilayers with 1-μm spacers.

In the 1D PC with FLC defect as shown in Figure 1(a), an In-Sn oxide (ITO) layer deposited on glass substrate was used as electrodes for control the FLC molecules directions. The top surface of the dielectric multilayer is coated with a polyimide (JSR Corporation, AL1254) and unidirectionally rubbed along the *y*-axis shown in Figure 1. In absence of an electric field, the molecular axis of the FLC aligns parallel to the substrate. DC voltage was applied between ITO layers to change the molecular orientation of the FLC in the defect layer. In order to investigate the characteristic of the defect mode, the transmission spectrum of the light propagating through the 1D PC with FLC defect was measured from the opposite side of the cell using a charge-coupled device (CCD) multichannel spectrometer (Hamamatsu Photonics, PMA-11) and a halogen lamp was used as light source. Resolution of the CCD multichannel spectrometer is 3 nm.

On the other hand, in order to control NLC director in defect layer, six directional Cr-Au electrodes are patterned on top surface of the dielectric multilayer as shown in Figure 1(b). Thicknesses of Cr and Au electrodes are 20 nm and 50 nm, respectively. The width of electrodes is 25 μm and the distance of opposite electrodes is 100 μm. The top surfaces of the dielectric multilayer and Cr-Au electrodes patterned dielectric multilayer are coated with a polyimide (JSR Corporation, JALS-2021-R2) for a homeotropic alignment layer. In absence of an electric field, the molecular axis of the NLC aligns perpendicular to the substrate. A rectangular wave voltage of 1 kHz was applied between six electrodes to change the molecular orientation of the

NLC in the defect layer. We observed reorientation of the NLC molecules with a polarization microscope (Nikon, ECLIPSE E600POL). The transmission spectra were measured by the CCD multichannel spectrometer attached to polarization microscope.

RESULTS AND DISCUSSION

Figures 2(a)–(c) show transmission spectra of the 1D PC with the FLC defect layer as a function of the angle θ between the polarization direction of the light and the director of FLC molecules. The incident light is linearly polarized using a polarizer installed in front of the sample cell. The stop band appeared between 530 nm and 740 nm. DC voltage of 10 V was applied between ITO layers in order to align FLC molecules in the defect layer unidirectionally, and the polarizer was rotated with respect to the orientation direction of FLC molecules. As is evident from Figures 2(a) and (b), three peaks appear in the stop band, which correspond to the localized state in the PBG caused by the introduction of the defect layer in the periodic structure. These are so-called "defect-mode". The wavelengths of defect modes depend on θ. These results indicate that the defect mode wavelength is

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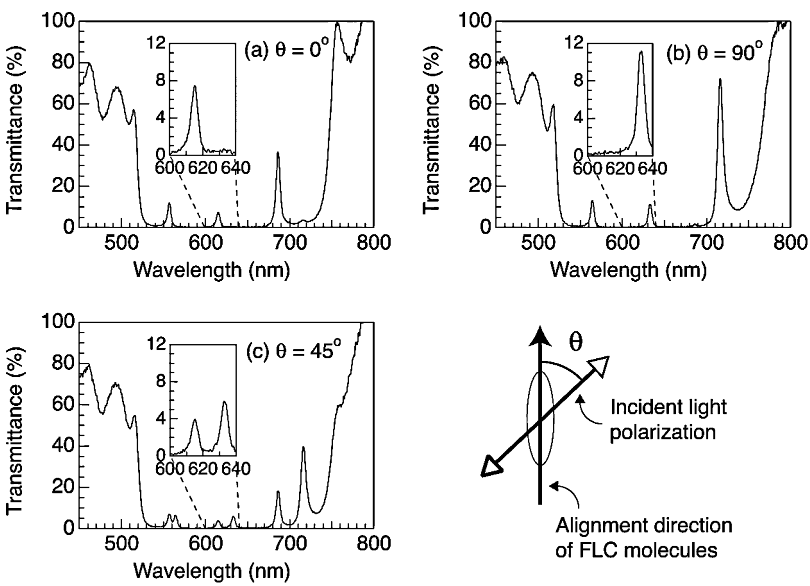

FIGURE 2 Transmission spectra of 1D PC with FLC defect as a function of incident light polarization angle.

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determined by the optical length of the defect layer and the incident light at $\theta = 0^\circ$ and 90° feels extraordinary and ordinary refractive indices, n_e and n_o, of the FLC, respectively.

On the other hand, at $\theta = 45^\circ$, six peaks appear in the stop band and their wavelengths coincide with those for $\theta = 0^\circ$ and $\theta = 90^\circ$, as shown in Figure 2(c). If the defect mode wavelength is determined by the effective refractive index of the defect $n(\theta)$ for the incident light, the defect mode peak at $\theta = 45^\circ$ should appear at an intermediate wavelength between these of $\theta = 0^\circ$ and 90°. However, as shown in Figure 2(c), the defect modes do not appear at the wavelengths corresponding to $n(\theta)$ of FLC defect layer but appear at both wavelengths corresponding to n_o and n_e of FLC molecules. In addition, the peak intensities at $\theta = 45^\circ$ are half of those at 0° and 90°. Therefore, these results indicate that in the 1D PC with FLC defect, the defect mode wavelengths is not determined by the effective refractive index in the defect layer and the degeneracy of refractive index of FLC is solved.

As pervious reported, the defect mode wavelength could be continuously tuned by changing the refractive index of the defect layer containing NLC [12]. In this PC with NLC defect geometry, the LC molecules are originally parallel to the y-axis in Figure 2 and incline toward the z-axis. In this case, there is no in-plane component of the molecular realignment. On the other hand, in the geometry of 1D PC with FLC defect studied here, the molecular long axis rotates in the x-y plane, which is quite different from the case of 1D PC with NLC defect.

Figure 3 shows the detail of the θ-dependence of the defect mode spectrum in the 1D PC with FLC. The defect mode peak wavelengths are independent of the polarization angle of the incident light, and only the peak intensities changed. For the defect mode at 609 nm, the transmission intensity has maximum at $\theta = 0^\circ$ and 180°. At these angles, the incident light polarization is parallel to the molecular long axis (n_e axis) of FLC in the defect layer. On the contrary, no transmission is observed at $\theta = 90^\circ$. In this case, the polarization of incident light is perpendicular to the n_e axis of FLC. These results mean that, for the defect mode at 609 nm, only the light with polarization parallel to the n_e axis can propagate through 1D PC with FLC defect. On the other hand, for the defect mode at 633 nm, the transmission intensity has maximum at 90°, while no transmitted light is obtained at 0°. This indicates that only the light with the polarization parallel to the molecules short axis (n_o axis) of the FLC in the defect can propagate through the 1D PC.

We demonstrated electrical tuning of the defect mode upon applying DC voltage. Figures 4(a) and (b) show transmission spectra at -10 V

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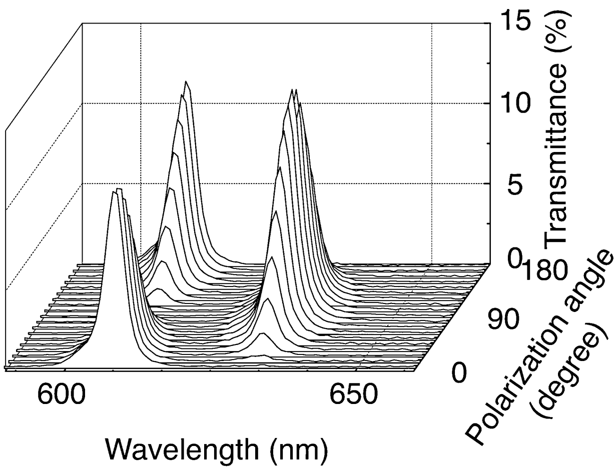

FIGURE 3 Incident light polarization angle dependence of defect mode peak of 1D PC with FLC defect.

and 10 V. The polarization direction of the light was parallel to the molecular alignment of the FLC at –10 V. The angle θ between the polarization direction of the incident light and the alignment direction of the FLC molecules at 10 V is 50°, because a molecular tilt angle of the FLC is 25°.

Therefore, transmission spectrum at –10 V shows three peaks originating from n_e, while transmission spectrum at 10 V shows six peaks due to both n_e and n_o. We have also measured applied voltage dependence of the transmission intensity at the defect mode. A triangular voltage was applied between ITO layers to change the

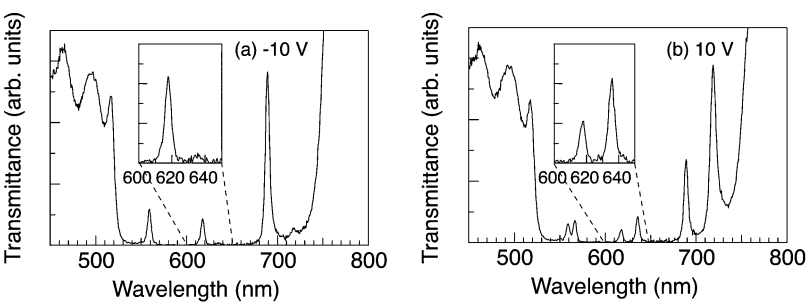

FIGURE 4 Transmission spectra of the 1D PC with the FLC defect (a) at – 10 V and (b) at 10 V.

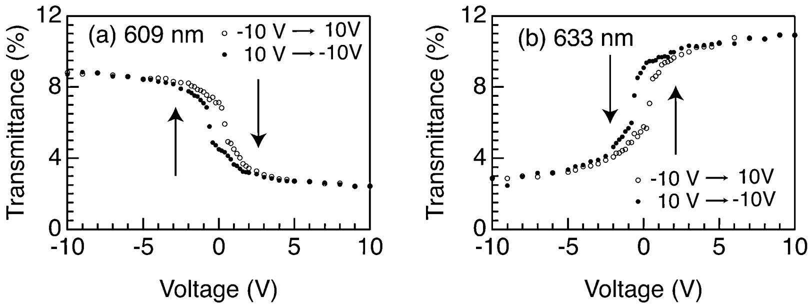

FIGURE 5 Voltage dependence of defect mode of 1D PC with FLC defect layer.

molecular alignment of the FLC in the defect layer. Figure 5 shows voltage dependence of defect mode peak intensities. Defect mode wavelengths didn't shift but defect mode peak intensities show hysteresis characteristics. We also confirmed bistability and memory effect of FLC defect mode.

From above results, it is found that the transmitted light at defect mode wavelength is polarized along ordinary or extraordinary optical axes of LC molecules in defect layer. In other words, 1D PC with FLC defect acts as a polarizer whose polarization direction can be controlled upon changing the optical axis in plane. In 1D PC with FLC, however, it is difficult to rotate LC director to any direction in plane. We fabricated 1D PC with in-plane switchable NLC defect layer to rotate LC director in plane as shown in Figure 1(b) and demonstrated to control polarization direction of the transmitted light at defect mode wavelength.

Polarization microscope images of the NLC defect layer are shown in Figure 6 when polarizers are set in crossed nicol position. In Figure 6, a rectangular wave voltage of 200 V with a frequency of 1 kHz was applied between hatched and non-hatched electrodes. The azimuthal angle ϕ is the direction of applied electric field at the center of image. In this system, ϕ can be controlled by adjusting the potential applied to six electrodes. When NLC director aligned along x-axis as shown in Figure 6(a), NLC at center of the electrodes is in dark state under the crossed nicol. On the other hand, in Figure 6(b), NLC aligned at $\phi = 60^\circ$ and bright state under is obtained. Therefore, we confirmed that direction of NLC molecules could be electrically controlled in plane of the defect layer.

We investigated the dependence of the defect mode peaks on the polarization direction of the incident light. Microscopic transmission

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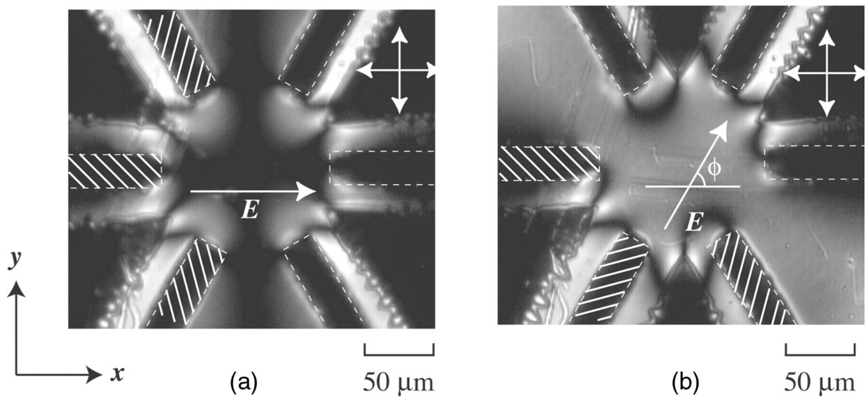

FIGURE 6 Polarization microscope images of the NLC defect layer as a function of direction of applied electric field (a) $\phi = 0^\circ$ and (b) $\phi = 60^\circ$.

spectra of the light propagating along z-axis were measured without an analyzer. Figure 7 shows the transmission spectra for the defect mode peaks at $\phi = 0^\circ$ as a function of the polarization angle of the incident light. The defect mode peak wavelengths did not shift by varying the polarization angle. On the other hand, peak intensities changed with the polarization angle of the incident light. As the same manner as the FLC defect mode, 1D PC with NLC defect transmits only the light with the polarization parallel and perpendicular to the molecular long axis in the defect layer.

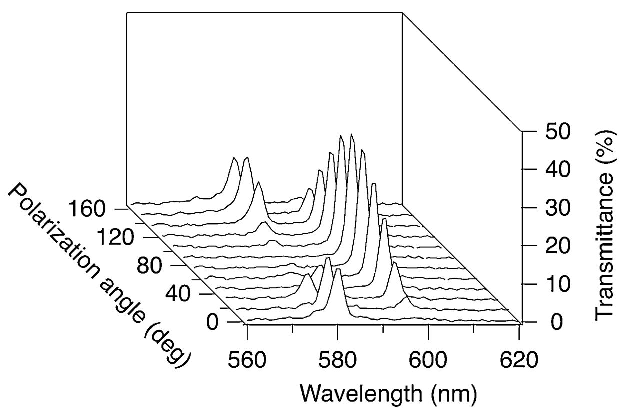

FIGURE 7 Incident light polarization angle dependence of defect mode peak of 1D PC with NLC defect.

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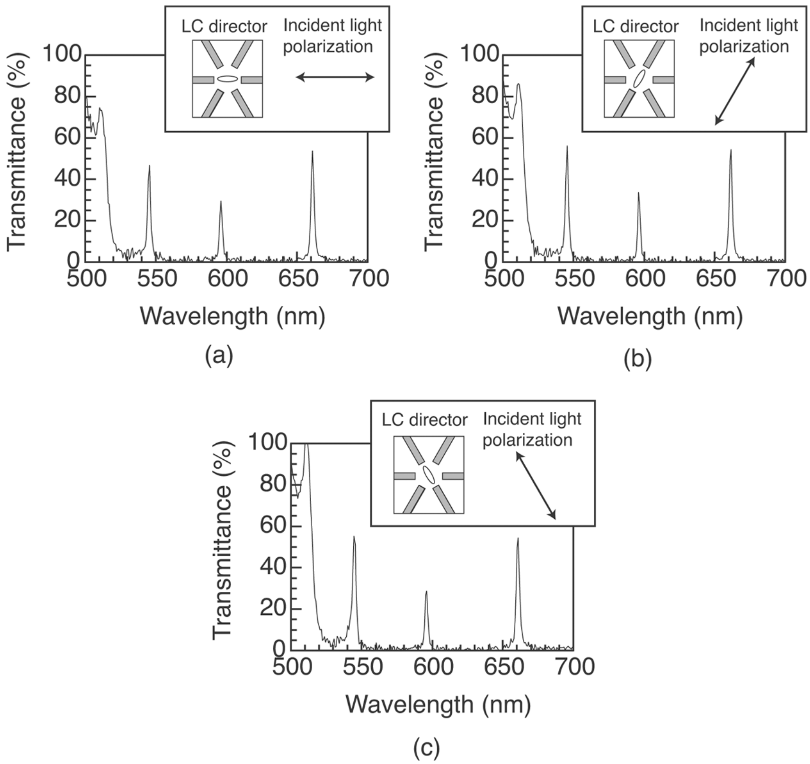

FIGURE 8 Transmission spectra of 1D PC with NLC defect as a function of incident light polarization angle and applied electric field direction.

Figure 8 shows transmission spectra of the 1D PC with in-plane switchable NLC defect as a function of incident light polarization angle and applied electric field direction. In Figure 7, transmission intensities of the defect modes varied with rotating incident light polarization, because transmitted light at defect mode wavelength was polarized. However, in Figure 8, the molecular alignment in also rotated by changing the light direction and is parallel to the incident light polarization. As a result, transmission intensities at defect mode wavelength are constant. This means that, at the defect mode wavelength, the light with the polarization parallel to the molecular long axis, i.e., parallel to the filed direction, can propagate through the 1D PC. Therefore, polarization angle of transmitted light at defect mode wavelength can be controlled by the rotation of NLC molecules in defect layer.

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CONCLUSIONS

Defect mode peaks were observed in the periodic structure including a FLC and a NLC as a defect layer. Upon applying voltage, the peak position remained unchanged, while peak intensities changed in 1-D PC with FLC defect. We also demonstrated that the polarization angle of the light propagating through 1D PC with in-plane switchable NLC defect could be controlled by field-induced in-plane realignment of NLC molecules.

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