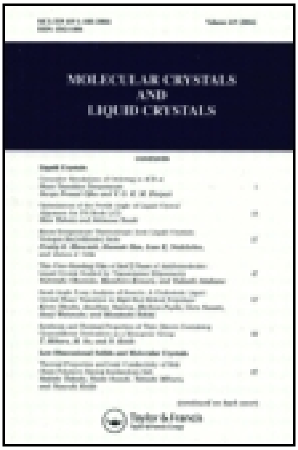

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Low Driving Voltage Tunable Laser Based on One-dimensional Photonic Crystal Containing Liquid Crystal Defect Layer

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Electrical tuning of a wavelength of a defect mode lasing in a one-dimensional periodic structure has been demonstrated using a dye-doped nematic liquid crystal as a defect layer in the periodic structure. Lasing wavelength is widely tuned upon applying the electric field, which is due to the refractive index change in the defect layer caused by the field-induced realignment of the liquid crystal molecules.

Keywords: defect mode; lasing; photonic crystal

INTRODUCTION

Photonic crystals (PC) are materials with a new concept that have a photonic band gap (PBG) in which the existence of light is forbidden when the medium has a three-dimensional (3D) periodic structure with the periodicity of the order of the optical wavelength [1,2]. PCs have attracted considerable attention from both fundamental and practical points of view. Novel physical concepts such as PBG have been theoretically predicted and various applications of PCs have been proposed. Especially, the study on a defect mode in PBG is one of the most attractive subjects, since photons are localized and low threshold

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laser based on the defect mode of the PCs should be expected. However a complete 3D PC with a periodicity equivalent to visible wavelength remains a technical challenge [3]. Not only 3D PCs but also one-dimensional (1D) PCs are attractive. Although the 1D PC does not have a complete PBG, there are plenty of applications using extraordinary dispersion of the photon and the localized photonic state in a defect layer. So far, intensive studies on 1D PC applications have been reported: the air-bridge microcavities [4], the photonic band-edge laser [5–7], the nonlinear optical diode [8] and the enhancement of optical nonlinearity [9,10].

On the other hand, liquid crystals (LCs) have a large optical anisotropy and are sensitive to an external stress such as an electric field, and therefore have been a vital material in electrooptic devices at present. Based on such optical anisotropy and field sensitivity, a tunable photonic crystal has been proposed in opal or inverse opal infiltrated with LC [11–16]. Although opal and inverse opal are simple and inexpensive approach to realize a 3D PC using self-organization of colloidal particles [17,18], the introduction of defect into the 3D periodic structure is a problem that must be resolved.

Recently we have introduced a LC layer in dielectric multilayer structure as a defect in a 1D PC [19], in which the wavelength of defect modes were controlled upon applying electric field in a basis of the change in optical length of the defect layer caused by the field-induced molecular reorientation of the LC. In this paper, we report wavelength tunable laser based on an electrically controllable defect mode in a 1D dielectric periodic structure containing a dye-doped LC as a defect layer. The lasing in 1D PC with a LC defect layer can be tuned in a wide range of wavelength upon applying electric field.

EXPERIMENTAL PROCEDURE

A 1D PC with a netamtic LC (NLC) defect is shown in Figure 1. A dielectric multilayer consisting of an alternating stack of SiO_2 and TiO_2 layers deposited on an In-Sn oxide (ITO) coated glass substrate is used as the 1D PC. 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 nm and 64 nm, respectively. The number of SiO_2-TiO_2 pairs on each substrate is five. The top surface of the dielectric multilayer is coated with a polyimide (JSR Corporation, AL1254) and unidirectionally rubbed along y-axis in Figure 1. The thickness of the polyimide layer is about 50 nm.

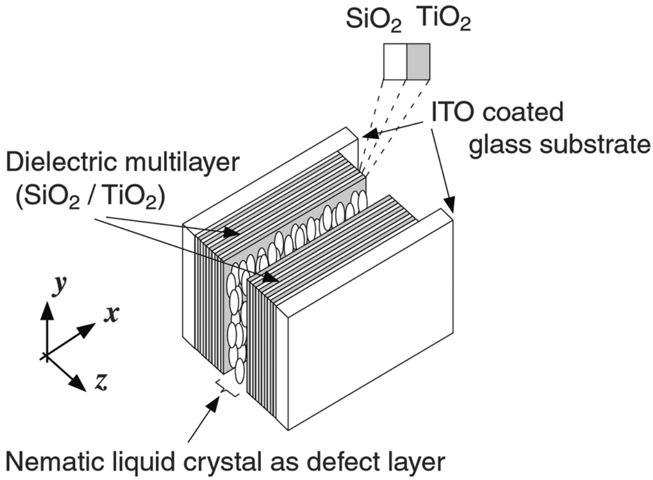

FIGURE 1 Schematic view of one-dimensional (1D) photonic crystal (PC) with nematic liquid crystal (NLC) defect layer.

In order to introduce the defect layer, a dye-doped nematic LC (Merck, E47) was sandwiched between substrates with dielectric multilayer using 1-μm spacers. The refractive index anisotropy Δn of E47 is 0.209 at room temperature. In the absence of an electric field, the long molecular axis of the LC is aligned parallel to the substrates (*y*-axis). As a laser dye doped in the LC [2-[2-4-(dimethylamino) phenyl] ethenyl]-6-methyl-4H-pyran-4-ylidene propanedinitrile (Exciton, DCM) was used. The concentration of the dye is 0.5 wt.%.

A rectangular wave voltage of 1 kHz was applied between ITO layers to change the molecular alignment of the LC in the defect layer. In order to investigate the characteristics of defect mode, the transmission spectrum of the linearly polarized light propagating along the *z*-axis was measured from the opposite side of the cell using a charge-coupled device (CCD) multi-channel spectrometer (Hamamatsu photonics, PMA-11) having a spectral resolution of 3 nm. A halogen lamp used as a light source and incident light entered perpendicularly to the cell plate.

A second harmonic light of a Q-switched Nd:YAG laser (Spectra Physics, Quanta-Ray INDI) is used for an excitation source of the lasing, whose wavelength, pulse width and pulse repetition frequency are 532 nm, 8 ns and 10 Hz, respectively. The illumination area on the sample is about 0.03 mm^2. The excitation laser beam irradiated the sample perpendicularly to the cell plate. The emission spectra from the 1D PC with a dye-doped nematic LC were measured from the opposite side of the cell using the CCD multi-channel spectrometer. In order to control the emission wavelength, the orientation of the LC molecules in the defect layer was changed upon applying a rectangular wave voltage of 1 kHz.

SIMULATION PROCEDURE

A distribution of electric field in the 1D PC with NLC defect was analyzed using a finite difference time domain (FDTD) calculation. This calculation is an analysis of the Maxwell equations by according to the Yee algorithm [20] in discrete time and lattices. In calculation, it is assumed that the light propagates through 1D PC with NLC defect along one direction (z-axis). Difference approximations of Maxwell equations as a function of z are given by

$$E_x^{t+1}(z) = -\frac{1}{\varepsilon\varepsilon_0}\frac{\Delta t}{\Delta z}\left\{H_y^{t+\frac{1}{2}}\left(z+\frac{1}{2}\right) - H_y^{t+\frac{1}{2}}\left(z-\frac{1}{2}\right)\right\} + E_x^t(z),$$

$$H_y^{t+\frac{1}{2}}\left(z+\frac{1}{2}\right) = -\frac{1}{\mu_0}\frac{\Delta t}{\Delta z}\left\{E_x^t(z+1) - E_x^t(z-1)\right\} + H_y^{t-\frac{1}{2}}\left(z+\frac{1}{2}\right),$$

where E_x, H_y, ε_0, μ_0 and ε are electric field, magnetic field, dielectric constant of free space, magnetic permeability of free space and dielectric constant of light propagating medium. ε_{NLC} at NLC defect layer is determined by NLC molecular dielectric constants ($\varepsilon_1, \varepsilon_2,$ and ε_3), tilt angle θ and azimuthal angle ϕ as shown in Figure 2, and is given by

$$\varepsilon_{NLC} = \varepsilon_2 \sin^2\phi + \left(\varepsilon_1 \cos^2\theta + \varepsilon_3 \sin^2\theta\right)\cos^2\phi.$$

In this calculation, ITO and polyimide layers are neglected. At boundaries of a calculation space, Mur's first order absorbing boundary condition has been used [21].

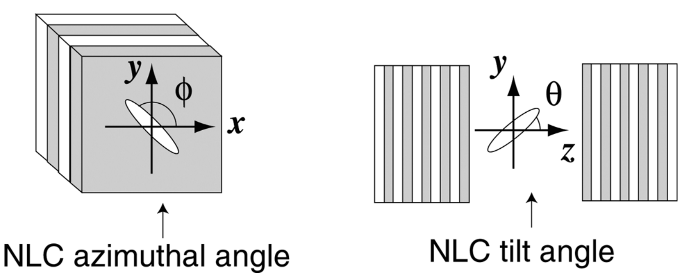

FIGURE 2 Schematic view of azimuthal angle ϕ and tilt angle θ of NLC molecules in defect layer.

RESULTS AND DISCUSSIONS

Figure 3 shows transmission spectra of the 1D PC with 1-μm NLC defect layer as a function of the applied voltage. The incident light was polarized along the *y*-axis which corresponds to the rubbing direction and the initial orientation direction of the NLC molecules in the defect layer. Regardless of the application of voltage, PBGs are observed in the spectral range from 530 nm to 750 nm and these bandwidths do not depend on the voltage. Some sharp peaks appeared in PBG. These peaks originate from defect mode induced by the introduction of NLC defect layer is the periodic structure. Peaks of the defect modes shift to shorter wavelengths with increasing voltage. This peak shift originates from the decrease in the optical length of the defect layer caused by the field-induced reorientation of the NLC molecules. Therefore, we confirmed that the wavelength of the defect mode in 1D PC with the NLC layer could be controlled upon applying voltage.

Figure 4 shows calculated electric field distributions in the 1D PC with NLC defect layer as functions of incident light wavelength λ and tilt angle θ of NLC in the defect layer. In this calculation, incident light given by sin curve with λ was entered from right side of 1D PC. NLC defect, SiO_2 and TiO_2 layer thicknesses are 1 μm, 103 nm and 64 nm, respectively, which correspond to our experimental conditions. In defect layer, ordinary and extraordinary refractive indices of NLC are 1.5 and 1.7, respectively. The background images are corresponded to the calculated 1D PC system and the tilt angle θ of the NLC defect

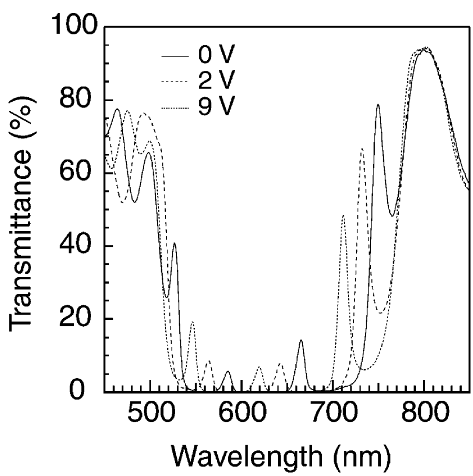

FIGURE 3 Transmission spectra of 1D PC with NLC defect layer as a function of the applied voltage.

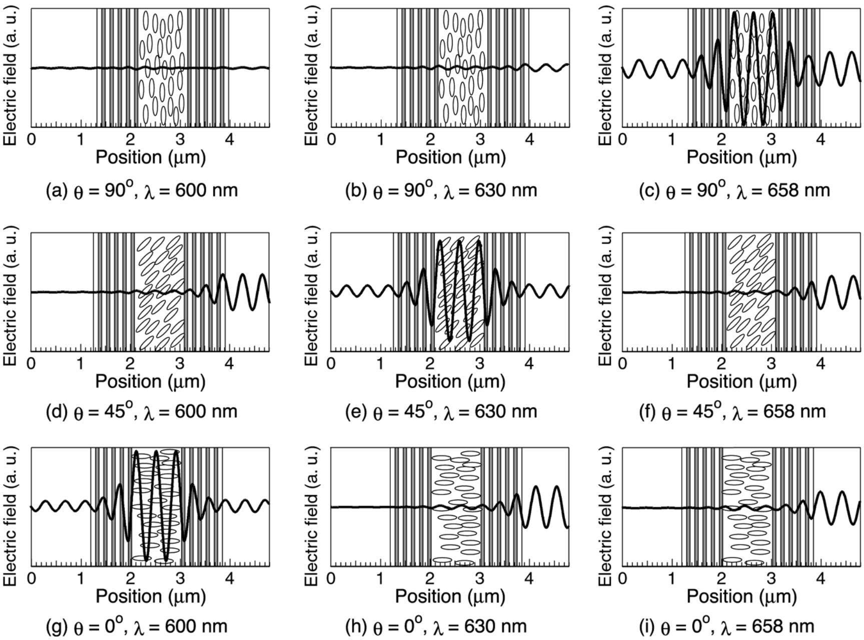

FIGURE 4 Distributions of electric field calculated by finite difference time domain (FDTD) method as functions of NLC molecular tilt angle θ and incident light wavelength λ.

layer. In Figures 4(c), (e) and (g), it is found that electric fields in the defect layer were amplified and standing wave modes arose, resulting in a partial transmission of the light. These results correspond to the defect mode in the band gap. On the other hand, in other conditions, electric fields of incident light are attenuated simply and there are no transmitted light. It should be noted that defect mode wavelength is shifted by changing NLC tilt angle θ. These calculated results explain the defect mode shift caused by the field-induced molecular reorientation shown in Figure 3.

Figure 5 shows emission spectra of the 1D PC with the dye-doped NLC as a function of the applied voltage. A sharp emission peak appears above a threshold of the excitation. In Figure 5, the pump energy is 10 μJ/pulse. Figure 6 shows the pump energy dependence of the emission peak intensity at 0 V. Above the threshold at a pump pulse energy of about 5 μJ/pulse, the emission intensity drastically increases. This indicates that there exists a lasing threshold above which a light amplification accrues. The full width at half maximum (FWHM) of the lasing peak is about 3 nm, which is limited by the

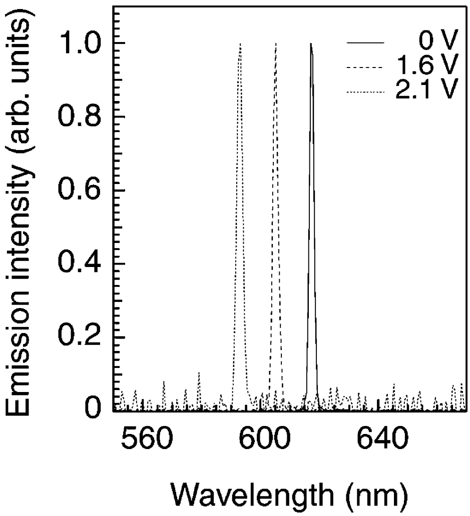

FIGURE 5 Lasing spectra of 1D PC with dye-doped NLC defect layer as a function of applied voltage.

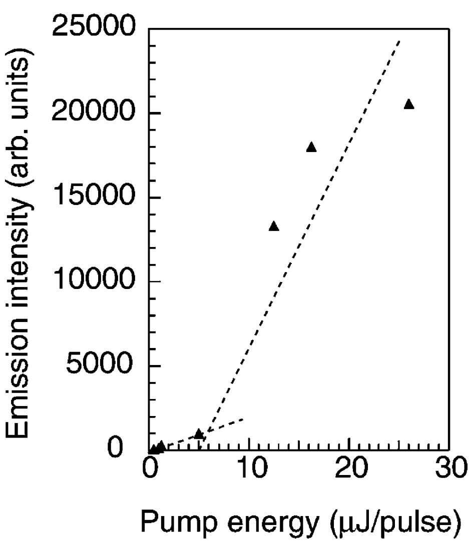

FIGURE 6 Pump energy dependence of emission intensity at defect mode wavelength.

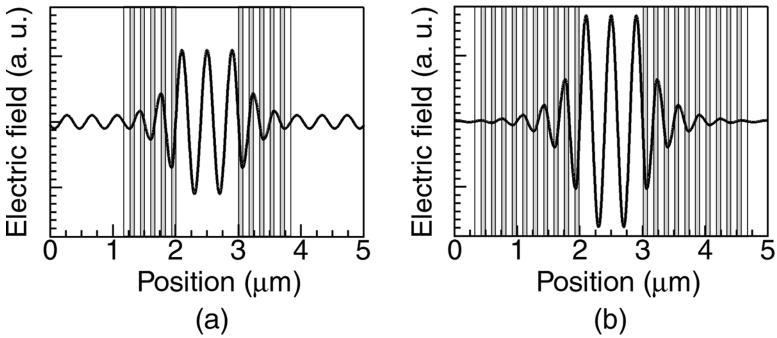

FIGURE 7 Distributions of electric field in the 1D PC with the defect calculated using a FDTD technique as a function of the periodicity of 1D PC.

spectral resolution of the CCD spectrometer used in this experiment. The FWHM of this emission peak is narrower than that of the transmission peak of the defect mode (10 nm) shown in Figure 3. This indicates that the emission peak in the band gap (Fig. 5) is not the spontaneous emission of DCM passing through the narrow band window of a defect mode. It should be noted that lasing peak shifts toward shorter wavelengths with increasing voltage as the same manner as the defect modes shift shown in Figure 3. The wavelength shift of the lasing peak is about 24 nm even upon applying low voltage.

Defect mode lasing mentioned above has been demonstrated by using 10-period 1D PC with dye-doped NLC defect. In order to realize lower threshold lasing, we should consider an optimization of 1D PC system. In 1D PC with NLC defect layer, amplification of electric field may be related to the strength of photon localization. Then we have calculated a dependence of the light localization at the defect layer on the periodicity of the 1D PC. Figure 7 shows distributions of the electric field of 1D PC with defect layer at defect mode wavelength as a function of periodicity of 1D PC. Defect layer thickness, refractive index of defect layer and incident light wavelength are 1 μm, 1.5 and 600 nm, respectively. Electric field of 20 period 1D PC with defect is more efficiently localized at the defect as shown in Figure 7(b). Low threshold defect mode lasing might be realized by an optimization of the periodicity of 1D PC.

CONCLUSIONS

We demonstrated the electrical tuning of the defect mode lasing in a 1D PBG using a nematic liquid crystal as a defect layer. The wavelength shift of the defect mode originates from the change in the optical length of the defect layer caused by the field-induced molecular reorientation of the LC, which was confirmed by numerical calculations. Laser emission was observed upon the irradiation of pump laser beam above the threshold energy. Lasing wavelength was widely tuned with a low voltage.

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