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Optical Characteristic and Laser Action in Hybrid Photonic Crystal with Cholesteric Liquid Crystal

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A photonic crystal having a periodic dielectric structure with a periodicity in a range of optical wavelength has attracted much attention from both fundamental and practical points of view. In the photonic crystal, the propagation of light is inhibited in the certain energy range of photons, which results in an appearance of a photonic band gap (PBG) [1]. The PBG is similar to the forbidden electronic energy band for electrons in a crystal with the periodic potential. Furthermore photons are localized by the introduction of a defect in the photonic crystal [2]. Various applications are expected by utilizing of the localization of photons such as low threshold lasers and microwaveguides [3-7].

On the other hand, CLCs and chiral smectic liquid crystals, which have periodic helical structures with a periodicity of optical wavelength, can be regarded as one-dimensional photonic crystals. Lasing at the band edge has been reported in CLCs [8-10] and chiral smectic liquid crystals [11]. These laser actions in the one-dimensional helical structure of chiral liquid crystals are interpreted to be based on the band edge effect of the one-dimensional PBG in which photon group velocity is suppressed.

In this paper, we have carried out the theoretical calculation in order to investigate the optical characteristic of a hybrid photonic crystal with CLC and investigated laser action in a hybrid photonic crystal with CLC.

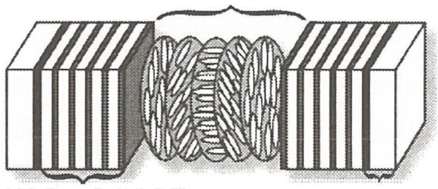

Fig. 1. Hybrid photonic crystal with CLC

Figure 1 shows a hybrid photonic crystal with CLC. The CLC was introduced between the dielectric multilayers consisting of the 5-periods alternating stack deposited on a glass substrate. We have performed theoretical calculations of the light propagation in a hybrid photonic crystal with CLC, using a method of characteristic matrices. This method is a numerical analysis based on the Maxwell equations that can be used to calculate the light propagation quantitatively in a medium with refractive index varying along one direction. The light propagating along the z-axis with frequency ω is given by

$$\frac{d\mathbf{\Psi}(z)}{dz} = \frac{i\omega}{c}\mathbf{D}(z)\mathbf{\Psi}(z),$$

where $\mathbf{D}(z)$ is a derivative propagation matrix and $\mathbf{\Psi}(z) = (E_x, H_y, E_y, H_x)^T$.

We assumed that the refractive indices of the dielectric multilayer are 1.46 and 2.35, which correspond to the refractive indices of SiO_2 and TiO_2, and thier thicknesses are 109 and 67 nm, respectively. The center wavelength of the PBG was about 650 nm as the optical thickness of each layer to be one-quarter of 650 nm.

The CLCs that have the helicoidal periodic structure were injected between dielectric multilayers. We assumed that the thickness, the helical pitch and the extraordinary and ordinary refractive indices of the CLC are 8.6 μm, 360 nm, 1.78 and 1.52, respectively, which correspond to those of CLC used in the followed experiment.

Figure 2 shows the calculated transmission spectra of a hybrid photonic crystal with CLC and CLC without the multilayers. The PBG of CLC is observed in the spectral range from 550 nm to 645 nm. On the other hand, the PBG of the hybrid photonic crystal is observed in the spectral range from 520 nm to 800 nm which corresponds to the PBG of the dielectric multilayer. In the transmission spectrum of a hybrid photonic crystal with CLC, many peaks appeared at regular interval in the PBG, which are related to the defect modes. As we took a look in detail at the spectrum, those peaks appeared at regular interval although the peaks out of the PBG of the CLC were split. However an additional peak appeared at 643.3 nm between the peaks observed at regular interval. It should be noted that the wavelength of the additional peak corresponds to the wavelength of the band edge of CLC. Full width at half-maximum of the peak is 0.02 nm, whose Q-value is 32165 that is more than 10 times higher than that of the other peaks.

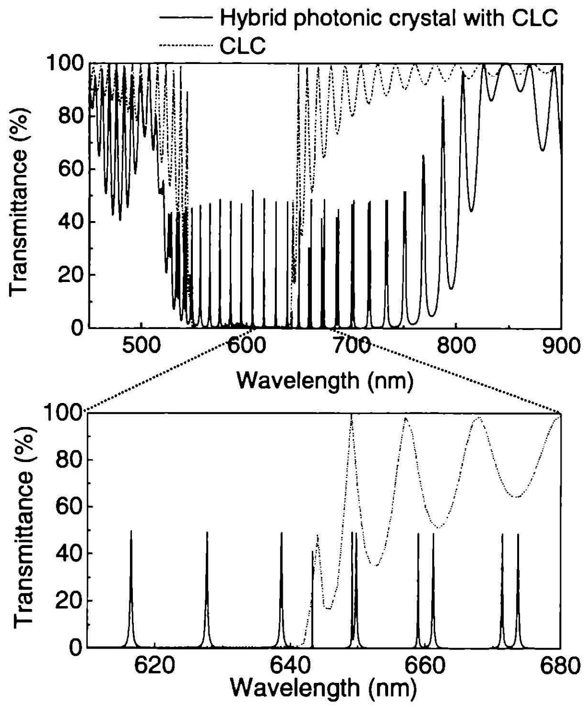

Fig. 2. Transmission spectra of hybrid photonic crystal with CLC and CLC without multilayers

We have composed a hybrid photonic crystal with CLC and investigated laser action experimentally. The dielectric multilayers consisting of the 5-periods alternating stack of SiO_2 and TiO_2 layers deposited on an In-Sn-Oxide (ITO)-coated glass substrate are used as the outer periodic structure. The top surface of the dielectric multilayer was coated with polyimide (JSR, AL1254) and unidirectionally rubbed to realize a planar alignment in which the helix axis is perpendicular to the substrates.

The CLCs were injected between dielectric multilayers. The CLC host with a left-handed helix was prepared by mixing an optically active agent with a chiral center (Merck, S-811) and a nematic liquid crystal (Merck, E44) with positive dielectric anisotropy. The S-811 concentration was 32 wt% in the nematic liquid crystals. As a laser dye dopant in the CLCs, [2-[2-4(dimethylamino)phenyl] ethenyl]-6-methyl-4H-pyran-4-ylidene propanedinitrile (Exciton, DCM) was compounded, whose concentration was 1 wt%.

A second-harmonic light of a Q-switch Nd:YAG laser (Spectra Physics, Quanta-Ray INDI) was used for the excitation of the doped dye in the CLC, whose wavelength, pulse width, and pulse repetition frequency were 532 nm, 8 ns, and 10 Hz, respectively. The excitation laser beam irradiated the sample perpendicularly to the cell plate and was focused with a lens. The emission spectra from the cell were measured from the opposite side of the cell using the CCD multichannel spectrometer (Oriel Instruments, MS257) having a spectral resolution of 0.2 nm.

Figures 3(a) and (b) show the emission spectra at 18 and 9.0 nJ/pulse pumping of the hybrid photonic crystal with CLC. At the pumping energy of 9.0 nJ/pulse shown in Fig. 3(b), many emission peaks appeared. These peaks are based on the spontaneous emission light passing out through narrow spectral windows due to the defect. Those peaks are observed at regular interval although the three peaks at longer wavelength (> 645 nm) were split. Furthermore one additional peak was observed at the wavelength of 643.4 nm. From the result, the peak at the wavelength of 643.4 nm is based on the mode with high-Q at the band edge of CLC.

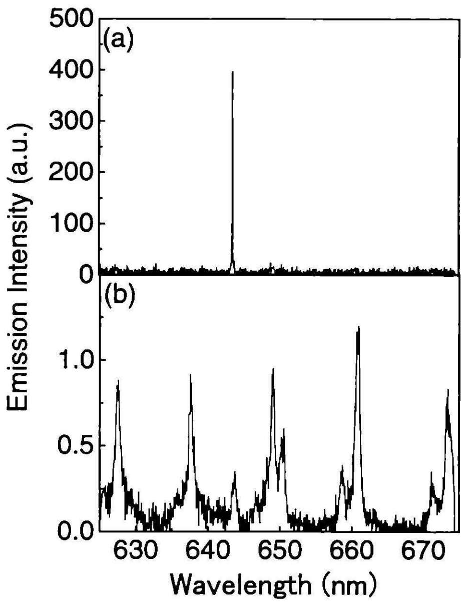

Fig. 3. Emission spectra of hybrid photonic crystal with CLC at the pumping energy of (a) 18 nJ/pulse and (b) 9.0 nJ/pulse

At the pumping energy of 18 nJ/pulse shown in Fig. 3(a), only one sharp emission peak appears. At a low pumping energy, emission intensity increases in proportion to pumping energy. Above a threshold at the pumping energy of 9.0 nJ/pulse, emission intensity nonlinearly increases and a sharp emission peak appears. From the result, the emission peak at the wavelength of 643.4 nm shown in Fig. 3(a) is based on the laser action. The single-mode lasing wavelength of 643.4 nm shown in Fig. 3(a) corresponds to the wavelength of the additional peak in Fig. 3(b). It should be noted that the single-mode laser action is based on the additional mode with high-Q at the band edge of CLC.

In conclusion, the theoretical calculation of light propagation in a hybrid photonic crystal with CLC was carried out and we found that one additional mode with high-Q exists at the wavelength of the band edge of CLC. The single-mode laser action was observed in the hybrid photonic crystal with dye-doped CLC experimentally, which was based on the additional mode with high-Q at the band edge of CLC.

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