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Electric Field Analysis of Defect Mode in Cholesteric Liquid Crystal Constructed with Different Periodicities

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Photonic crystals (PCs) having a three-dimensional ordered structure with a periodicity of optical wavelength has attracted considerable attention from both fundamental and practical point of view, because in such materials, a photonic band gap exists in which the existence of a certain energy range of photon is forbidden, and various applications of PCs have been proposed.[1,2] Particularly, the study of stimulated emission in the photonic band gap, a spontaneous emission is inhibited and low-threshold lasers based on photonic crystals are expected. In a one-dimensional (1D) periodic structure, laser action has been expected at the photonic band edge where the photon group velocity approaches zero.[3]

Liquid Crystals (LCs) including chiral molecules have a self-organized helical structure which can be regarded as a 1D periodic structure. In such system, there is a so-called stop band in which a light cannot propagate, which is considered a 1D pseudo-bandgap. Lasing at the band edge has been reported in cholesteric liquid crystal (CLC), chiral smectic LC and polymerized CLC.[4-7] These laser actions in the 1D helical structure of the chiral LCs are interpreted to be based on the band edge of the 1D photonic band gap in which the photon group velocity is suppressed.

On the other hand, a localization of a light based on a defect mode caused by an imperfection in the periodic structure has been expected as potential applications such as low-threshold lasers and microwavegides. In the chiral LC, several new type defect modes have been proposed. For example, an introduction of an isotropic defect layer into the periodic helical structure of the CLC has been theoretically studied.[8] From a concept of a phase jump, an existence of a twist defect which is a discontinuous point of the periodic helical structure has been predicted.[9] In this system, we have experimentally demonstrated the defect mode in the 1D photonic band gap of the CLC having the twist defect by using photopolymerized CLC (PCLC) films, and the laser action based on the twist defect mode has also been observed in the dye-doped PCLC composite film with the twist defect.[10] The defect mode caused by a partial deformation of the helix in the CLC has been proposed.[11] In this model, an optically induced local modulation of helical twisting power is used as a method to induce a helix defect, which can be achieved by photochemical effects. In a hybrid system consisting a nematic and a cholesteric LC, a phase retardation defect mode have been demonstrated by an introduction of a nematic LC defect layer into the PCLC.[12]

In this paper, we have studied the defect mode in the 1D photonic band gap of the CLC consisting two helicoidal periodicities. Optical properties of the CLC consisting two helicoidal periodicities have been analyzed by calculating electromagnetic wave transmission.

Figure 1 shows a schematic view of the CLC consisting two helicoidal periodicities. In this study, CLC_1 and CLC_2 are defined as both sides CLCs and a center part, respectively. The helical pitch of CLC_2 is shorter than the CLC_1, but refractive indices of the CLC_1 and CLC_2 are equivalent. Therefore, the variation of CLC_2 from CLC_1 is only the helical pitch.

In order to investigate optical properties of CLC, we have performed a theoretical calculation of the light propagation in the CLC consisting two helicoidal periodicities by using a 4x4 matrix. This method is a numerical analysis of Maxwell equations which can quantitatively calculate the light propagation in a medium with a refractive index varying along one direction. The light propagating along the *z*-axis with frequency ω is given by

$$\frac{d\Psi(z)}{dz}=\frac{i\omega}{c}D(z)\Psi(z) \qquad (1)$$

where D(z) is a derivative propagation matrix and $\Psi(z) = (E_x, H_y, E_y, H_x)^T$. From this equation, we can obtain transmission or refrection properties of the CLC.

We have also calculated the electric field distribution in the CLC consisting two helicoidal periodicities by using a finite difference time domain (FDTD) method. This calculation is an analysis of Maxwell equations by according to the Yee algorithm in discrete time and lattices. When Maxwell equations of the electromagnetic field propagating in the anisotropic medium along *z*-axis are approximated by finite differences, we obtain

$$E_x^{t+1}(i)=-\frac{\varepsilon_{yy}\varepsilon_0}{\varepsilon_{xx}\varepsilon_{yy}-\varepsilon_{xy}\varepsilon_{yx}}\frac{\Delta t}{\Delta z}\left\{H_y^T(j+1)-H_y^T(j)\right\}-\frac{\varepsilon_{xy}\varepsilon_0}{\varepsilon_{xx}\varepsilon_{yy}-\varepsilon_{xy}\varepsilon_{yx}}\frac{\Delta t}{\Delta z}\left\{H_x^T(j+1)-H_x^T(j)\right\}+E_x^t(i) \qquad (2)$$

$$E_y^{t+1}(i)=-\frac{\varepsilon_{xx}\varepsilon_0}{\varepsilon_{xx}\varepsilon_{yy}-\varepsilon_{xy}\varepsilon_{yx}}\frac{\Delta t}{\Delta z}\left\{H_x^T(j+1)-H_x^T(j)\right\}+\frac{\varepsilon_{xy}\varepsilon_0}{\varepsilon_{xx}\varepsilon_{yy}-\varepsilon_{xy}\varepsilon_{yx}}\frac{\Delta t}{\Delta z}\left\{H_y^T(j+1)-H_y^T(j)\right\}+E_y^t(i) \qquad (3)$$

$$H_x^{T+1}(j)=-\mu_0\frac{\Delta t}{\Delta z}\left\{E_y^t(i+1)-E_y^t(i)\right\}+H_x^T(j) \qquad (4)$$

$$H_y^{T+1}(j)=-\mu_0\frac{\Delta t}{\Delta z}\left\{E_x^t(i+1)-E_x^t(i)\right\}+H_y^T(j) \qquad (5)$$

where Δ*z* relating the resolution of the calculation is 2 nm. On both sides of the structure, the following first-order absorbing boundary condition is used. A sinusoidal point optical source is used as the excitation source to incident light into the cell.

Figure 2 shows calculated transmission spectra of single CLC and composite CLC films. Broken lines in Fig. 2 shows calculated transmission spectra of the CLC_1 and the CLC_2 single films. Both the number of the helical pitch of the CLC_1 and the CLC_2 single films is 10, and ordinary and extraordinary refractive indices are 1.5 and 1.7, respectively.

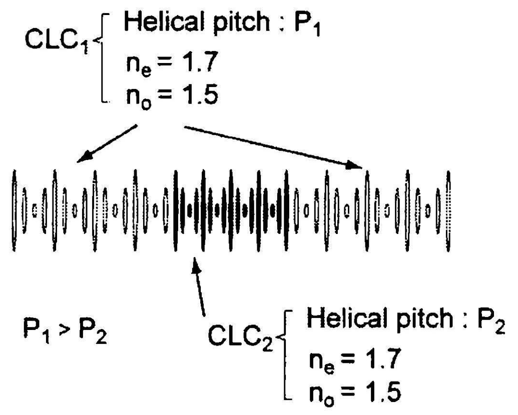
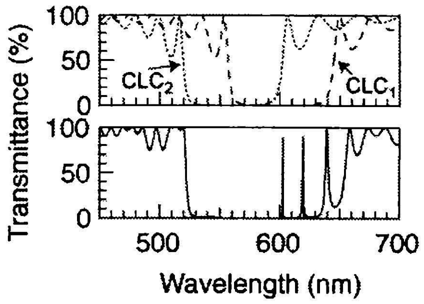
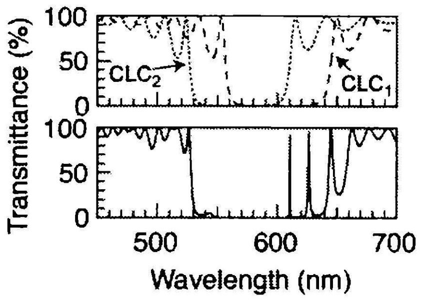


Fig. 1 Cholesteric liquid crystal consisting two helicoidal periodicities.

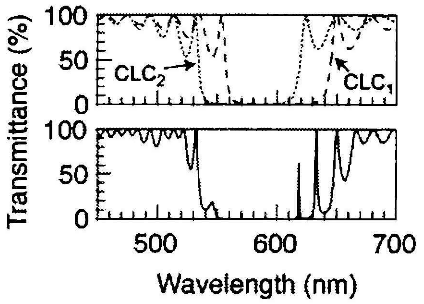
Pitch length of the CLC_1 is 375 nm constantly, but the pitch length of the CLC_2 varies from 350 nm to 360 nm, that is to say, distinctions in Fig. 2 are only pitch length of the CLC_2. In this condition, stop bands in transmission spectra of the CLC_1 and the CLC_2 overlap slightly. Solid line in Fig. 2 shows calculated transmission spectra of the CLC consisting two helicoidal periodicities as shown in Fig. 1. In the composite CLC, the pitch number of the CLC_2 at center and the CLC_1 at one side are 10 and 5, respectively. Since this composite CLC is composed of different pitches, the wide stop band in the transmission spectrum appears. In addition, defect mode peaks caused by the introduction of the CLC_2 layer appear in the stop band. On account of that defect modes are due to resonance between two CLC_1 films, defect mode peaks appear in the stop band of the CLC_1 excepted in the overlap with the stop band of the CLC_2. It should be noted that defect mode peaks in any condition appear at the band edge wavelength of the CLC_2. In generally, the defect mode wavelength is determined by the optical length or the phase retardation of the defect layer. However, in the CLC consisting two helicoidal periodicities, defect mode always appears at the band edge wavelength of the CLC_2.



(a) P_2 = 350 nm



(b) P_2 = 355 nm



(c) P_2 = 360 nm

Fig. 2 Transmission spectra of single and composite CLC films calculated by a 4x4 matrix method as a function of the pitch length of the CLC_2 (P_2). Upper graph shows calculated transmission spectra of single CLC_1 and single CLC_2. Lower graph shows calculated transmission spectra of CLC consisting two helicoidal periodicities.

In order to investigate the origin of the defect mode at the band edge of the CLC_2, we have also calculated the distribution of the electric field in the CLC consisting two helicoidal periodicities by using the FDTD method. Figure 3 (a) shows the electric field distribution in the CLC consisting two helicoidal periodicities at the band edge wavelength of the CLC_2, where parameters in this calculation are follow as: the pitch length of CLC_1 and CLC_2 are 375 nm and 350 nm, the incident light was circularly polarized and has the same sign of rotation as the CLC helix. When the incident light wavelength is in the photonic band gap, the electric field of the incident light simply decrease. However, the propagating light through the composite CLC is amplified at the center of the CLC_2. This is because the incident light arriving at the CLC_2 is amplified by the CLC_2's own periodicity. This means that the defect mode origin is not from the resonance between CLC_1s but from the the band edge effect of the CLC_2. In other words, the defect mode peak indicates the band edge wavelength of inside CLC in a different form. Figure 3 (b) shows the electric field distribution of in single CLC_2 film at the band edge wavelength. It should be noted that the electric field enhancement in CLC consisting two helicoidal periodicities is stronger than single CLC film. The cause of a high enhancement of composite CLC films is that electric field is amplified by two effects of CLC_1s as distributed Bragg reflector and CLC_2 as distributed feedback resonator. Therefore, it is found that a combination of the defect mode and the band edge attains an efficient confinement of the light.

In conclusion, we have studied the optical properties of the CLC consisting two helicoidal periodicities by 4x4 matrix and FDTD methods. One of the defect mode peaks always appeared at the band edge wavelength of CLC_2. This is because the incident light arriving at the CLC_2 is amplified by the CLC_2's own periodicity. In other words, the defect mode peak indicates the band edge wavelength of inside CLC in a different form. Furthermore, it is found that the CLC consisting two helicoidal periodicities is capable of a high electric field enhancement.

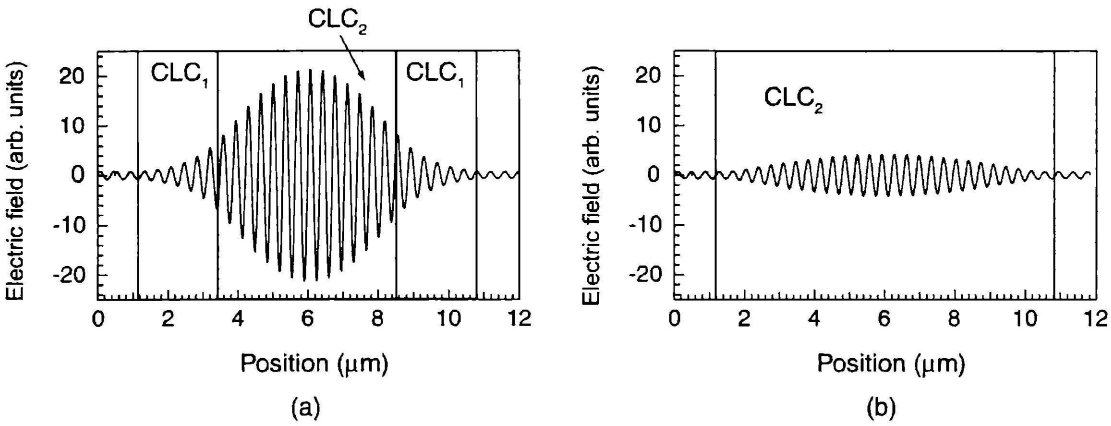


Fig. 3 (a) Electric filed distribution of CLC consisting two helicoidal periodicities at the band edge wavelength of the CLC_2. (b) Electric filed distribution of CLC_2 film at band edge wavelength. These results are calculated by FDTD method.

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