Tunable photonic defect modes in a cholesteric liquid crystal induced by optical deformation of helix

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We have demonstrated, based on numerical analyses, that the introduction and tuning of photonic defect modes in a cholesteric liquid crystal (CLC) can be realized by the local deformation of its one-dimensional periodic helical structure. The defect modes appear in transmission spectra only when incident circularly polarized light has the same handedness as CLC's. The tuning of defect modes position can be performed upon both local elongation and shortening of the helix; however, the direction of the shift of the defect mode wavelength is opposite. By controlling the degree of the deformation of helix, a continuous shift of the defect modes can be realized. Our results will open the way for the optical introduction and tuning of defect modes in CLC's.

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I. INTRODUCTION

Since proposals of Yablonovitch [1] and John [2], a photonic crystal (PC) which is made from a periodic dielectric structure with a periodicity in a range of optical wavelengths has attracted much attention from both fundamental and practical points of view [3]. In the PC, the propagation of light is inhibited under the Bragg condition, which results in the appearance of an optical stop band or a photonic band gap (PBG). When PC's have a defect in their periodicity, localization of photons can be achieved [4–9]. Utilizing defects in PC's, various applications such as narrow-band-pass filters [5], low-threshold lasers [6], low-loss waveguides [7,8], optical add and drop [9], and so on have been demonstrated.

Recently, chiral liquid crystals (LC's) such as cholesteric LC (CLC) [10–14], ferroelectric LC [15,16], and cholesteric blue phase [17] have attracted much attention as self-organized PC's. These LC's have a chirality in the molecular structure and form periodic helical structures in the optical range spontaneously. In the CLC, LC molecules align their molecular long axes (director) homogeneously in the plane perpendicular to the helical axis and rotate the direction of the director continuously along the helical axis. In such LC's with helical structure, a circularly polarized light with the same handedness as the helix propagating along a helical axis is selectively reflected (selective reflection) and a stop band appears [18]. Utilizing these chiral LC's, a low-threshold laser action was observed at the edge of the stop band [10–17], and various functional lasers were proposed utilizing LC's such as CLC elastomer [12], photopolymerized CLC (PCLC) [13,14], and so on. The defect modes in CLC's have also been discussed so far. Yang *et al.* showed, based on numerical analyses, that an isotropic thin layer introduced in the middle of a CLC layer can act as a defect [19]. They showed the tunability of defect modes by changing the refractive index of the isotropic medium. On the other hand, Kopp and Genack numerically demonstrated that the discontinuity of the helix could cause the twist defect mode (TDM) [20], and Schmidtke *et al.* [21] and Ozaki *et al.* [22] demonstrated low-threshold lasing from TDM-utilizing PCLC. TDM has quite a high Q factor; however, it is difficult to control by means of external fields.

In this paper, we show the numerically analyzed results of the tuning of the defect mode in CLC's. We suppose that the introduction and tuning of the defect modes are achieved by the optically induced local deformation of the helix in the middle of the CLC layer (Fig. 1). We show first that the local modulation of helical twisting power (HTP) can induce the appearance of defect modes and then give detailed discussions of the tunability of them.

As a method to induce and modulate defects, we suppose that the local modification of HTP is induced by a focused

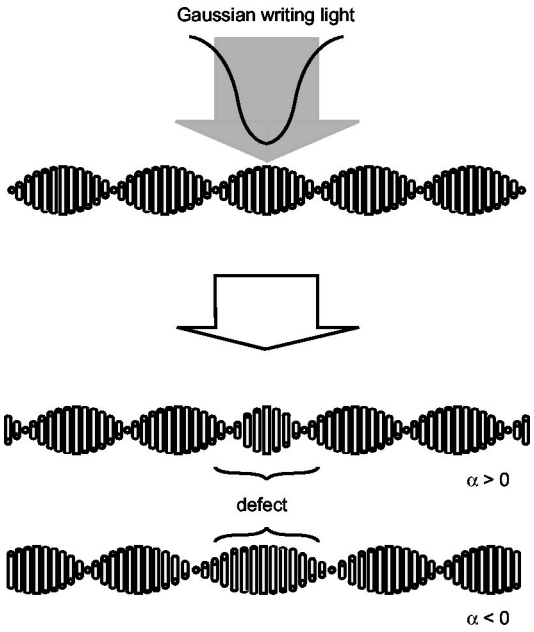

FIG. 1. Schematic explanation of a photonic defect in CLC's formed by optically induced deformations ($\alpha > 0$, shortening; $\alpha < 0$, elongation) of the helix.

Gaussian laser light. Optical control of HTP can be realized using photochemical effects of the doped azobenzene [23–26], nonlinear optical effects [27], or simple heating. Photoinduced reversible control of the HTP of CLC's has been demonstrated in the CLC containing photochromic azobenzene, and applications to a reflection-type display devices, an optical shutter, an optical memory, and so on have been studied [23–26]. By the *trans-cis* photoisomerization of the doped azobenzene, HTP of the host CLC changes, so that photoinduced control of HTP can be realized. On the other hand, Winful theoretically suggested that an intense light can induce a change of HTP of the CLC by the coupling of the optical field to the local dielectric anisotropy [27]. Moreover, the helical pitch of the CLC depends on temperature, so that a local deformation of helix can also be performed by an optical heating. From these characteristics of the CLC and the mixture with azobenzene molecules, our model of calculation can be considered as a realizable assumption.

II. NUMERICAL ANALYSES

Numerical analyses of the optical transmission in the helical structure were performed based on Berreman's 4×4 transfer matrix [28], which enable quantitative calculations of light propagation in a medium with refractive index varying along one direction. Light propagating along the z axis with frequency ω is given by

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

where $\mathbf{D}(z)$ is a derivative propagation matrix and $\mathbf{\Psi}(z) = (E_x, H_y, E_y, H_x)^T$. The physical parameters used in this study are as follows: ordinary and extraordinary refractive indices of LC are $n_o = 1.5$, $n_e = 1.7$, refractive index of substrates is $n_s = 1.5$, and the pitch of the helix is $p = 350$ nm. The total thickness of the CLC layer is 5 μm. The helix of the CLC is set to be right handed. We assume only normal incidence of the light to the CLC (along the helical axis of the CLC). HTP is defined as a rotation angle of the director θ per unit length (1 nm): $q_{\mathrm{HTP}} = 2\pi/p$ rad/nm, which concurrently means a wave number of the helix. Therefore, initial HTP without deformation is $q_{\mathrm{HTP}} = 2\pi/350$ rad/nm. As mentioned above, we suppose that the electric field of a writing laser light has a Gaussian distribution and can be expressed as follows:

$$E(z) = E_0 \exp(-z^2/w^2), \tag{2}$$

where the z axis is parallel to the helical axis and $2w$ is a beam width of the writing light. Supposing the induced modulation of HTP $[\Delta q_{\mathrm{HTP}}(z)]$ is proportional to the intensity of the writing light $I(z)$ $[I(z) \propto E(z)^2]$, $\Delta q_{\mathrm{HTP}}(z)$ can be expressed as

$$\Delta q_{\mathrm{HTP}}(z) = \Delta q_{\mathrm{HTP}_0} \exp(-2z^2/w^2), \tag{3}$$

and then substitute $\alpha q_{\mathrm{HTP}_0}$ for $\Delta q_{\mathrm{HTP}_0}$, HTP can be derived as

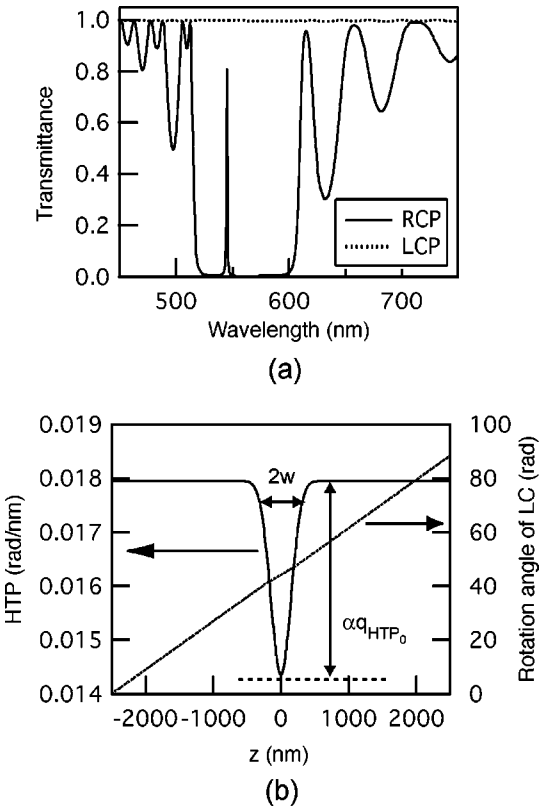

FIG. 2. (a) Transmission spectra of RCP (solid line) and LCP (dotted line) lights passing through the CLC containing deformation-induced defects for the fraction of the change of HTP $(\Delta q_{\mathrm{HTP}_0}/q_{\mathrm{HTP}_0})$, $\alpha = -0.20$ and beam width $w = 300$ nm. (b) The distribution of the HTP and rotation angle of the LC director in the thickness of the CLC layer.

$$q_{\mathrm{HTP}}(z) = q_{\mathrm{HTP}_0} + \Delta q_{\mathrm{HTP}}(z) = q_{\mathrm{HTP}_0}\{1 + \alpha \exp(-2z^2/w^2)\}, \tag{4}$$

where α is fraction of $\Delta q_{\mathrm{HTP}_0}$ to q_{HTP_0} $(\Delta q_{\mathrm{HTP}_0}/q_{\mathrm{HTP}_0})$. The value of α depends on the inherent HTP of the doped azobenzene, absorption of the doped dye, the amount of dopants, the intensity of the writing light, and so on. Using this expression, the degrees of local modification of HTP can be parametrized by α and w. In this paper, calculations were performed with varying α from −1 to 1, where minus and plus α correspond to elongation and shortening of the helix, respectively, with changing w as 300 nm, 600 nm, and 1000 nm. In our model, the rotation of the director was set to be continuous and contained no twist defect.

III. RESULTS AND DISCUSSION

Figure 2(a) shows the transmission spectra for right-handed circularly polarized (RCP: solid line) and left-handed circularly polarized (LCP: dotted line) lights passing through the CLC containing deformation-induced defects ($\alpha = -0.20$, $w = 300$ nm). In Fig. 2(b), the distribution of the HTP and the rotation angle of the director are also shown. A transmission peak based on the defect mode was observed (at 545 nm) in the stop band in the case of RCP incidence. On the other

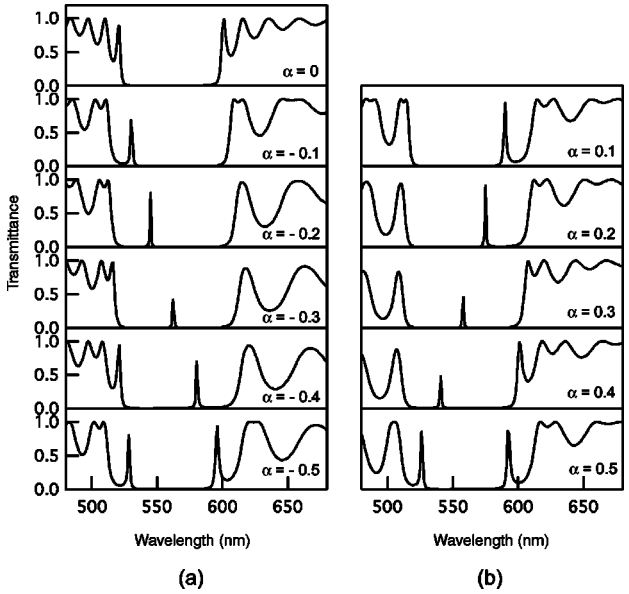

FIG. 3. Transmission spectra of the RCP lights passing through the CLC containing deformation-induced defects of various values of the fraction of the change of the HTP α, for beam width $w=300$ nm. The value of α was (a) decreased from 0 to minus and (b) increased from 0 to plus.

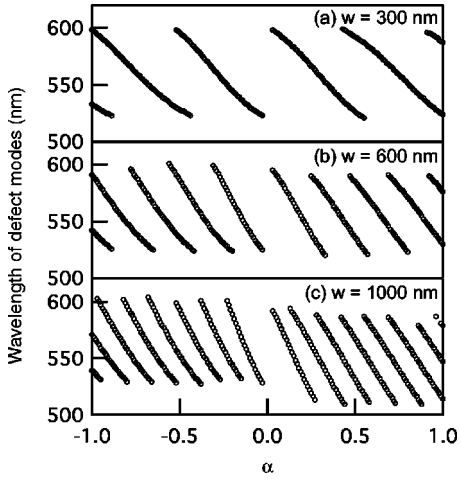

FIG. 4. The peak wavelength of the defect modes as a function of the fraction of the change of HTP α in the case of (a) $w=300$ nm, (b) $w=600$ nm, and (c) $w=1000$ nm.

hand, when the incident light was LCP, no defect mode was observed. This differs from the results of the isotropic defect reported by Yang *et al.*, which shows the same value of reflectance for both RCP and LCP incidences [19]. Based on their model,the optical tuning of the defect mode can also be expected using a photoinduced change of the refractive index of the isotropic defect. However, there is an essential difference between their model and ours in the point of polarization of localized light. In our model, localization of photons can be realized for only the RCP incidence. This localized mode of the single circularly polarized light is similar to the results of TDM.

Figure 3(a) shows the transmission spectra for RCP lights in the CLC containing deformation-induced defects at various values of α (decreased from 0 to minus), in the case of $w=300$ nm. With decreasing α, a transmission peak based on the defect mode appeared at the shorter-wavelength edge of the stop band and shifted toward the longer wavelength, and finally that peak reached the longer-wavelength edge of the stop band when $\alpha\sim-0.5$. When α reached ~-0.45 and was decreased further, another new peak appeared at the shorter-wavelength edge of the stop band and showed a redshift in the same way. On the other hand, with increasing α from 0 to plus, the peak appeared from the longer-wavelength edge of the stop band and shifted oppositely as shown in Fig. 3(b). From these results, it was found that the introduction and tuning of defect modes could be realized by both local elongation and shortening of the helix. Similar behaviors were observed in the case of $w=600$ and 1000 nm. It should be noted that, to introduce and tune the defect mode, such a small deformation as half of the initial HTP is enough.

Figure 4 shows the peak wavelength of the defect modes as a function of α in the cases of (a) $w=300$ nm, (b) $w=600$ nm, and (c) $w=1000$ nm. As discussed above, with increasing α, the transmission peak showed a blueshift, and with decreasing α, it showed a redshift. The appearance and shift of the defect mode is continuous to α. It is difficult to recognize the distinct threshold value of α for the appearance of defect modes, because the appearance of the defect mode is from the edge of the stop band and looks more like thresholdless. As w gets larger, the shift of the wavelength of defect modes versus α becomes steeper. This means that if the writing laser light is focused tightly—in other words, w is small—large deformation of the HTP should be needed in order to sweep the localized mode from the higher (lower) edge to the lower (higher) edge of the stop band.

Moreover, when w gets larger, the number of defect modes increased; for example, in the case of $w=1000$ nm, three defect modes appear when $\alpha\sim0.43$. Generally, the number of defect modes in one-dimensional PC's depends on the optical thickness of the defect, which is defined as a product of the refractive index of the medium and the thickness of the defect layer. When the effective thickness of the defect layer is large, the number of defect modes which can be confined in the defect layer also gets larger. It is considered that a similar assumption can be applied to CLC; that is, also in the deformation-induced defect in CLC, the number of localized modes depends on the effective thickness of the defect region. Consequently, in order to realize a wide tunability of the single-defect mode throughout a band gap, the writing laser light should be focused tightly and the spatial distribution of the deformation-induced defect should be suppressed in a narrow region. These results are considered to depend strongly on the optical anisotropy Δn $(=n_e-n_o)$ of LC molecules, because the effective thickness of the deformation-induced defect should be evaluated from the spatial distribution of the deformation-induced defect, the degree of the deformation, and Δn. Detailed results concerning Δn, the Q factor of the defect mode, will be discussed elsewhere.

Sackmann reported a photoinduced change of the wavelength of the maximum reflectivity from 610 to 560 nm in

cholesteric mixtures of cholesteryl-chloride- and cholesteryl-nonanoate-containing azobenzene molecules at a concentration of 0.35 mol [23].This change of wavelength of the maximum reflectivity is equivalent to the change of the HTP from $2\pi/610$ to $2\pi/560/\mathrm{rad/nm}$ using our definition. These value correspond to a 108.9% change of the HTP—that is, $\alpha=0.089$. Kurihara *et al.* [24] and Lee *et al.* [26] reported the value of $\alpha\sim0.52$, and 0.22, respectively, in cholesteric mixtures of cyanobiphenyl-based nematic LC, chiral dopant, and azobenzene derivatives. Therefore, the estimated value of $\alpha\sim0.5$ discussed above can be regarded to be experimentally attainable one.

IV. CONCLUSION

In conclusion, we have demonstrated based on numerical analyses that the introduction and tuning of photonic defect modes in the CLC can be realized by the local deformation of the helix in the middle of the CLC layer. The defect modes appear only when the incident circularly polarized light has a same handedness as the CLC. The tuning of the defect mode can be performed by both local elongation and shortening of the helix, and by elongation of the helix, defect modes show a redshift, and by shortening of the helix, defect modes show a blueshift. By controlling the degree of the modulation of the HTP, a continuous shift of the defect modes can be realized. Our model can be applied to the optical control of the defect mode in the CLC, and there is no need for a complicated fabrication process such as an the introduction of a isotropic thin layer, stacking of PCLC films, and so on. Based on our model, various applications can be expected such as reversible tuning of the defect modes, optical switches, and transient introduction and tuning of the defect modes. Such a spatially localized optical field can be attained utilizing an interference of two laser beams. The tuning of the defect modes discussed in this paper can be realized on the basis of the self-organizability of CLC. Utilizing these characteristics, intelligent optical devices can be expected.

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