Hindawi
Advances in Condensed Matter Physics
Volume 2018, Article ID 5384329, 8 pages
https://doi.org/10.1155/2018/5384329

Research Article

Circular Polarization and Wavelength Selective Gratings Based on Holographic Cholesteric Liquid Crystal Templates

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Received 6 May 2018; Revised 5 August 2018; Accepted 5 September 2018; Published 3 October 2018

Academic Editor: Jörg Fink

Refilling cholesteric liquid crystal (CLC) template gratings with circular polarization, wavelength selectivity, and dual operation mode are first demonstrated. The gratings with template and nontemplate regions are obtained through the two-beam interfering photo-polymerization, washing-out, and refilling procedure. The refilling CLC has different chiral handedness (left or right) and reflection band (at green and red regions). When the wavelength of a probe beam is within the refilled CLC reflection band of the nontemplate region, the device works as an amplitude grating since the sample in the template and nontemplate regions reflects distinct colour region. In addition, the diffraction intensity of the grating can be electrically controlled. Therefore, this CLC-based device can be potentially used in controllable diffraction elements in optics.

1. Introduction

Cholesteric liquid crystal (CLC) is a soft matter with a self-organized helical structure and can be regarded as a one-dimensional photonic crystal [1]. It has multiple responses under various external stimuli and can thus be applied on tunable photonic devices, such as tunable optical filter [2], diffraction grating [3], mirror-less laser [4], microlens [5], and eye protector [6]. CLCs can exhibit various textures, including planar (uniformly standing helix), fingerprint (uniformly lying helix), and focal conic, depending on the orientation of the helical axes in CLCs. Fingerprint CLCs exhibit modulation of refractive index in lateral direction and are suitable for use in developing optical gratings. By embedding the photosensitive moieties or doping some of the additives with photosensitivity into the fingerprint CLC, the helical pitch of the fingerprint CLC can be compressed or extended by light irradiation and can function as an optically tunable diffraction grating [7].

The optically tunable diffraction grating can be used for beam control and wide-range spectral scanning applications [7–9]. Fingerprint CLC can have the function of a tunable grating [10]. However, gratings based on fingerprint CLCs present no circular polarization selectivity, which is an attractive feature of CLCs. Therefore, gratings based on planar CLCs for diffracting circularly polarized light are developed in recent years [11–13]. Using holographic interference or a mask to generate a periodic distribution of light on photo-sensitive planar CLC-based materials leads to the periodic variations of CLC orientations and thus light diffraction [14, 15]. For example, a CLC grating can be fabricated via a spatial arrangement of the vertical and planar arrangement of the CLC molecules by two-beam interference [11]. A photo-induced surface relief phase grating can be realized on a photoresponsive CLC polymer film through the optical isomerization for reducing the molecular order parameters [12]. Polarization-selective CLC polymer gratings because of periodic phase modulation by phototunable helical pitch have also been demonstrated [13]. However, the planar CLC gratings based on photosensitive materials have stability issues. To improve the stability and functions of the planar CLC grating, a new type of CLC grating must be developed.

Table 1: Prescription of the refilled right-handed and left-handed CLC (RCLC and LCLC, respectively) materials. The indices of "red" and "green" behind RCLC or LCLC mean that the CLC materials reflect at red and green regions, respectively.

wt%	RCLC-red	RCLC-green	LCLC-red	LCLC-green
HTW114200-100	77	73	77	73
R811	23	27		
S811			23	27

In this work, optical gratings are fabricated on the basis of two-beam interference and fabrication technique of CLC template (washing-out/refilling) [16–18]. By refilling left- or right-handed CLC (LCLC and RCLC, respectively) into a right-handed CLC polymer template grating, the refilled CLC template grating can diffract light with specific wavelength. In addition, the refilled CLC template grating shows different diffraction efficiencies for left- and right-handed circular polarization (LCP and RCP, respectively) in reflection and transmission modes. The diffraction intensity can also be electrically controlled. The beam steering device exhibits electrical controllability and circular polarization and wavelength selectivity with dual operation modes.

2. Materials and Methods

The mixture used for fabricating CLC templates is composed of E7 (NLC, from Fusol-Material), R811 (right-handed chiral dopant, from Fusol-Material), R1011 (right-handed chiral dopant, from Fusol-Material), RMM691 (chiral monomer, from Merck), RMM257 (achiral diacrylate monomer, from Merck), and Irg184 (photoinitiator, from Pufeng). The weight ratio of these materials is 66.8:13:2:15.5:2.5:0.2. The uniform mixture was injected into an PVA-rubbed empty cell with a cell gap of 38 μm. Two UV laser beams from a He-Cd Laser (from Kimmon) were adjusted to construct an interference pattern on and cure the sample, resulting in a spatially periodic polymerized and nonpolymerized regions inside the sample. The cured sample was immersed in acetone for one day to wash-out the nonreactive materials. After evaporating the acetone, a dried grating with spatially periodic template and nontemplate regions was obtained. Last, another CLC material was then refilled into the grating to finish the fabrication of the refilling CLC template grating. In this paper, four types of refilled CLC materials composed of NLC (HTW114200-100, from Fusol-Material) and chiral dopants (S811 and R811, from Fusol-Material), as shown in Table 1, were prepared to refill into the sample. The four refilled CLCs are labelled as RCLC-red, RCLC-green, LCLC-red, and LCLC-green, in which "R" and "L" in front of CLC mean right- and left-handednesses of chirality, respectively, and "red" and "green" in the labels are the reflection bands at red and green regions, respectively.

As shown in Figure 1, one CW probe beam (λ = 532 nm or 633 nm) with right-handed or left-handed circular polarization was aligned to normally probe the refilling CLC template grating sample. Two photodetectors were used to measure the first-order diffraction efficiencies in the reflection and transmission modes of diffraction beams.

3. Results and Discussion

3.1. Refilled CLC Template Grating Samples with Various Refilled CLC Materials. As described in the previous section, the template grating was fabricated by refilling the CLC material (shown in Table 1) into the holographically cured sample with a grating spacing of about 7.3 μm. Two different regions are formed after refilling the CLC material into the sample, template, and nontemplate regions, which correspond to the constructive and destructive interference regions, respectively. Since the CLC cannot completely fill the nanopores of the template region, the reflection band of the refilled template region blue-shifts from its original state. The reflection band of the nontemplate region is attributed to the reflection of the refilled CLC. Therefore, the two regions can reflect at different colour regions. In other words, if a probe beam with a specific wavelength probes on the grating sample, the sample can be regarded as an amplitude grating. Given that the reflection of CLC is for a specific circular polarization, the refilled CLC template grating can be designed to reflect lights of a specific wavelength and circular polarization by refilling CLCs with different handednesses and reflection bands. For describing the circular polarization selectivity of the refilled template grating, a parameter called g-value is defined as [19]

$$g = \frac{2(\eta_L - \eta_R)}{(\eta_L + \eta_R)}, \tag{1}$$

where η_L and η_R represent left-handed and right-handed circularly polarized diffraction efficiencies, respectively. A positive g-value indicates that the diffraction efficiency with LCP is greater than that with RCP. Therefore, a large absolute g-value near 2 means a good circular polarization selectivity of the refilled CLC template grating.

Figure 2 shows the circular polarization selectivity of the template grating refilled with CLC material reflecting red light (RCLC-red and LCLC-red, reflection region: 590 nm–650 nm). When the refilled material is RCLC-red, the nontemplate region can reflect red RCP light but the template region reflects blue RCP light, which can be observed via the reflection spectrum shown in Figure 2(a). In the reflection mode, the diffraction efficiency of the RCP red light is greater than that of the LCP red light ($g = -1.14$) [Figure 2(a)]. On the contrary, the effect of the transmission mode is opposite to the reflection mode ($g = 1.38$) [Figure 2(b)]. If the wavelength of the probe beam is 532 nm, then the light cannot be reflected either by the template or the nontemplate region and thus should not experience an amplitude grating. However, the refractive index difference between the template

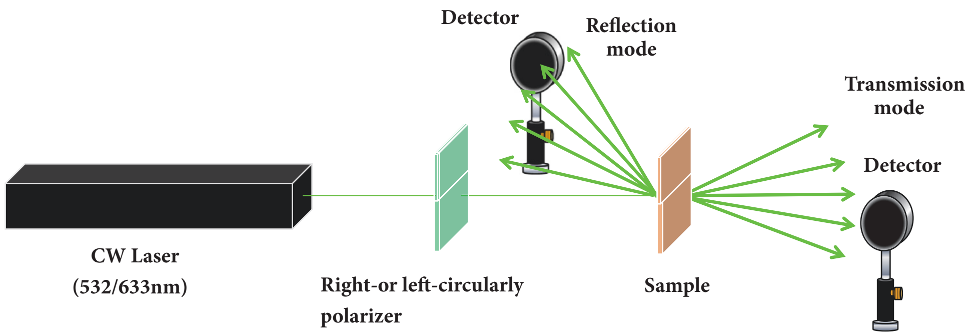

Figure 1: Setup for measuring the diffraction efficiencies of the refilled CLC template grating sample in reflection and transmission modes of diffraction beams.

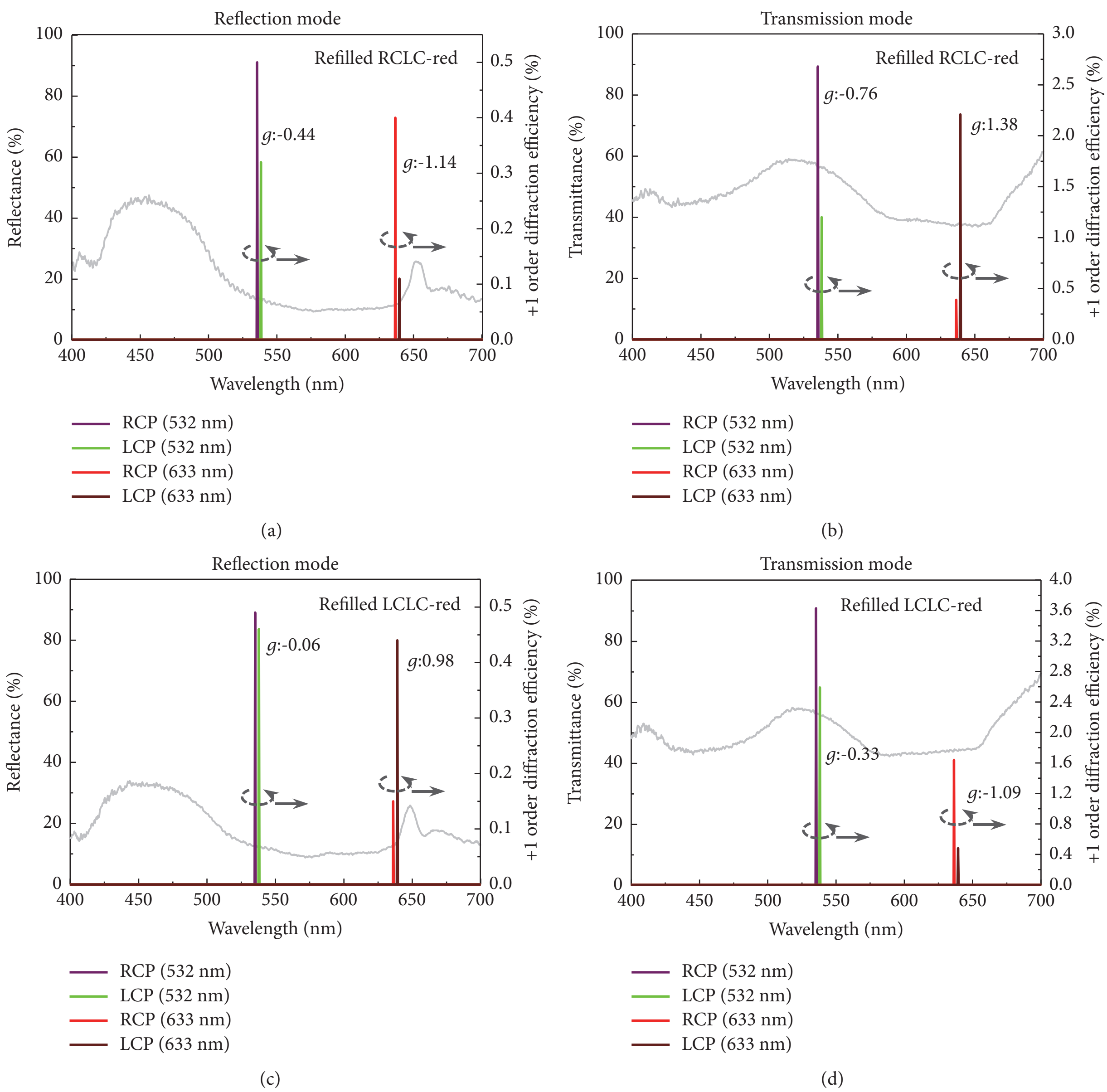

Figure 2: Measured +1 order diffraction efficiencies of the refilled CLC template grating in (a)/(c) reflection mode and (b)/(d) transmission mode by the RCP and LCP lights with the wavelengths of 532 and 632 nm, respectively. The refilled material is RCLC-red in (a)/(b) and LCLC-red in (c)/(d).

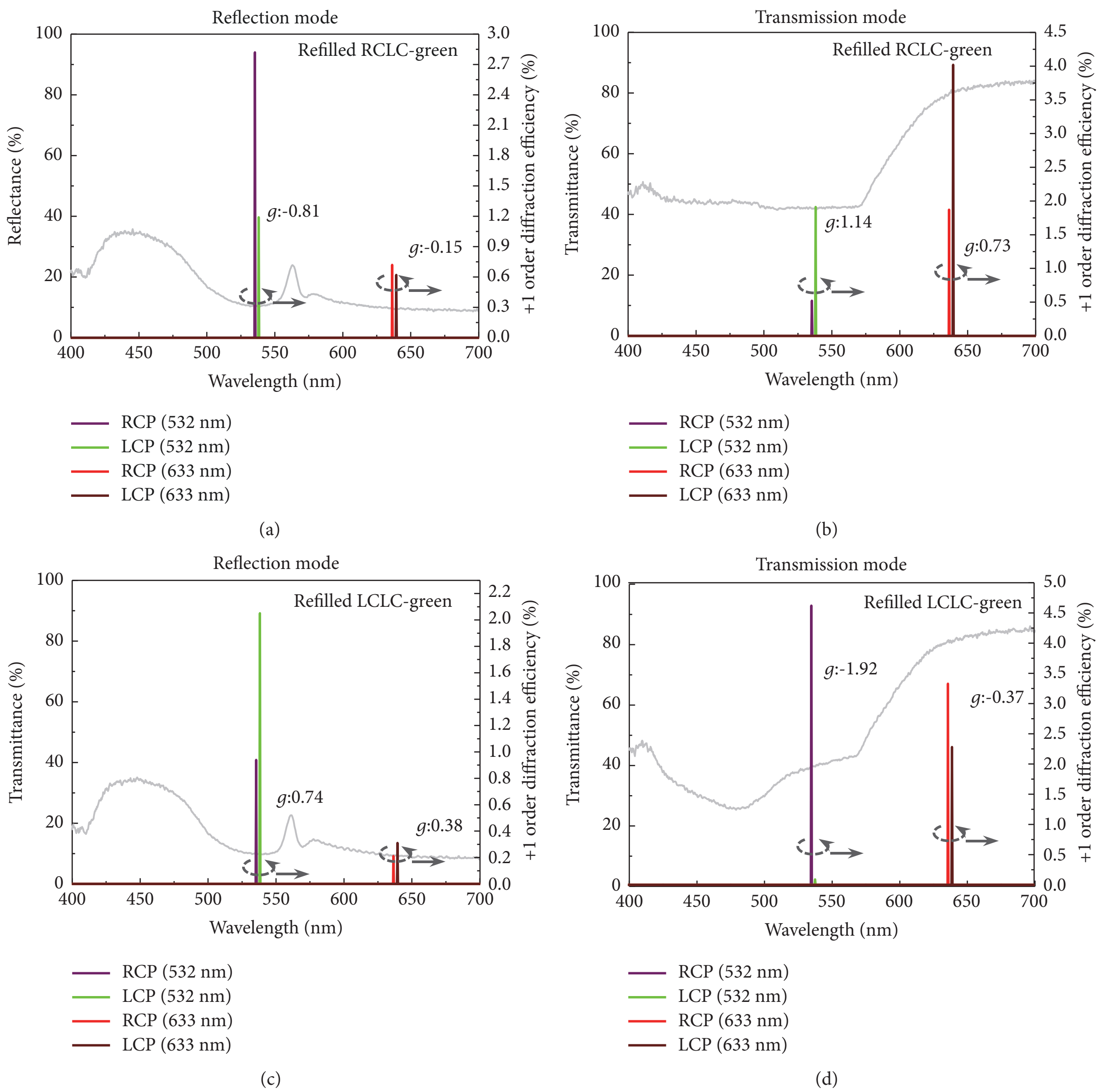

FIGURE 3: Measured +1 order diffraction efficiencies of the refilled CLC template grating in (a)/(c) reflection mode and (b)/(d) transmission mode by the RCP and LCP lights with the wavelengths of 532 and 632 nm, respectively. The refilled material is RCLC-green in (a)/(b) and LCLC-green in (c)/(d).

and nontemplate regions results in a slight effect of phase grating. Therefore, the green light can also be diffracted, but the absolute g-value is smaller than that of the red light. This condition represents no circular polarization selectivity for green light in this sample. When the LCLC-red is used as the refill material, the refilled CLC template grating sample exhibits two reflection bands in the blue and red regions, as shown in Figure 2(c). The properties of the refilled material are similar to RCLC-red, except for the opposite chirality. In the reflection mode, the diffraction efficiency of the RCP red light is smaller than that of the LCP red light ($g = 0.98$), as shown in Figure 2(c). On the contrary, the effect of the transmission mode is opposite to that of the reflection mode ($g = -1.09$), as shown in Figure 2(d). The absolute g-value in the green region is smaller than that in the red region, and no regular circular polarization selectivity occurs for green light in either the reflection or transmission mode. In other words, the polarization selectivity of the grating is only for red light when the refilled CLC reflects red light.

By refilling RCLC-green with reflection band in the green region (reflection region: 510–570 nm), the refilled CLC template grating causes the circular polarization selectivity of the green light. In the reflection mode, the diffraction efficiency of the RCP green light is greater than that of the LCP green light ($g = -0.81$), as shown in Figure 3(a). Conversely, the effect of the transmission mode is opposite

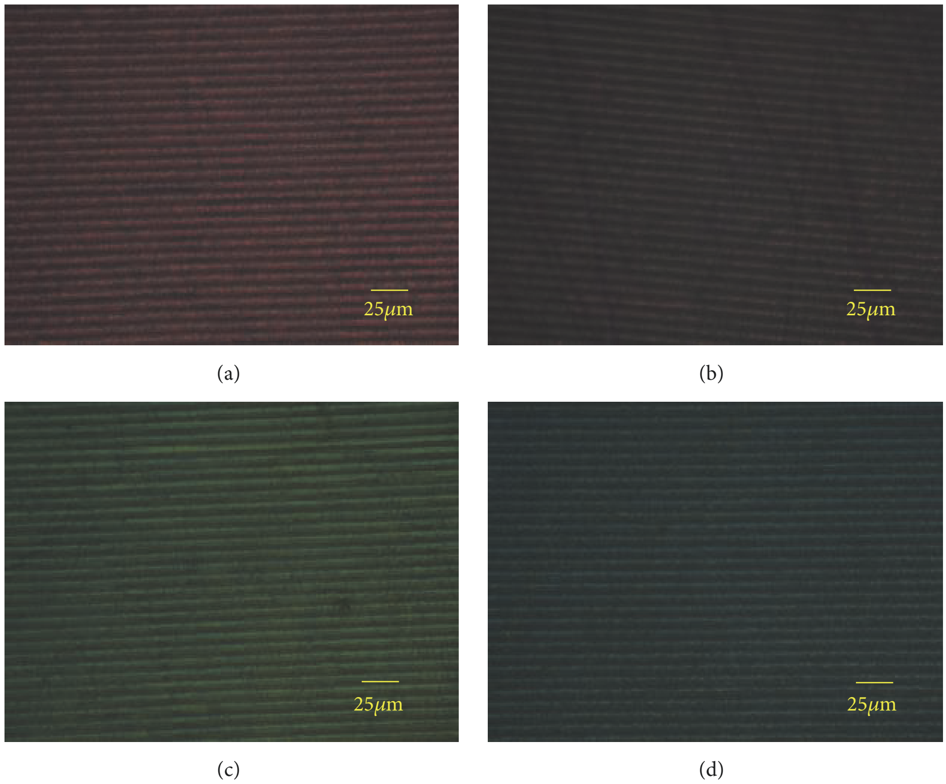

Figure 4: Reflected polarized optical microscopic image of the CLC polymer template gratings refilled with (a) RCLC-red, (b) LCLC-red, (c) RCLC-green, and (d) LCLC-green, respectively. The scale bar is 25 μm.

to that of the reflection mode ($g = 1.14$), as shown in Figure 3(b). When the refill material is LCLC-green, the refilled CLC template grating sample exhibits two reflection bands in the blue and green regions. The properties of the refilled material are similar to RCLC-green, except for the opposite chirality. In the reflection mode, the diffraction efficiency of the RCP green light is smaller than that of the LCP green light ($g = 0.74$), as shown in Figure 3(c). Conversely, the effect of the transmission mode is opposite to that of the reflection mode ($g = -1.92$), as shown in Figure 3(d). Figure 4 shows the reflected polarized optical microscopic images (with crossed polarizers) of the refilled template gratings discussed in Figures 2 and 3. In Figures 4(a) and 4(b), the red colour of the stripes is due to the reflection of the refilled red CLC materials, RCLC-red and LCLC-red. Similarly, the green stripes shown in Figures 4(c) and 4(d) are caused by reflection of the refilled green CLC materials.

Since the gratings in the work are fabricated by two-beam interference, the spatial distributions of refractive index and transmittance in the gratings can be expressed by a sinusoidal function. That is, the gratings can be regarded as sinusoidal transmittance gratings or sinusoidal phase gratings, depending on the experimental condition. If the incident light can be reflected by the CLC template or the refilled CLC, the sample is a sinusoidal transmittance grating. On the contrary, the sample can be regarded as a sinusoidal phase grating when the wavelength or polarization of the incident light does not match the reflection band or handedness of the CLC template or the refilled CLC. For a sinusoidal transmittance grating, the first-order diffraction efficiency varies as the square of the amount of swing of the sinusoidal transmittance modulation Δt, and is given by the formula $\eta_t = (\Delta t/2)^2$. Because the maximum value of Δt is 0.5, the maximum value of the first diffraction efficiency is 6.25% ideally [20]. The experimental values are lower than the maximum theoretical value because the transmittance modulations of the refilled CLC template gratings are smaller than 0.5. For a sinusoidal phase grating, the first-order diffraction efficiency can be expressed by a first-order Bessel function of the phase modulation of the grating $\Delta\varphi$, that is, $\eta_p = J_1{}^2(\Delta\varphi)$. It means the diffraction efficiency of a sinusoidal phase grating can be ranged from 0 to 33.8%, depending on the value $\Delta\varphi$, which is related to the variation of the refractive indices and thickness of the grating [20]. Since the variation of the refractive indices of the refilled CLC template gratings and thus $\Delta\varphi$ is very small, the diffraction efficiency is not high. In addition, the scattering of light from the refilled CLC template grating is another factor for the low diffraction efficiency.

3.2. Electrically Controlled Diffraction of Refilled CLC Template Grating Sample. Considering that the arrangement of the refilled CLC can be changed by applying an electric field, the diffraction of the refilled CLC template grating can be controlled by AC electric field (1 kHz). As displayed in Figure 5, when the electric field is applied, the CLC in the nontemplate region can be converted from planer to

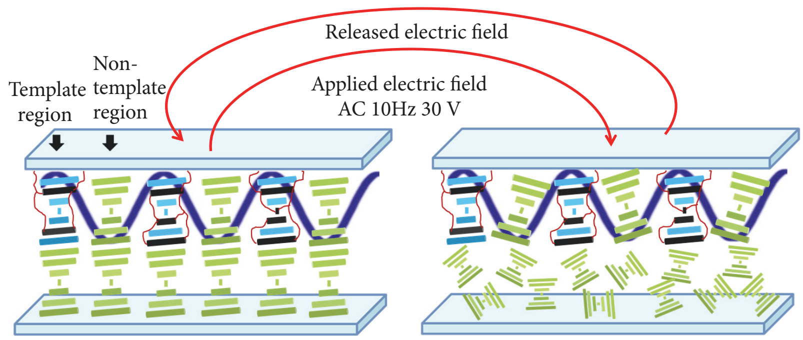

FIGURE 5: Schematic of conversion between planer and focal conic states in the refilled CLC template grating by the presence of an applied electric field.

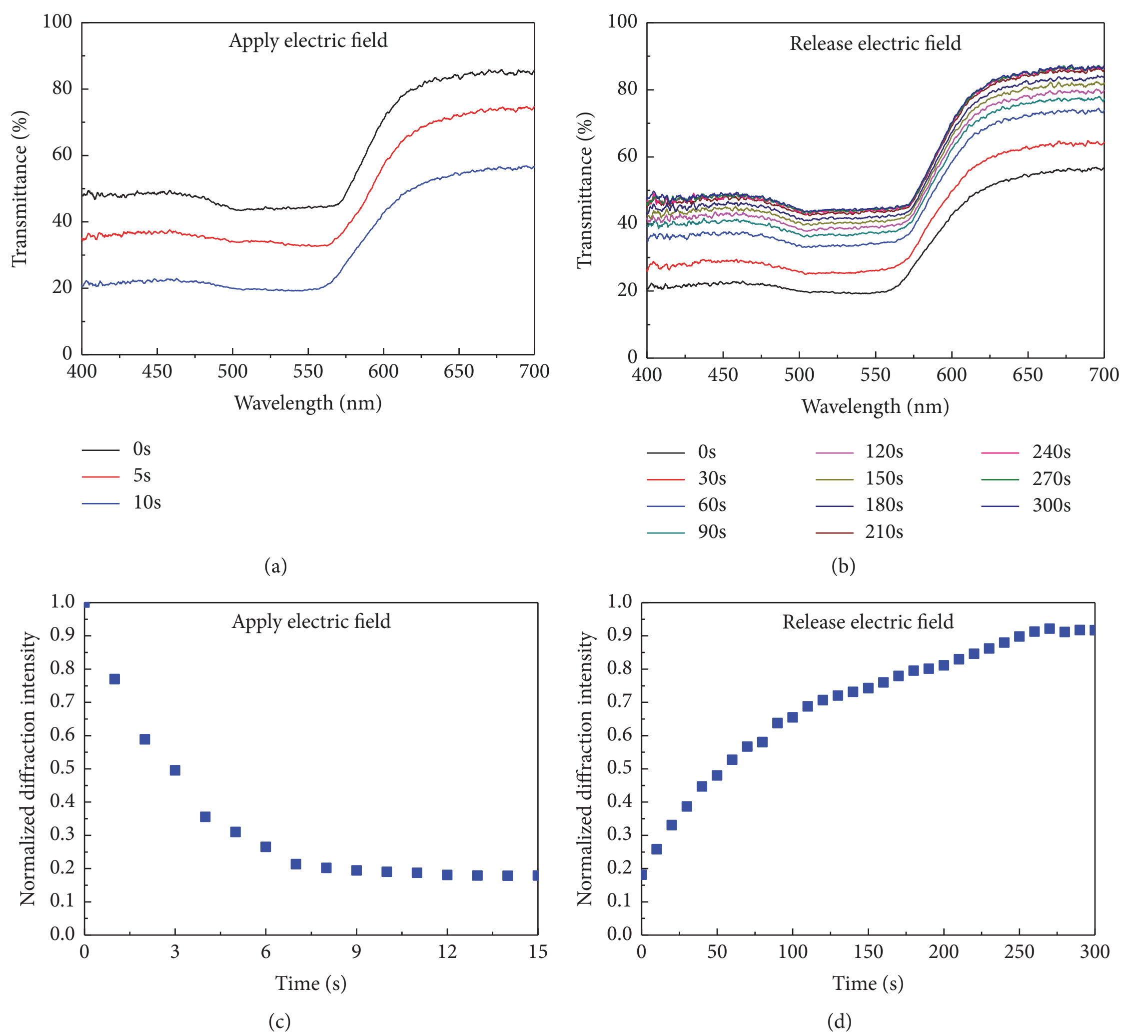

FIGURE 6: Dynamical variations of (a)/(b) the transmittance and (c)/(d) diffraction intensity of the refilled CLC template grating when (a, c) applying and (b, d) releasing the electric field.

focal conic state [21]. The refilled CLC in the nontemplate region will return from focal conic state to planer state when the electric field is released. The CLC molecules in the nontemplate region of the sample enter into a focal conic state when an electric field with 30 V is applied. The strong scattering of the focal conic state gradually reduces the transmittance, as shown in Figure 6(a). When the electric field is removed, the transmittance gradually rises back to its initial state, as shown in Figure 6(b). The electrically controlled scattering and transmittance results in the variation of the diffraction intensity with electric field [22]. Therefore, the diffraction intensity of the refilled CLC template grating can be controlled to decreases and increase with the electric field, as shown in Figures 6(c) and 6(d), respectively. In this work, the distance between the detector and the sample is 30 cm. The contrast ratio of the electrically switched diffraction can be higher if less scattered light is received by the detector, which can be achieved by increasing the distance between the detector and the sample.

4. Conclusions

In this paper, holographic interference is used to fabricate diffraction devices based on CLC polymer template gratings with circular polarization and wavelength selectivity. The refilled CLC template gratings can be operated in reflection and transmission modes. The diffractions of the reflection and transmission modes exhibit different circular polarization. By replacing the refilled CLC, the device can diffract light with specific circular polarization and wavelength. Finally, the electrical controllability of the device is demonstrated by switching the CLC texture between planer to focal conic states with an electric field.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Authors' Contributions

Hsien-Kuo Chin and Hui-Ying Kuo contributed equally to this paper.

Acknowledgments

This research is financially supported by clinical research grants from Kaohsiung Armed Forces General Hospital, Taiwan [no. 105-14], and the Ministry of Science and Technology of Taiwan (Contract no. MOST 103-2112-M-006-012-MY3).

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