Continuous Pitch Stabilization of Cholesteric Liquid Crystals and Display Applications

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ABSTRACT

We report a mechanism of the continuous pitch variation of the cholestric liquid crystal (CLC) with reactive mesogen based on the phase separation model and the 4×4 matrix analysis. From the density variation of the polymerized RM with chirality, the corresponding pitch variation was directly estimated and the reflectance was calculated using the 4×4 matrix analysis. The calculated result quantitatively coincided with the experimental result with broadband reflection spectrum. Also, we demonstrated a simple transflective LC display using the CLC white reflector with broadband reflection spectrum covering entire visible range.

RUNNING HEAD: Continuous Pitch Stabilization of Cholesteric LC

KEYWORDS: Cholesteric liquid crystal, wideband reflection, phase separation, transflective liquid crystal display

1. INTRODUCTION

The cholesteric liquid crystals (CLCs) have attracted much attention since the tunability of their helical pitch and the corresponding wavelength-selective reflection [1]. In principle, the helical pitch of the CLCs and the resultant reflected color from them are directly governed by concentration of a chiral agent and temperature. For device applications, the pitch stabilization of the CLC against temperature variation has been explored by introducing photopolymer to the CLCs [2-5]. In such polymer/CLC composite systems, the polymer structure suppresses thermal variation of the CLC pitches and thus various CLC pitches formed at different temperature are stabilized even in a single-layered configuration [5]. In the CLC composite systems with photocurable monomers, ultraviolet (UV) intensity gradient normal to the UV incident direction generates the pitch gradient of the CLCs covering whole visible range [6-8]. Although the continuous pitch stabilization of the CLCs is widely used for device applications, a complete picture of the pitch variation in the polymer/CLC composite systems has not been understood so far.

In this work, we report a mechanism of the continuous pitch variation in the polymer/CLC composite systems based on the phase separation model [9] and demonstrate display applications using the continuous pitch stabilizations in vertical direction to the substrates. The UV intensity gradient produced the concentration variations of photopolymer with chirality, and thus the corresponding pitch gradient was obtained. The concentration distribution of the photopolymer with chirality directly governs the pitch distribution of the CLC in the cell. Simultaneously, the polymer stabilizes the continuously varying pitch in the vertical direction to the substrates and thus the CLC film with broadband reflection spectrum is achieved. The white reflectors with broadband reflection spectrum covering entire visible range were widely used as a transflective mirror in the transflective LC displays [10-12]. Also, we demonstrated a simple transflective LC display consisting of the conventional LC layer with single linear polarizer as a switching unit and the CLC white reflector as a transflective mirror [12].

2. EXPERIMENTAL

The CLC film with broadband reflection spectrum covering entire visible range was fabricated by UV exposure to the CLC mixture with reactive mesogen (RM) with chirality. For the CLC mixture, host nematic LC (87 wt.%, E. Merck E48) was mixed with RM monomer with right-handed chirality (12 wt.%, E. Merck RMM703) and photoinitiator (1 wt.%, Ciba Speciality Chemicals Igacure651). The CLC mixture was injected into sandwiched cell by capillary action in an isotropic phase [11]. The sandwiched cell was prepared by two glass substrates sputtered by indium-tin-oxide (ITO) and the cell thickness was maintained using glass spacers of 6 μm. The inner surfaces of the sandwiched ITO substrates were coated with a polyimide alignment layer (Nissan Chemical RN1199) and rubbed antiparallelly to promote planar alignment. After injection of the CLC mixture, we cooled slowly down to room temperature for achieving a stabilized planar texture of the CLC and exposed UV light (0.12 mW/cm^2) for 4 min to produce broadband spectrum covering entire visible range [6-8,11].

For an optical switching unit in the transflective LC display, a planar aligned nematic LC mode was used. The nematic LC used in this work was MLC6233 (E. Merck) whose optical anisotropy and dielectric one are $\Delta n = 0.0901$ and $\Delta\varepsilon = 4.3$, respectively. The SE7492 (Nissan Chemical) was coated on the ITO sputtered substrates, followed by unidirectional rubbing for planar alignment. The rubbing axis of the planar aligned LC layer was rotated by an angle of 45° with respect to one of crossed polarizers so that the LC layer acted as a $3/4\lambda$ plate in the absence of an external field. The cell gap was maintained using glass spacers of 5.3 μm thick.

The UV-visible spectrophotometer (JASCO) and the polarizing optical microscope (Nikon E600 Wpol) were used for investigating the optical properties of the CLC white reflector and the transflective LC display. The electro-optical (EO) properties of the transflective LC display were measured using a He-Ne laser (632.8 nm), an arbitrary function generator (Stanford Research System DS345), a digital multimeter (Keithley DMM2000), and a photodetector. Note that any LC modes are applicable to our transflective LC display as an optical modulator.

3. RESULTS AND DISCUSSION

3.1 Wideband Pitch Stabilization

A wavelength-selective reflection of the CLC layer is governed by the cholesteric pitch and the circular polarization state of the reflection coincides with the helical sense of the CLC. To vary the resultant reflection color, we control the pitch of the CLC which is governed by concentration of a chiral agent as well as temperature. Particularly, the temperature-dependent pitch variation of the CLC gives rise to some problems in performance stability and/or reliability for device applications. To achieve the pitch stability against temperature, the photo-polymers were generally introduced [6-8,11].

When a CLC film with RM monomers is irradiated by UV light, the LC and RM molecules absorb UV light and the UV intensity is gradually reduced crossing the cell thickness. The UV intensity gradient gives rise to the diffusion of the RM monomers and the density gradient of the polymer since the UV intensity determines a polymerization rate of the RM monomers. In the CLC mixture with the RM monomers with chirality, the density gradient of the polymer determines the pitch of the CLC since it is directly related to the density of chiral agent. Using the one-dimensional (1D) phase separation model [9], we numerically calculated the polymer fraction (ratio of polymer to nematic LC) crossing the cell thickness as shown in Fig. 1. The polymer fraction was gradually reduced and thus the corresponding pitch would be increased with increasing the distance from the UV illuminated surface.

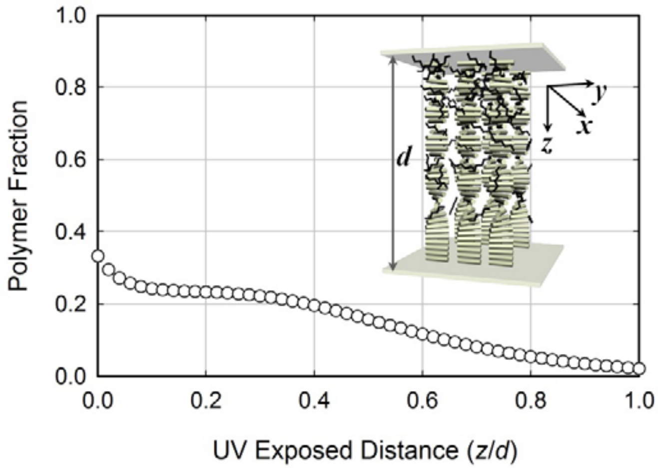

Figure 1. The volume fraction of the RM polymer with chirality and schematic diagram as function of the distance from UV illuminated surface. (Figure appears in color online.)

Figure 2 shows the measured reflectance and the calculated reflectance of the CLC white reflector prepared with continuous pitch stabilization. Here, inset image represents the reflected microscopic texture, which shows a typical Grandjean texture of the CLC in planar alignment. As shown in Fig. 2(a), the broadband reflection spectrum from about 460 nm to about 760 nm was obtained. Using the polymer fraction in Fig. 1 and the 4×4 matrix analysis [13], we calculate the reflectance (*R*) for the CLC film with continuously varying pitch (*p*) as function of the wavelength (λ) following as,

$$R(\lambda) = \frac{k^4\delta^2 \sin^2(\beta n)}{4q^2\beta^2 + k^4\delta^2 \sin^2(\beta n)}, \tag{1}$$

$$\beta^2 = k^2 + q^2 - k\sqrt{4q^2 + k^2\delta^2}, \tag{2}$$

$$k = \frac{\pi(n_e + n_o)}{\lambda}, \tag{3}$$

$$\delta = \frac{n_e^2 - n_o^2}{n_e^2 + n_o^2}, \quad (4)$$

where $q = 2\pi/p$ and n depicts a number of the pitch. To consider dispersions of the extraordinary (n_e) and ordinary (n_o) refractive indices of the E48, Li's experimental results were used [14]. The final reflection spectra were obtained by integrating the individual reflectance for the continuous varying pitch as shown in Fig. 2(b). Semi-quantitatively, both measured and calculated spectra coincide with each other. Now, the CLC white reflector with broadband reflection spectrum covering whole visible range can be applicable to a dual-functional film (a circular polarizer and reflector) for the transflective LC displays.

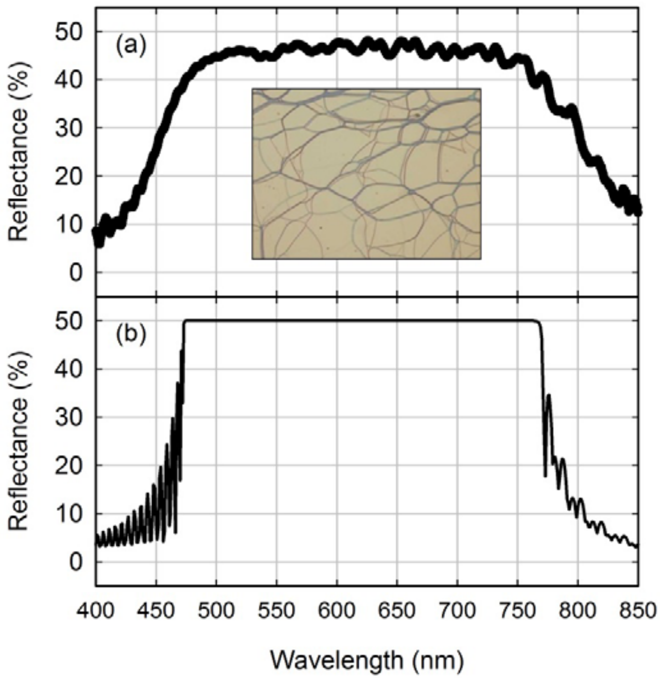

Figure 2. (a) Measured and (b) calculated spectra of reflection from the cholesteric white reflector. Inset image represents the reflected microscopic texture. (Figure appears in color online.)

3.2 **Transflective Liquid Crystal Display**

Transflective LC displays have been extensively researched for mobile display applications such as tablet personal computer, e-book, and mobile phone since their superior performance under both indoor and outdoor environments. In general, two sub-pixel configurations for the transmissive and reflective parts were widely studied to obtain the equivalent EO characteristics [15-21]. However, the degradation of the light efficiency induced by dividing each pixel in two regions can be unavoidable.

Figure 3 shows a schematic diagram and Poincaré Sphere representations of our transflective LC display with a CLC white reflector in a single pixel configuration without dividing into sub-pixels [12]. As shown in Fig. 3(a), the single pixel transflective LC display consists of the switchable LC layer with single linear polarizer and the CLC white reflector which selectively reflects a certain circular polarization but transmits the orthogonal circular polarization in entire visible light. It should be noted that no applied voltage is required in the CLC white reflector for switching the display modes from transmissive to reflective modes and vice versa.

In a transmissive mode, the CLC white reflector acts as a circular polarizer transmitting incident light from a backlight unit (BLU). The circularly polarized light passing through the CLC film enters the LC layer acting a $3/4\lambda$ plate in the absence of an external field and is blocked by the linear polarizer as shown in Fig. 3(b). In the presence of the applied field, the LC layer acts as a $1/4\lambda$ plate and thus the circularly polarized light passing through the CLC film is changed to a linear polarization parallel to the front polarizer by passing through the LC layer as shown in Fig. 3(c). As a result, the bright state was obtained.

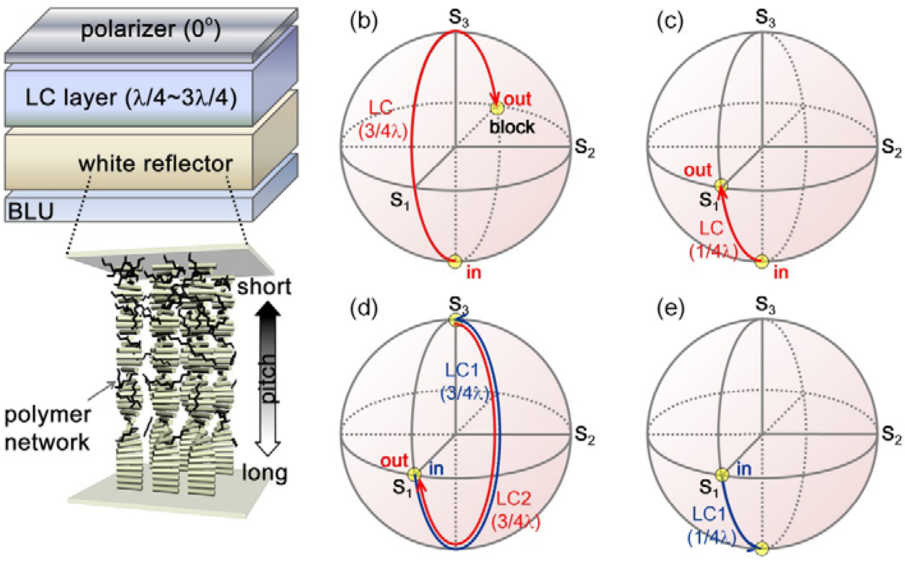

Figure 3. (a) Schematic diagram and (b)-(d) polarization representations of our proposed transflective LC display consisting of the nematic LC display as a conventional light modulator and the cholesteric white reflector as a transflective mirror. Optical pathways for (b) dark and (c) bright states in the transmissive mode, and for the (d) bright and (e) dark states in the reflective mode represented on the Poincaré Sphere. (Figure appears in color online.)

In a reflective mode, the circularly polarized light passing through the LC layer (3/4λ plate) under no applied field is totally reflected from the CLC reflector since the handedness of the incident light into the CLC reflector coincides with the helical sense of the CLC reflector as shown in Fig. 3(d). The reflected light is linearly polarized by the LC layer and passes the front linear polarizer. Under the applied field, the incident light passing through the LC layer (1/4λ plate) is circularly polarized and the circular polarization is blocked by the CLC film due to its orthogonal circular polarization as shown in Fig. 3(e).

The operation of the transflective LC display was observed with the microscopic textures and the EO measurements as shown in Fig. 4. In the absence of an applied voltage, the LC layer acts as the $3/4\lambda$ plate and thus the dark state is obtained in the transmissive mode and the bright state in the reflective mode as aforementioned. With increasing the applied voltage, the phase retardation in the LC layer is decreased. As a result, the transmittance is gradually increased but the reflectance is gradually decreased as shown in Fig. 4. Although the inversion images between the transmissive and reflective modes were obtained, the light efficiency in both modes is superior to the previous transflective LC displays using the CLC film with broadband reflection spectrum [10,11]. In the single pixel configuration without dividing into sub-pixels, the disparity between the transmissive and reflective modes is not serious since the whole pixel contributes the EO properties irrespective of the transmissive and reflective modes.

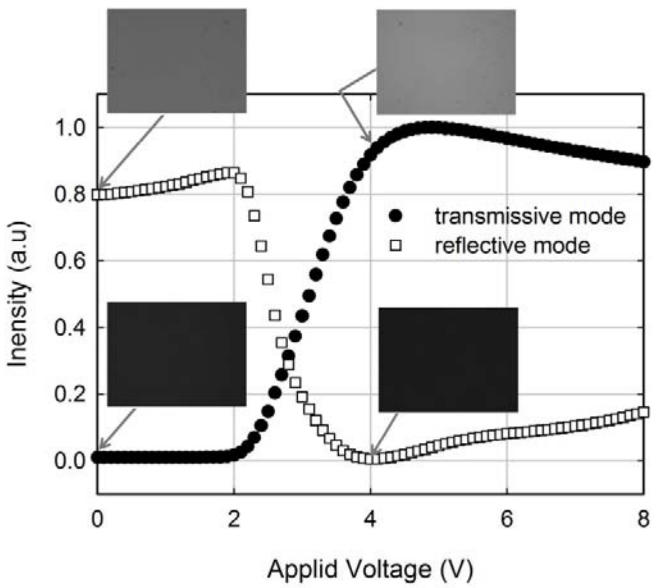

Figure 4. Measured electrooptic properties and corresponding microscopic textures in both transmissive and reflective modes.

4. CONCLUSION

We reported the mechanism of the continuous pitch variation in the CLC mixture with photopolymer based on the 1D phase separation model and the 4×4 matrix analysis. From 1D phase separation model [9], the RM monomer with chirality was diffused into the higher UV intensity region by the density gradient of the RM monomer caused by the anisotropic photopolymerization. The UV intensity was gradually reduced with increasing the distance from the UV illuminated surface since the absorption of the RM monomer and nematic LC. As a result, the density of a chiral agent was gradually reduced and thus the resultant cholesteric pitch was continuously increased crossing the cell. Using the 4×4 matrix analysis [13], we directly calculated the reflectance coinciding with the experimental result with broadband reflection spectrum covering entire visible range. Also, we demonstrated a simple transflective LC display consisting of the conventional LC layer with single linear polarizer as a switching unit and the CLC white reflector as a transflective mirror.

5. ACKNOWLEDGEMENT

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