Flexible area-color reflective displays based on electric-field-induced blueshift in a cholesteric liquid-crystal film

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Abstract — An electrically controllable blueshift of the reflection band is observed in a cholesteric liquid crystal with either positive or negative dielectric anisotropy. The change in optical properties is a result of a two-dimensional periodic undulation of the cholesteric texture, known as Helfrich deformation. This blueshift mechanism was used to demonstrate area-color reflective displays in a cholesteric cell and a rollable polymeric film.

Keywords — *Multicolor display, cholesteric liquid crystal, flexible display.*

1 Introduction

Cholesteric liquid crystals (ChLCs) offer bright colors without the use of color filters and polarizers, so they are attractive for reflective display applications.[1] Low-power-consumption reflective displays have been developed by utilizing the bistability of the planar and focal-conic textures of ChLC.[2] With the support of polymer walls or polymer encapsulation, flexible bistable ChLCDs have been demonstrated.[3,4] A full-color reflective display can be realized by stacking three ChLC layers reflecting red, blue, and green, respectively.[5]

Various methods have been developed to actively tune the reflection band of a ChLC. The reflection peak can be tuned by varying the device temperature.[6] External fields can be utilized to modulate the helical structure and thereby change the reflection wavelength as well.[6] An in-plane electric field generated by interdigitated electrodes can elongate the helical pitch and thereby shift the reflection to a longer wavelength.[7,8] The electrically controllable red shift can be utilized in display applications. With the assistance of an appropriate polymer network, an electrically driven red shift of the reflection band has been demonstrated in polymer-stabilized ChLC. Such a device can serve as tunable filters or in tunable-distributed feedback lasers.[9]

In this paper, we demonstrate an electrically tunable blue shift of the reflection color in planar-aligned ChLCs. The color of the cell is controlled by the amplitude of the voltage across the cell. The change in optical properties of the device results from electric-field-induced two-dimensional undulation of the helical structure which is known as Helfrich deformation.[10] This phenomenon takes place in ChLCs with either positive or negative dielectric anisotropy ($\Delta\varepsilon$).[11] In a positive $\Delta\varepsilon$ CLC, the formation and expansion of focal conic area through oily streak is also observed when an electric field is applied across the cell. Such a process does not happen in the negative $\Delta\varepsilon$ cholesteric liquid crystal. If the transition to focal conic structure through oily streak can be suppressed, devices using either positive or negative $\Delta\varepsilon$ ChLC can be used for reflective displays.

One way to solidify the liquid-crystal director distribution and the corresponding optical properties is to employ reactive mesogens. These monomers exhibit a liquid-crystal phase in certain temperature range and can be polymerized by irradiation or thermal curing, and thereby maintain the optical properties of the system. A practical example is to make polymer film/pigments to reflect the desired color by curing the cholesteric reactive mesogen at its cholesteric phase.[12] Pixelated color filters were fabricated using photochemically isomerizable cholesteric compounds and patterned-masked curing to generate and consolidate pixelated pitch variation in cholesteric polymer films.[13] Similarly, the electrically undulated helical structure and the resulting color change can also be recorded by UV curing the cholesteric reactive mesogen cell when voltage is applied. By masked-curing a cholesteric reactive mesogen cell at different voltages, multi-color patterns can be written into a single cell. And by peeling off the glass substrates, a flexible colorful film is achieved, which is not electrically switchable.

2 Electrically induced blue shift in a positive $\Delta\varepsilon$ CLC

We observed an electrically controllable blue shift when a voltage is applied across a planar-aligned ChLC cell. The ChLC we employed is a mixture of BL006 (a positive $\Delta\varepsilon$ nematic liquid crystal) and CB 15 (a chiral dopant). The mixture is capillary-filled into an indium tin oxide (ITO) glass cell in the isotropic phase. The glass substrates were coated with a thin polyimide layer and rubbed in anti-parallel directions to achieve homogeneous alignment. After filling, the cell is cooled down to room temperature and a planar cholesteric texture is established. The initial color of the ChLC cell can be selected by varying the percentage of the chiral dopant.

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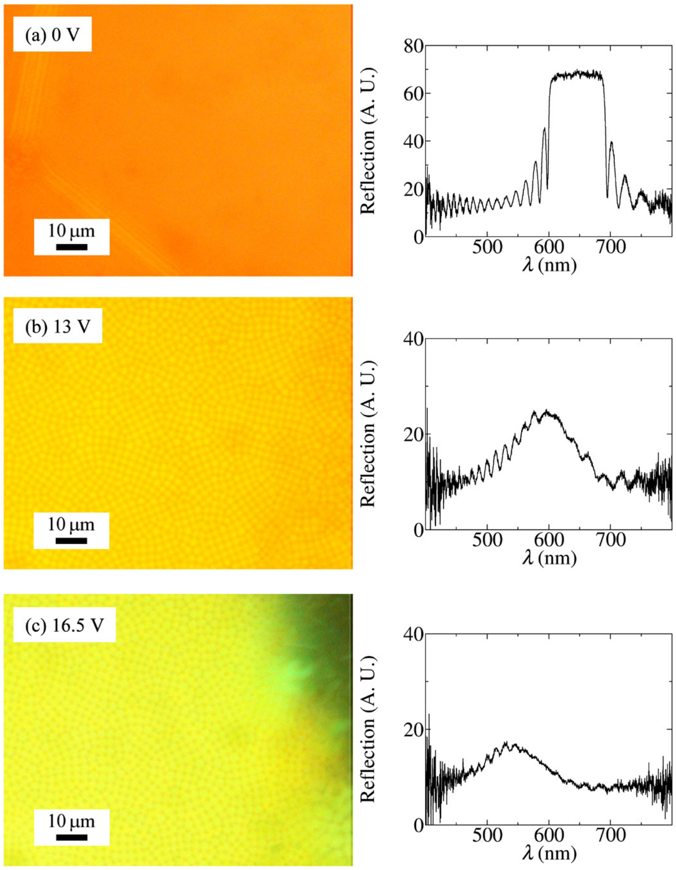

FIGURE 1 — The reflective microscope photos (left) and reflection spectra (right) of a 5-μm planar-aligned cell filled with a positive Δε ChLC at different voltages.

Figure 1 shows the reflection microscope photos and reflection spectra of a 5-μm cell at different voltages. When no voltage is applied, the liquid crystal has a perfect planar texture and shows a selective reflection to right-handed circularly polarized light centered at ~650 nm, as shown in Fig. 1(a). A 100-Hz ac voltage is utilized to address the cell. When the applied voltage is greater than ~10 V_{rms}, a two-dimensional periodic undulation of the helical structure takes place, resulting in color change. At $V = 13\ V_{rms}$, the cell color turns to yellowish as shown in the left side of Fig. 1(b). The reflection spectrum presented on the right side of Fig. 1(b) indicates that the reflection peak shifts toward a shorter wavelength, but its bandwidth is broadened and peak reflectance decreased. The color of the cell appears greenish, as Fig. 1(c) shows, when the voltage is increased to 16.5 V, but its peak reflectance is further decreased. If we keep increasing the voltage across the cell, the ChLC will be turned into the focal-conic state and then the homeotropic state, neither of which exhibits selective reflection.

The two-dimensional periodic undulation is the electrically induced Helfrich deformation. Such a change in texture happens when the voltage is higher than the threshold value:[1]

$$V_{Helfrich} = \frac{4\pi(2K_{22}K_{33})^{1/2}}{\Delta\varepsilon\varepsilon_0}\frac{h}{P_0}, \tag{1}$$

where K_{22} and K_{33} are the twist and bend elastic constants of the ChLC, h is the cell gap, and P_0 is the pitch length at zero field. The spatial period of the undulation is[10]

$$\lambda = (2K_{33}/K_{22})^{1/4}(P_0 h)^{1/2}. \tag{2}$$

In the first-order perturbation approximation, the undulated pitch length is given by[10]

$$2\pi\left(\frac{1}{P} - \frac{1}{P_0}\right) = \tau_0 \sin\left(\frac{\pi z}{h}\right)\cos\left(\frac{\pi x}{\lambda}\right), \tag{3}$$

where P is the local pitch length, the z axis is the cell normal direction, the x axis is parallel to the cell surface, and τ_0 is the perturbation amplitude which depends on the electric field. The inhomogeneity of the helical pitch, as described by Eq. (3), results in the broadening of the reflection peak and the decrease of peak reflectance. Once the voltage is removed, the undulation will disappear and the cell will fall back to the original planar texture.

Another electrically induced change in cholesteric texture, the transition to focal-conic texture through oily streak, also takes place when a voltage is applied. The dark area in the upper right corner of Fig. 1(c) (left) is the oily streak/focal-conic region. The threshold voltage of the oily streak is lower than that of the Helfrich deformation due to the defects in the planar texture. The formation of oily streak is slower than the Helfrich deformation. However, the entire cell will turn into the focal-conic state through the formation of oily streak. To suppress the formation and expansion of the focal conic region, the following factors are helpful to avoid using cell spacers, to eliminate defects and inhomogeneity in alignment layers, to improve cell-gap homogeneity, and to choose an appropriate ChLC. If the transition to focal-conic texture through oily streak can be controlled, this device would be useful for multi-color reflective displays.

3 Electrically induced blue shift in a negative Δε ChLC

The electrically induced blue shift also occurs in planar-aligned ChLC with negative dielectric anisotropy, which was theoretically predicted and experimentally observed in the 1970s.[11,14] This phenomenon can also be used to realize controllable optical performance tuning. A mixture of ZLI-4788 (Merck, $\Delta n = 0.1647$ at $\lambda = 589$ nm and $\Delta\varepsilon = -5.7$ at $f = 1$ kHz) and S1011 (a chiral dopant) was capillary-filled into a 5-μm ITO-glass homogeneous cell. As depicted in Fig. 2(a) (left), the cell shows a perfect planar texture when no external field is present. The reflection spectrum in the right side of Fig. 2(a) confirms this observation.

During experiments, we used a 100-Hz ac voltage to drive the cell. When the applied voltage exceeds ~25.5

V_{rms}, signs of distortions start to appear near the spacers. As the voltage increases, clusters of undulations begin to take place and soon expand to the entire cell. The undulated helical structure gives the cell a different color appearance. Figure 2(b) (left) shows the reflection microscope photo of the cell at ~43 V_{rms}. The two-dimensional undulation shows a hexagonal spatial pattern, which is different from the square pattern in the cell filled with a positive $\Delta\varepsilon$ liquid crystal. The spatial patterns in this cell drift with time, while the spatial pattern in the cell filled with a positive $\Delta\varepsilon$ liquid crystal is relatively static. The color of the cell shifts to yellow-green. The reflection spectrum of the cell reveals a blue shift on the reflection peak, together with the broadened reflection bandwidth and decreased peak height. Further blue shift of the cell color can be realized by increasing the applied voltage, as shown in Fig. 2(c). It is interesting to note that the peak reflectance is higher than that at 43 V. Because of the negative dielectric anisotropy, the cell will not be turned into focal-conic or homeotropic state by the electric field across the cell. When the electric field is removed, the cell returns to its original perfect planner texture. Therefore, this device may be used in multi-color reflective displays.

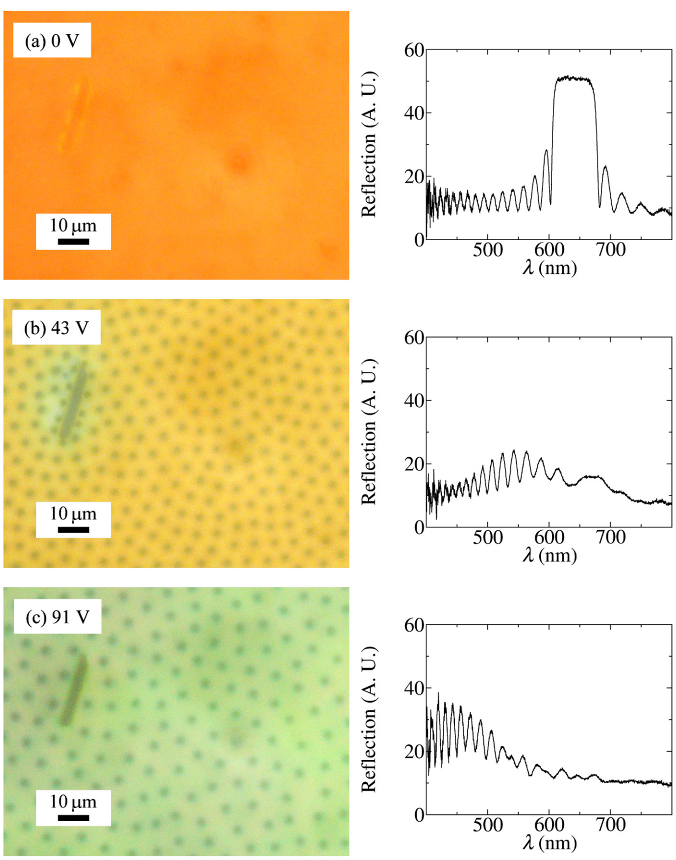

FIGURE 2 — The reflective microscope photos (left) and reflection spectra (right) of a 5-μm planar-aligned cell filled with a negative $\Delta\varepsilon$ ChLC at different voltages.

4 Flexible multi-color reflective displays

In a photo or thermally polymerizable liquid crystal reactive mesogen, the director distribution can be fixed by using the polymerization process. In this experiment, we use a positive $\Delta\varepsilon$ cholesteric reactive mesogen to record the electrically undulated helical structure and the resulting change in reflection spectrum. The mixture contains RMM254 (reactive mesogen mixture, Merck), RM82 (reactive mesogen, Merck), and CB15 (chiral dopant, Merck). The zero field pitch is controlled by varying the ratios of the components.

Planar-aligned cholesteric reactive mesogen cells were UV cured when different voltages were applied. A scanning electron microscope (SEM) was utilized to observe the modulation of the helical structure, and a spectrometer was utilized to examine the resulting optical performance change. Figure 3 shows the SEM photos of the cross sections of the cured cholesteric reactive mesogen cells. The cross section of a cell cured without an external field is dis-

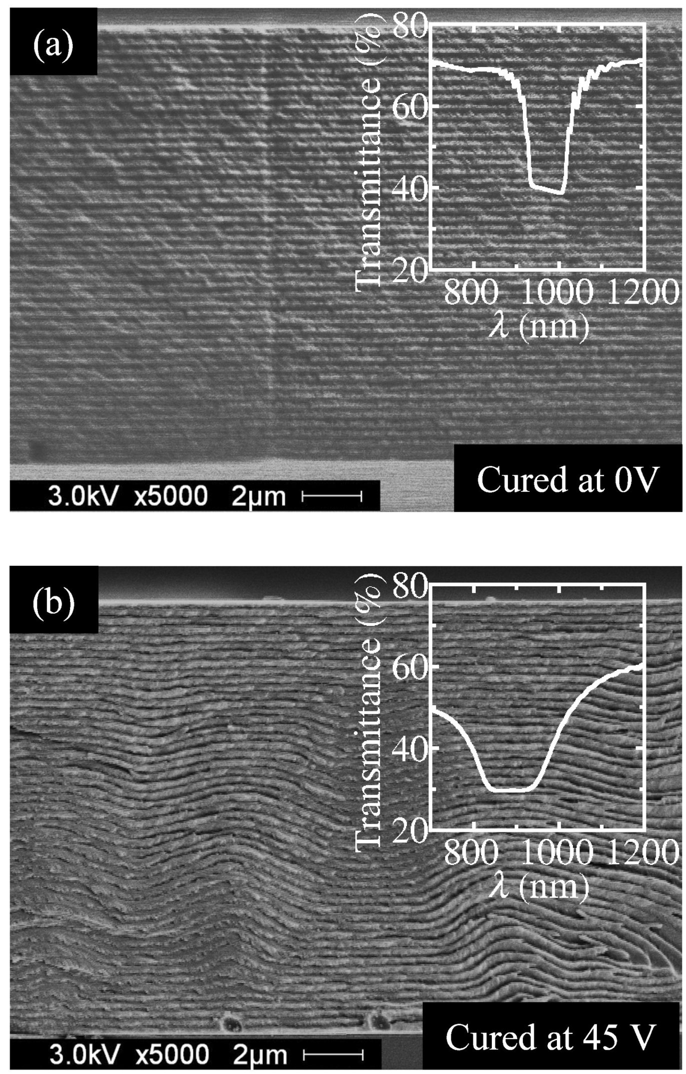

FIGURE 3 — SEM images of a cross section of a cholesteric film cured at (a) $V = 0$ and (b) $V = 45\ V_{rms}$. The transmission spectrum of each film is shown in the inset.

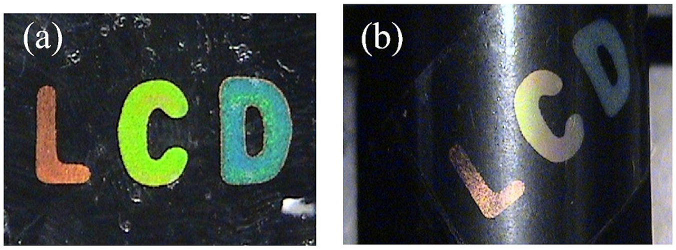

FIGURE 4 — A three-color rollable cholesteric polymer film: (a) before bending and (b) when the film is attached to a cylindrical post holder. The "LCD" characters were exposed when different voltages were applied. The film thickness is 8 μm.

played in Fig. 3(a). The uniform layered structure indicates a perfect planar texture with homogeneous pitch distribution. The corresponding transmission spectrum, as shown in the inset of Fig. 3(a), confirms this configuration. Figure 3(b) shows an undulated structure when the cell was cured at 45 V_{rms}. The change in director distribution leads to the change in transmission spectrum: the blue shift of the transmission notch and the expansion of notch width, as shown in the inset of Fig. 3(b). The correlation between the cholesteric texture and optical properties is clearly established by this comparison.

The SEM image in Fig. 3(b) shows that the undulated texture does not exactly follow the first-order sinusoidal perturbation suggested by Helfrich. The variation in cholesteric pitch and in the tilt angle of cholesteric layers is not always minimized at cell substrates, which is indicated by Eq. (3). A better theoretical model for understanding the director undulation mechanisms and their associated optical-property change remain to be developed.

The electrically induced color change in cholesteric reactive-mesogen cells can be permanently recorded through UV curing when the voltage is applied.[15] An area-color pattern can be recorded into a single cell by masked curing each part when different voltages are applied. The film thickness is controlled by the cell gap, which is 8 μm in our experiment. The glass substrates can be peeled off and a flexible film with area-color pattern is fabricated. Figure 4 shows a polymer film with three characters "LCD" written in; with each character in a different color. This film can be bent and conformed to a curved surface, as exhibited in Fig. 4(b). The above process can be applied to produce films for decoration and to write security marks. However, once cured the displayed images cannot be switched by an electric field.

5 Conclusions

We have demonstrated electrically controllable blue shift in a planar-aligned ChLC with either positive or negative dielectric anisotropy. The optical performance change originates from a two-dimensional periodic undulation of the planar texture. The device filled with a negative $\Delta\varepsilon$ ChLC can be used in reflective color display. If the transition to focal-conic texture through oily streak can be suppressed in planar aligned cells filled with a positive $\Delta\varepsilon$ ChLC, such a device can also be used in reflective displays. The electrically tuned color change can be solidified by curing the cholesteric reactive mesogen when the voltage is applied. By masked curing at different voltages, multiple color patterns can be recorded into a flexible polymer thin film, which can be used as a decoration film or security prints.

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