4.1: Rollable Reflective Multicolor Cholesteric Displays

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Abstract: A rollable reflective multicolor display using an electrically tunable blue shift of both cholesteric reactive mesogen and none reactive cholesteric liquid crystal is observed. The electrically undulated director configuration in cholesteric reactive mesogen was solidified by UV curing when a voltage is applied. SEM photos revealed that the blue shift is due to the Helfrich deformation. The field induced change in optical properties of the cholesteric reactive mesogen cells can also be recorded by photopolymerization. Multi-color patterned can be written into a single film by masked curing the cholesteric reactive mesogen at different voltages.

Keywords: reflective display; cholesteric; rollable display; polymer

Introduction
Cholesteric liquid crystals exhibit various colors due to the selective Bragg reflection. This property has been utilized in various applications such as reflection display [1, 2, 3], color filter arrays [4], and mirrorless lasing [5, 6]. The color of a cholesteric cell can be tuned by changing the pitch length via varying the temperature or applying external field [7]. Red shift in reflection band was demonstrated in polymer-stabilized cholesteric liquid crystal cells and such devices can be utilized in tunable filters and lasers [8]. With an in-plane electric field perpendicular to the helical axis, the pitch length can be electrically elongated in planar cholesteric cells, resulting in a red shift in the reflection/transmission spectrum [9, 10].

Reactive mesogens are liquid crystal materials that can be photopolymerized. The director field in reactive mesogen systems can be configured using the same method to configure non-reactive liquid crystal material and the resulted configuration can be recorded through photopolymerization of the system. A particular example is the using cholesteric reactive mesogen mixture to make polymer films with desired reflection/transmission spectrum [11].

A blue shift of reflection wavelength was observed in planar aligned cholesteric reactive mesogen and non-reactive cholesteric liquid crystal cells when an electric field was applied across the cells. The color of the cell is controlled by the amplitude of the applied electric field. The change in optical properties is the result of a two dimensional periodic undulation in helical structure induced by external field, the Helfrich deformation. The undulated helical structure in cholesteric reactive mesogen cell can be solidified via photopolymerization. The change in optical properties is also fixed simultaneously. By curing different areas at different voltages, multi-color patterns can be written into in a single cell. A flexible colorful film can be fabricated by peeling the glass substrates from the cured cell. In both cholesteric reactive mesogen and non-reactive cholesteric liquid crystal cells, the competition between the formation of focal conic region through oily streak and Helfrich deformation was observed and this competition is temperature dependent. If an appropriate condition can be found under which the transition to focal conic texture through oily steak can be totally suppressed while the Helfrich deformation is allowed, this device is suitable for reflective display application.

Blue Shift in Cholesteric Reactive Mesogen
The electrically controllable blue shift in reflection band was observed in cholesteric reactive mesogen cells with perfect planar texture. A cholesteric reactive mesogen mixture consisting RMM254 (reactive mesogen mixture, Merck), RM82 (reactive mesogen, Merck) and CB15 (chiral dopant, Merck) was capillary-filled into ITO (Indium-Tin-Oxide) glass cells with anti-parallel rubbing (chiral dopant, Merck) was capillary-filled into ITO (Indium-Tin-Oxide) glass cells with anti-parallel rubbing on the polyimide coatings in an isotropic phase and slowly cooled down to cholesteric phase. The zero field reflection wavelength of the cell can be tuned by varying the percentage of components in the mixture.

We applied an AC electric field (~100 Hz) across the planar cell. When the applied voltage was higher than a threshold value, a two-dimensional periodical undulation began to take place. Figure 1 shows the photo and reflection spectrum of a 5 μm cholesteric reactive mesogen cell when different voltages were applied. The cell exhibits perfect planar texture when no voltage is applied and reflects red light at specular angle. We gradually increase the voltage across the cell. When the voltage is greater than 22 V scattering begins to appear, indicating the deviation from perfect planar texture. With the increase of the applied voltage, the reflection band of the cell moves to longer wavelengths and the color of the cell evolves from red to green, and then to blue. Meanwhile, the reflection bandwidth increases but the reflectance decreases. Further increase of the applied voltage turns the cell into focal conic texture and then to homeotropic state. Selective reflection cannot be found in either of these two states.
Helfrich Deformation

The two-dimensional undulation in cholesteric texture can be identified under microscope. A transmission microscope photo of a cholesteric reactive mesogen cell between crossed polarizers is displayed in Figure 2. The photo is taken when a voltage was applied across the cell and the undulation in the cell is clearly exhibited. The color of the undulated area can be observed using reflection microscope, which helps to confirm the relation between the undulation and the blue shift. Oily streak and focal conic regions also appear in Figure 2. When a voltage is applied, oily streak expands slowly along defect lines increases the focal conic area of the focal conic region. The expansion of focal conic area through oily streak accelerates when the applied voltage increases.

The two-dimensional periodic undulation in cholesteric texture by electric field is the Helfrich deformation. The threshold voltage of Helfrich deformation is given by [2]:

\[ V_{\text{Helfrich}} = \frac{4\pi \left( \frac{2K_{22}K_{33}}{\Delta \varepsilon \varepsilon_0} \right)^{1/2}}{P_0} \]  

(1)

where \( K_{22} \) and \( K_{33} \) are the twist and bend elastic constants of the cholesteric liquid crystal, \( h \) is the cell gap, and \( P_0 \) is the pitch length at zero field. The spatial period of the undulation is [12]

\[ \lambda = \left( \frac{2K_{33}}{K_{22}} \right)^{1/4} (P_0 h)^{1/2}. \]

The undulation in cholesteric pitch is given in first order perturbation [12]:

\[ 2\pi \left( \frac{1}{P} - \frac{1}{P_0} \right) = \tau_0 \sin \left( \frac{\pi \varepsilon}{h} \right) \cos \left( \frac{\pi \varepsilon}{\lambda} \right), \]

(2)

where \( P \) is the local pitch length, \( z \) axis is the cell normal direction, \( x \) axis is parallel to the cell surface, and \( \tau_0 \) is the perturbation amplitude which depends on the electric field. The pitch inhomogeneity in Helfrich deformation, as exhibited in Equation (2), results in the broadening of the reflection band and the decrease of peak reflectance. Due to the undulated nature of the Helfrich deformation, scattering from the cell increases with the increased voltage, which also contributes to the decreased reflectance.

Consolidation of the Undulated Texture

We froze the undulated texture in cholesteric reactive mesogen cells by photopolymerizing the cell when a voltage is applied. The cross-section of the cells was observed using scanning electron microscope (SEM) to reveal the deformed helical layer structure. Figure 3 (a) and 3 (b) are the SEM images of two cholesteric reactive mesogen cells cured at 0 V and 45 V respectively. The transmission spectra of the cells are presented in the insets of Figure 3 to show the relation between the optical
properties and the cholesteric textures. A uniformed pitch distribution is exhibited in Figure 3 (a), which is the characteristic of a perfect planar texture when no external field is present. The transmission spectrum of the cell cured at 0V is also typical for a planar cholesteric cell. On the other hand, the texture in the cell cured at 45 V bears spatial pitch variation and distortion due to the electrically induced Helfrich deformation, as exhibited in Figure 3 (b). This deformed structure leads to not only a blue shift but also a broadened bandwidth and decrease in transmittance, as displayed in the inset of Figure 3 (b). The undulated texture shown in Figure (b) does not exactly follow the first order sinusoidal perturbation form suggested by Helfrich. The variation in cholesteric pitch and tilt angle of cholesteric layer is not always minimized at the cell substrates, which is indicated by Equation (2). A more precise mathematical description of the undulated director field distribution and the optical properties of such distribution are under investigation.

**Multi-color Film from Masked Curing**

We wrote different color patterns into a single cell by masked curing a cholesteric reactive mesogen cell at different voltages. A flexible film is acquired by peeling of the glass substrates. The film thickness is controlled by the cell gap, which ranges from several microns to tens of microns. Therefore, the resulted films are highly flexible. A polymer film with “LCD” written in, each letter having a different color, is exhibited in Figure 4. This film can be easily rolled over a cylindrical optical post, as demonstrated in Figure 4 (b). Such films may be used for display in decoration and security/identification applications.

**Blue Shift in Non-reactive Cholesteric Liquid Crystal**

We also observed the electrically tunable blue shift in non-reactive cholesteric liquid crystal cells. The cholesteric liquid crystal we study is a mixture of BL006 (nematic, Merck) and CB15 (chiral dopant, Merck). Planar cells filled with this mixture were made. Electrically induced blue shift due to the Helfrich deformation can also be realized in these cells. Figure 5 shows the reflective microscope photos of a 5 μm planar cell under different voltages. In these cells, the formation of oily streak happens at a lower voltage than the Helfrich deformation. The expansion of oily streak in these cells is faster than that in the cholesteric reactive mesogen cells. The expansion speed of oily streak is temperature dependent and slower at lower temperature. We also noticed that the oily streak forms from defects and domain walls. If we can eliminate the defects and domain walls and thereby suppress the formation of oily streak in the planar cholesteric liquid crystal cells, these devices can be used in reflection display applications.

**Conclusion**

We have demonstrated an electrically tunable blue shift of the reflection band in cholesteric reactive mesogen cells and in non-reactive cholesteric cells. The variation in optical performance of the cells is due to a two-dimensional periodic undulation in cholesteric texture induced by electric field. In cholesteric reactive mesogen cells, the undulated texture and the corresponding variation in optical properties can be frozen via photopolymerization when a
voltage is applied. Flexible and rollable polymer films with multiple color patterns can be fabricated with masked curing at different voltages, and can be used as color filters, decoration films, and security prints. If the formation of oily streak can be suppressed in the non-reactive cholesteric planar cells, these devices can be utilized in reflective displays.

References