A Polymer-Stabilized Single-Layer Color Cholesteric Liquid Crystal Display with Anisotropic Reflection

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The authors report a method of fabricating single-layer color cholesteric liquid crystal displays from a polymer-stabilized cholesteric liquid crystal. The reflective wavelength can be electrically switched to reflect blue or green from a cell initially reflecting a red color. The color change is a result of the compression to the helical pitches in planar layers in response to the applied voltage. The unique feature of the polymer stabilization is in the fact that the electrically switched colors preserve good reflectivity and the colors are reversible with voltage ramping. Conspicuously, the polymer-stabilized cholesteric display exhibits anisotropic reflection and has a temperature independent of reflected color. © 2007 American Institute of Physics. [DOI: 10.1063/1.2790499]

Reflective liquid crystal displays with features such as sunlight legibility and low-power consumption have wide range applications ranging from electronic papers, electronic books, mobile displays, to electronic sign displays. Among the available color display technologies, cholesteric reflective displays are particularly suitable for these display applications because the reflected wavelength and bandwidth can be preselected by its helical pitch at a planar structure. The selective reflection from a cholesteric liquid crystal makes it possible to for vivid color images to be displayed without color filters and crossed polarizers. The reflected wavelength of cholesteric liquid crystal is generated by the photonic band gap from the periodical cholesteric helical orientation. The cholesteric pitch p is defined as the distance in which cholesteric liquid crystal molecules rotate 360° along its helical. When light wavelength (λ) falls in the region $n_o p < \lambda < n_e p$, where n_o is the ordinary refractive index and n_e is the extraordinary refractive index of liquid crystal molecule, the refractive index seen by the incoming light beam becomes imaginary. Light with the same handedness as that of the cholesteric liquid crystal will be circularly reflected, while the component with opposite handedness will be circularly transmitted.[1]

Color reflective cholesteric displays can be fabricated by using either a single-panel or stacked-panel method.[2–7] A high brightness color cholesteric liquid crystal display (CLCD) can be prepared by using stacking technique. The stacked-panel technique provides a feasible solution of reflective cholesteric LCDs to display full colors. Although this approach gives maximum brightness to the color panels, volume manufacturing of CLCDs using stacked-panel technology requires overcoming the cost and yield, such as driver electronics and pixel registration issues.

It was reported that applying voltage on cholesteric liquid crystal molecules enables the color tuning by extending the helical pitches or inducing tilt of helices.[8–13] The electric-field-induced color change in cholesteric liquid crystal color can be traced back from the late 1960s. Harper showed the blueshift of cholesteric liquid crystal after the application of electric filed when the light is incident from an oblique

angle.[8] De Genne and Meyer predicted the untwisting of cholesteric helix when the magnetic field or electric field is applied to the cholesteric liquid crystals. Kahn experimentally demonstrated the color change from blue to red because of pitch dilation with voltage applied in the direction of helical axis.[9] In the case of using interdigitized electrodes to untwist the helix with in-plane field, the reported color change from blue to red in a cholesteric liquid crystal is because of pitch extension.[10,11] However, it requires high voltage because the field distributed within the cell is inhomogeneous and the electric torque applied to different layers of cholesteric liquid crystal to unwind the helix is nonuniform. A dramatic loss in reflectivity with increasing voltage is also observed because the number of layers decreases as the pitch is elongated. Instead of extending cholesteric pitch, Hikmet and Kemperman[12] used polymer network to create liquid crystal gels, which made the reflected wavelength showed blueshift with increasing voltage. The mechanism is referred to as the Helfrich deformation,[13] indicating uniformly periodical layer deformations in the cholesteric liquid crystals. The local tilting of helix leads to shortening of pitch observed from a normal direction, thus the reflection band moves to a shorter wavelength. It was also observed that the reflection bandwidth is increased with greater voltage. A flexible cholesteric liquid crystal polymer film was produced by Xiayu *et al.*[14] to retain the color induced by voltage. However, the electrically induced color is not tunable after the polymerization of the polymer network.

In this work, we present an electrically switched color cholesteric display with good reflectivity. Conspicuously, the polymer-stabilized cholesteric display exhibits a unique anisotropic reflection only from one side of the cell. The reflectivity remains in a certain value while the reflected wavelength is electrically switchable. Instead of broadening, the reflection bandwidth decrease slightly with increasing voltage.

A polymer stabilized cholesteric liquid crystal material is comprised of a nematic liquid crystal (62.20% E44), a chiral dopant (32.75% CB15), a reactive mesogen (5% RM257, a mesogenic diacrylate; the above three all obtained from Merck), and 0.05% of Ir651 (a photoinitiator from Ciba Additive). The concentration of chiral dopant was formulated to

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(a)

(b)

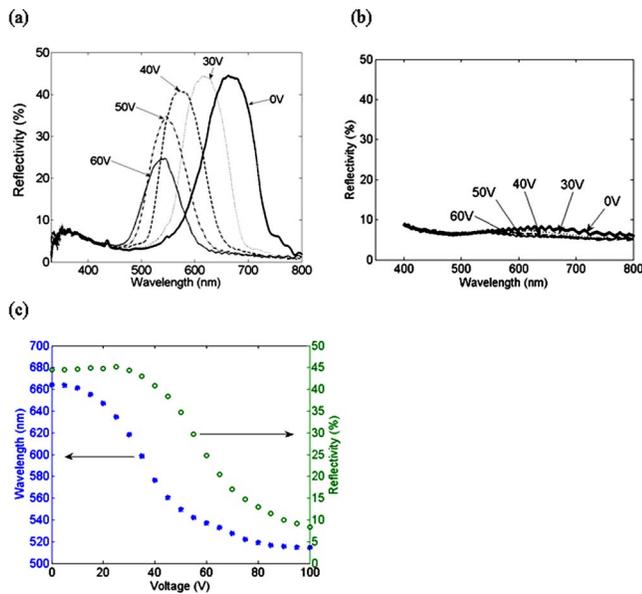**(c)**

(a) **(b)** **(c)**

FIG. 1. (Color online) Reflection spectra of (a) the reflected wavelength as a function of applied voltage measured from side A of the cell and (b) the reflected wavelength vs voltage of side B of the cell. (The side which is closer to the UV lamp during curing process is defined as side A and the other side as side B.) (c) The reflectivity (empty circle) of electrically switched color and the reflected central wavelength (solid circle) vs applied voltage (rms).
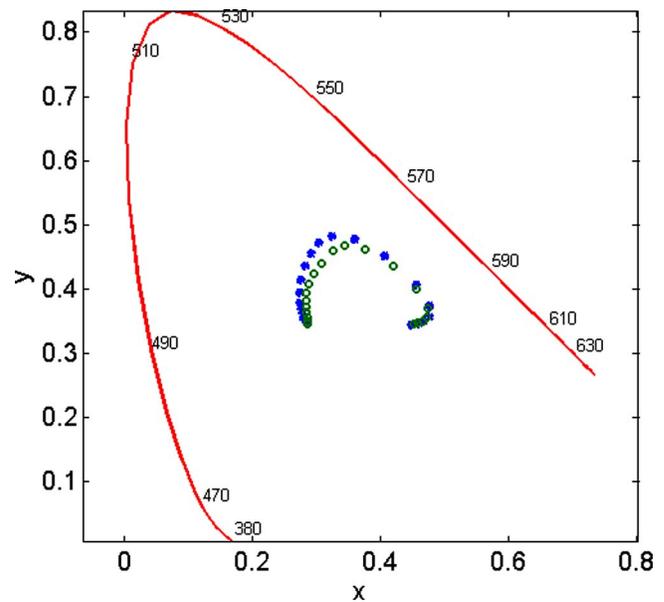
FIG. 2. (Color online) CIE 1931 chromaticity diagram 2° viewing angle of reflection wavelength of electrically switched, polymer-stabilized cholesteric liquid crystals. Solid circles show the color coordinates of the reflected color in increasing voltage, and the empty circles are in decreasing voltage.

reflect a selected wavelength in the visible range. An electro-optical cell with 10 μm cell gap, whose inner surfaces were coated with polyimide alignment layers. The polyimide layers were uniaxially rubbed for homogeneous alignment. The cholesteric mixture was filled in the cell by a capillary action at around 80 °C (the isotropic state of the cholesteric liquid crystal). The cell was irradiated with UV light at a wavelength of 365 nm (0.4 mW/cm^2) for 30 min to initiate the polymerization. The reflected spectra measurement of the cell in response to applied voltages is carried out at normal incident of white light illumination and detected from a normal angle by using an Ocean Optics spectrometer. The applied voltage is a square wave with a frequency of 1 kHz. As a ramification, the polymer-stabilized cholesteric liquid crystal in a planar state exhibits a blue shift in reflected wavelength with increasing voltage.

The polymer network provides anchoring for cholesteric helices in the bulk in addition to the anchoring from the alignment layer. At zero voltage, the polymer-stabilized cholesteric cells exhibit anisotropic reflectivity from only one side of the sample. The differential reflectivity is a result of inhomogeneous distribution of the polymer network during UV light induced curing. The photomonomer is polymerized faster at one side than the other and, thus, causing the unbalanced localization of polymer network on one substrate.[15,16]

In reference to Figs. 1(a) and 1(b), the side closer to the UV lamp (side A) reflects the incident light, while the other side (side B) appears to scatter light when the cell is turned over for reflectivity measurement. The light scattering of side B is because, after first time switching the cell, liquid crystal molecules close to side B with weaker anchoring from polymer network is switched to a focal conic state. The contrast ratio of reflectivity at 0 V from sides A and B is 4.5. The electrically tunable wavelength is observed from the side closer to the UV lamp (side A). The effective refractive index of extraordinary wave can be expressed as n_{eff}

$= n_e n_o / \sqrt{n_e^2 \cos^2 \theta + n_o^2 \sin^2 \theta}$, where θ is the angle between the director and the propagation direction of light. As θ decreases with increasing voltage, n_{eff} becomes smaller while n_o remains the same. Therefore, the photonic band gap, $(n_{\text{eff}} - n_o)p$, decreases with the voltage increasing. Figure 1(a) shows that the edge of higher energy band gap $n_o p$ is moving toward a shorter wavelength, meaning that the pitch of the planar layers is shortened. Upon the application of a voltage across the cell, the majority of cholesteric helices initially at a planar texture are compressed by the oriented liquid crystal molecules from the side B region. In the meantime, the reflectivity from side A remains in a certain value when the reflected wavelength starts responding to the applied voltage. This is because the strong polymer network anchoring suppresses the formation of focal conic/fingerprint textures in the bulk and close to side A. After a critical voltage, which is 40 V in this case, the number of reflecting layer is not enough to keep the same reflectivity as it is in a zero field, which explains the drop in the reflectivity. With a sufficiently high voltage, higher than the critical field of helix unwinding, we will be able to obtain a black state of polymer-stabilized CLCD by aligning the cholesteric in the homeotropic texture.

As shown in Fig. 1(c), the electrically switched reflective wavelength is a two-stage process. First, it has a threshold at approximately 2.0 V/μm. Afterwards, the electrically switched reflective wavelength is linearly proportional to the applied voltage beyond 20 V with a maximum alteration range of 140 nm from the original planar state at zero voltage. The tuning range and critical voltage of the initial reflectivity decreasing are found to be controllable either by varying the cell thickness or flexibility of the polymer network by mixing the mesogenic reactive diacrylate with a flexible isotropic diacrylate.

Figure 2 shows the chromaticity diagram calculated according to CIE 1931 2° viewing angle of electrically switched colors of a polymer-stabilized CLCD. Each circle corresponds to the color obtained from the applied voltage.
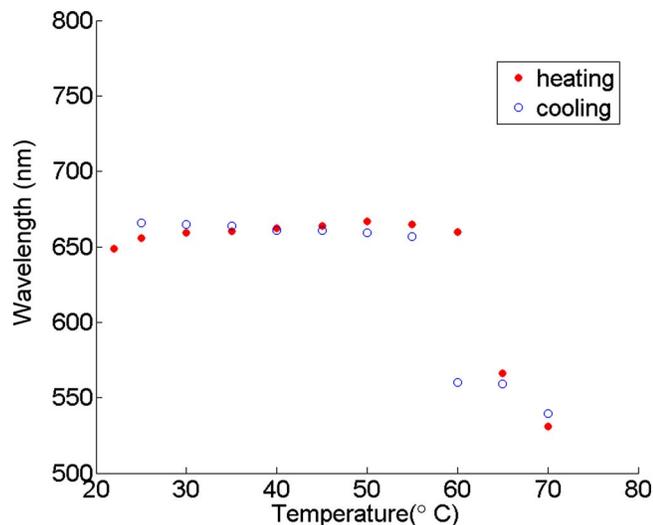
FIG. 3. (Color online) Temperature independentce of the reflected color of a single-layer CLCD.
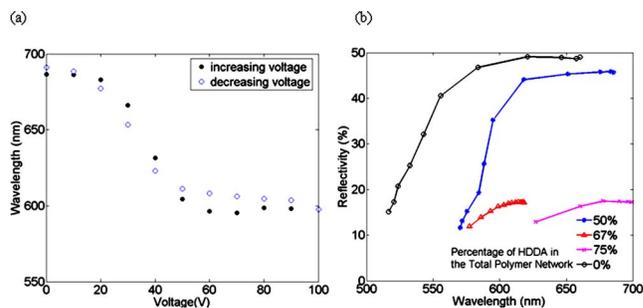

FIG. 4. (Color online) (a) Reflected wavelength vs applied voltage (rms) of a sample containing 50% of HDDA soft polymer network for voltage ramping up and down. (b) Reflectivity vs electrically switched color (reflected wavelength) of samples having different content of HDDA in the total of 5% polymer network concentration.

The electrically switched colors follow a counterclockwise fashion with the increase in applied voltage. The electrically switched colors are reproducible upon the reversal of applied voltages. The color change with the increase in applied voltage can be easily observed from the pictures taken directly from the cell as the three examples shown in the insert of Fig. 2.

At zero applied voltage, the cell shows a good thermal stability in both the heating and cooling processes. Unlike the temperature dependence of pitch change in cholesteric liquid crystals, the cell with polymer network suppresses the pitch elongation as temperature increase. The clear point of pure E44 is 100 °C. After doping E44 with CB15 and RM257, the clear point is measured to be at 73 °C. In reference to Fig. 3, the polymer-stabilized CLCD shows negligible deviation in reflected wavelength from room temperature up to 60 °C. The decrease in reflected wavelength beyond 60 °C is observed when the liquid crystal is approaching the isotropic transition temperature. With the polymer network constraint, the extended helical pitches at side B (focal conic region) or in midlayers compress those at the boundary layers and, thus, the reflected color is blueshifted.

The influence of polymer network flexibility on the maximum range of electrically switched color is also investigated. With the addition of a soft polymer network of hexanediol diacrylate (HDDA) of up to 50% by weight of total polymer network concentration [see Fig. 4(a)], the reflected color is still tunable and the process is reversible. For the samples consisting of HDDA soft polymer network concentration exceeding 50%, when the applied voltage is larger than 20 V, the reflected spectra are no longer reversible because the focal conic domains start to appear. This focal conic state stays even when the field is turned off. However, this state shows a broadband scattering; no distinguishable reflected color is observed. In the case of 100% of soft polymer network, no reflection peak is shown on the spectrum because of the strong scattering from the cell. In reference to

Fig. 4(b), with the concentration of soft polymer network HDDA increasing from 50% to 67%, and to 75% monomer, the reflectivity becomes low and the reversible wavelength range becomes smaller in response to the voltage ramping.

To conclude, we have demonstrated a single-layer color cholesteric liquid crystal display by using a small amount of polymer network to stabilize the electrically switched color with anisotropic reflection. The delicate balance between the field-induced pitch extension and polymer-network-squeezed pitches serves to provide maximum number of helical pitches to display a switched color with minimum sacrifice of the reflectivity. Moreover, the display shows good thermal stability and the electrically switched color is reversible. In the case of influence of polymer network flexibility on the range of electrically switched color, when the concentration of a soft polymer network exceeds 50% by weight of total polymer network, the tunable color range of the sample diminishes quickly. Our results also suggest an avenue for applications ranging from ultraviolet to infrared region by properly selecting the Bragg reflective wavelength of a cholesteric material.

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