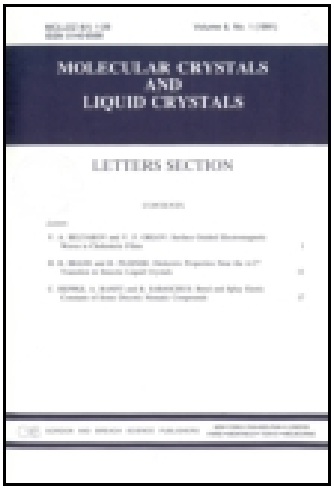

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Yan Jin[a], Zhe Hong[a], Chang Woo Jeon[a], Burm Young Lee[b], Kyoung-Sun Kim[b] & Soon-Bum Kwon[ab]

[a] Department of Display Engineering, Hoseo University, Asan, Chungnam, Korea

[b] NDIS Corporation, Asan, Chungnam, Korea

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A Novel Flexible Color Display Using Two-Step UV Exposure Method

YAN JIN,[1] ZHE HONG,[1] CHANG WOO JEON,[1] BURM YOUNG LEE,[2] KYOUNG-SUN KIM,[2] AND SOON-BUM KWON[1,2,*]

[1]Department of Display Engineering, Hoseo University, Asan, Chungnam, Korea
[2]NDIS Corporation, Asan, Chungnam, Korea

We developed two-step UV exposure method to achieve high performance flexible cholesteric LC displays: first exposure to form polymer walls and second exposure to get colors. The dependence of the parameters such as monomer concentration, UV irradiation energy, and temperature was extensively investigated for clear polymer wall formation and high reflectance of the cholesteric LCDs. Good RGB color cholesteric LCDs were achieved by doping a photo-sensitive chiral dopant into the mixture of cholesteric LC and monomer and by irradiating UV light with appropriate energy. The approach for flexible color Ch-LC displays is discussed in detail.

Keywords Flexible display; polymerization-induced phase separation; polymer walls; color Ch-LCD

1. Introduction

In recent years, flexible liquid crystal (LC) displays have drawn much attention by virtue of the significant improvement of the mechanical stability and electro-optical properties. Polymer wall formation using phase separation between LC and polymer in LC layer was known for an effective way to achieve the improvement. Extensive investigation into the polymer wall formation for nematic [1–5], smectic [6] and cholesteric [7–10] LC cells has been carried out. Among them, the research on the color pixelation Ch-LCD using photo-tunable chiral dopant was particularly of interest from the application point of view [9–10].

Lu et al. [9] proposed the realization method of the color pixelation Ch-LCD; polymer walls were formed by photo-polymerization induced phase separation and color pixelation was achieved by light-induced pitch change for desired color stripes using appropriate photo-masks. Braganza et al. [10] reported a single layer full color cholesteric display based on glass substrate; glass panel with horizontal polymer walls formed beforehand was assembled and Ch-LCs with photo-tunable chiral dopant were vacuum filled into the cells, and then red, green and blue colors were obtained through the adjustment of UV energy.

In this work, we developed a high performance flexible cholesteric liquid crystal (Ch-LC) display using two-step UV exposure method, applicable to roll-to-roll fabrication

*Address correspondence to Soon-Bum Kwon, Department of Display Engineering, Hoseo University, Asan, Chungnam 336-795, Korea. E-mail: sbkown@hoseo.edu

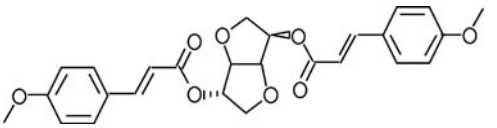

Figure 1. Molecular structure of the methyloxy-cinnamoylglucitol.

process. As compared to the polymer wall formation for nematic LC cells, more parameters have to be considered in that for Ch-LC cells. We will give some details about the dependence of the parameters, such as monomer concentration, UV irradiation energy, and temperature. Ch-LCs in general have much higher viscosity than nematic LCs, so that the phase separation temperature as a control parameter of the viscosity plays an important role in phase separation process. In order to achieve good color performance, we controlled the PSCD concentration, temperature and UV irradiation energy.

2. Experimental

Two step UV exposure method for polymer wall formation and color rendering in Ch-LCDs was carried out as follows: (1) Ch-LC with photo-sensitive chiral dopant (PSCD) was mixed with di-acrylate monomer, and then the mixture was coated into the plastic cells. After the coating of the mixture, the cell was irradiated by UV light through a photo-mask, and then the polymer walls were formed vertically and horizontally via photo-polymerization induced phase separation method. (2) The chiral pitch of the Ch-LC cell was changed corresponding to the selective reflection wavelength through the adjustment of UV irradiation energy, which changed the chiral pitch of the PSCD.

Main Ch-LCs used in experiment were CH-100-550 (Slichem Co.) for green Ch-LCD and CH-100-650 + PSCD for color Ch-LCDs. The PSCD was methyloxy-cinnamoylglucitol, the molecular structure of which is shown in Figure 1. The Cholesteric liquid crystal was mixed with PSCD of 3.3 wt%. For preparation of monomer mixtures, di-acrylate monomer was blended with crosslinking agent and photo-initiator. The Ch-LC materials and monomers for LC layer were mixed at the ratio range of 95:5 $\sim$ 80:20.

LC cells were prepared by using polycarbonate plastic substrates which were deposited by Indium Zinc Oxide (IZO). The cell thickness was 5 um. The mixture of Ch-LC and monomers was coated on the plastic substrate at room temperature, after that the cell was irradiated at a certain temperature through a photo-mask with a hexagonal pattern, whose width (D) was 200 um and the distance (L) between the patterns was 10 um (Figure 2).

A halogen lamp was used as a UV source covering 365 nm band effective for photo-polymerization. Figure 3 (a) and (b) show the schematic diagram of the polymer wall formation by photo-polymerization induced phase separation and the color rendering in the Ch-LC cell with PSCD respectively.

The cell fabrication process is depicted in Figure 4. All unit processes were carried out at room temperature and atmospheric pressure, which would be suitable for roll-to-roll mass production.

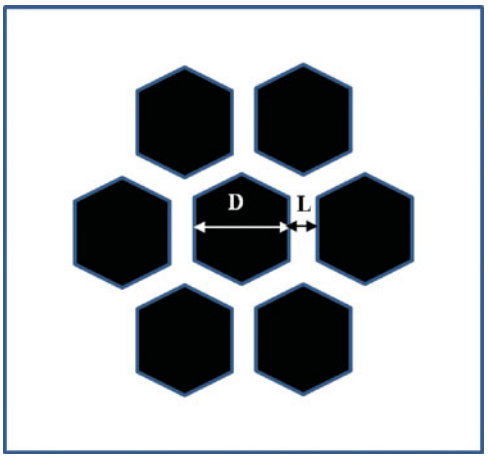

Figure 2. Photo-mask pattern used in polymer wall formation process.

3. Results and Discussion

3.1 Formation of Polymer Walls

Several parameters such as monomer concentration, UV intensity and exposure time, and temperature have to be considered for effective photo-polymerization induced phase separation. The effect of UV exposure energy on the phase separation was investigated. Figure 5 (a) shows the polarizing optical microscopy (POM) images of the cells with UV exposure time of 5, 10, 15, and 20 minutes with intensity of 10 mW/cm^2. The polymer wall width of the cells UV-exposed for 5, 10, 15, and 20 minutes were measured as 13.4, 16.5, 17.4 and 17.5 *u*m respectively. The width increased with the increase of the UV exposure time from 5 to 15 minutes, and was not nearly changed from 15 to 20 minutes. Monomers could be sufficiently expelled from the LC-rich region when UV exposure time was 15 minutes and longer. The remained monomers in LC-rich region affected the reflectance of

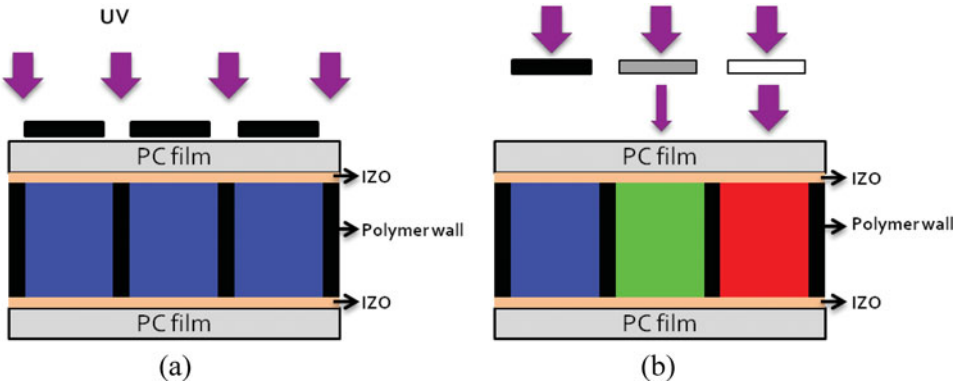

Figure 3. Schematic diagram of (a) polymer wall formation by photo-polymerization induced phase separation and (b) color rendering in the Ch-LC cell with PSCD.

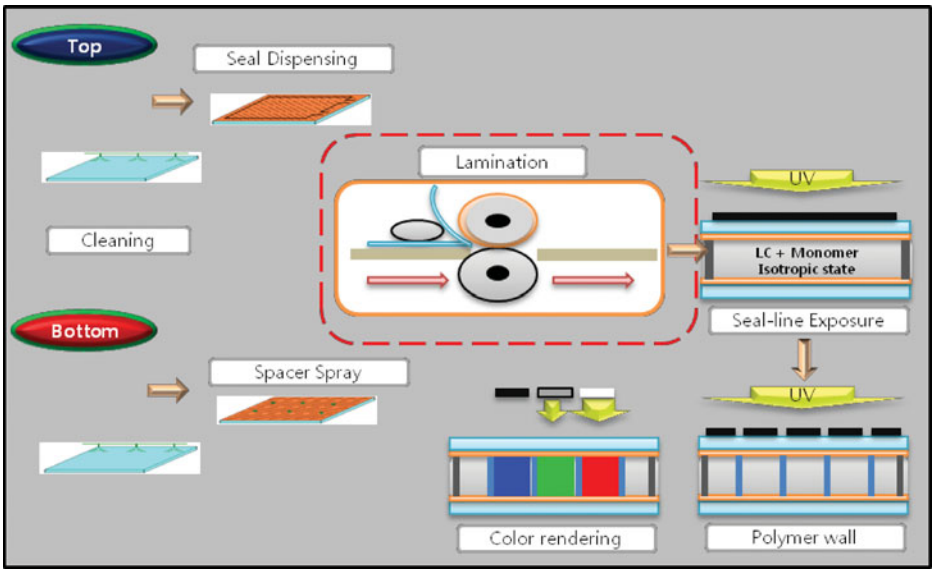

Figure 4. Schematic diagram of fabrication process of flexible color Ch-LCDs.

the Ch-LCDs probably due to the disturbance of planar alignment of Ch-LC. As shown in figure 5 (b) the brightness of the cell UV-exposed for shorter time was lower. From these results, it was revealed that 15 minutes as a UV exposure time was appropriate for the high reflectance and sufficient polymer wall formation.

The photo-polymerization induce phase separation is in general greatly dependent on the monomer -LC concentration ratio. To investigate the monomer concentration dependence of phase separation phenomenon, we varied the monomer concentration as 5 wt%, 10 wt%, 12.5 wt%, 15 wt% and 20 wt%. The monomer and Ch-LC materials were mixed at room temperature, which was cell fabrication process temperature. Figure 6 shows the mixing states of the mixtures. It was found out that the mixture with monomer concentration of 10 wt% and less exhibited the liquid crystal phase and the mixture with monomer

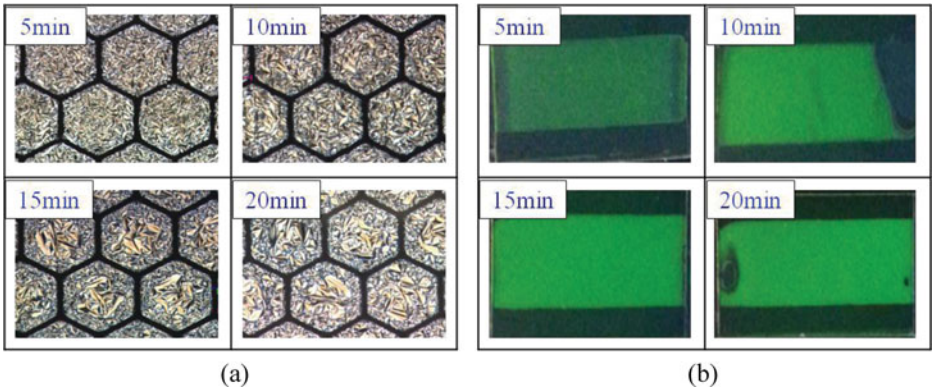

Figure 5. (a) POM images, (b) visual images of Ch-LC cells exposed by UV light with intensity of 10 mW/cm^2 for different times.

Figure 6. Mixing states of LC-monomer mixtures with different monomer concentrations at room temperature.

concentration of 12.5 wt% and more showed the isotropic state, which is in general good for uniform phase separation.

All the cells were irradiated by UV light with the same intensity of 10 mW/cm^2 through the same photo-mask for 15 minutes. Figure 7 (a) and (b) show the POM images and visual images of the Ch-LC cells with different monomer concentrations respectively. When the cells were irradiated by UV light, the polymerization of monomers occurred in the unmasked areas, that is to say in the inter-pixel regions.

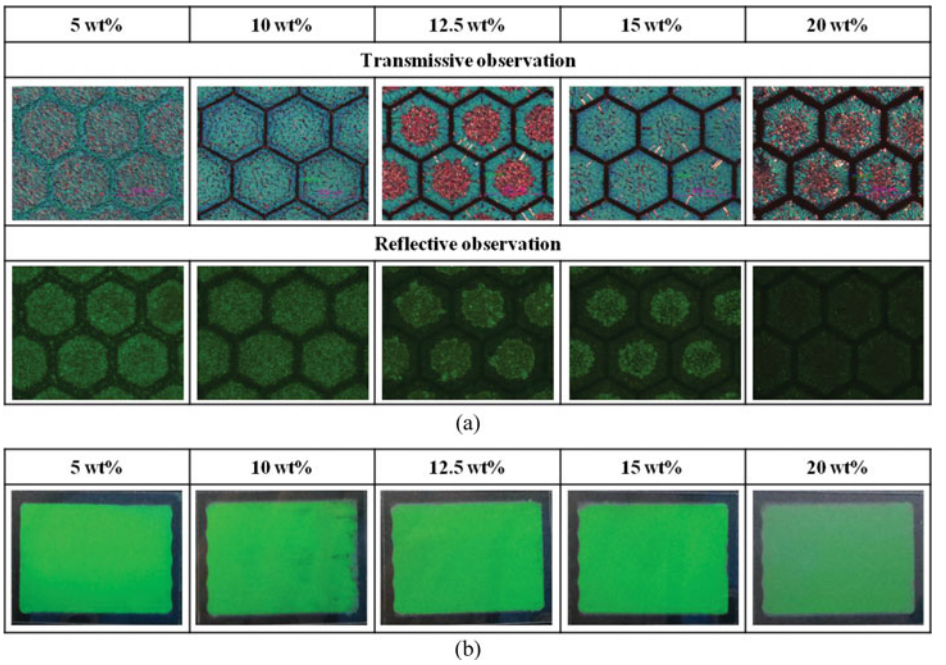

Figure 7. (a) POM images and (b) visual images of the Ch-LC cells with different monomer concentrations.

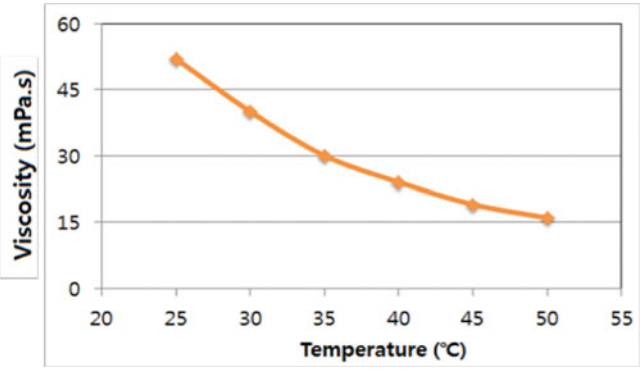

Figure 8. Viscosity to temperature relation of CH100-550.

As shown in Figure 7 (a), polymers did not completely separate from the LC-rich region when the monomer concentration was 10 wt% and less. In this case, polymer walls were not sufficiently formed, which resulted in the liquid crystal flow through the pixels when an external force to the cell was given. When the monomer concentration was 12.5 w% and more, the degree of phase separation was nearly the same. As shown in Figure 7 (b), the brightness of Ch-LC cell decreased with the increase of monomers. From these results, the best monomer concentration was 12.5 wt% from the reflectance and polymer wall formation point of view.

The degree of photo-polymerization induced phase separation is influenced by the viscosity of mixture. If the viscosity is too high, it is in general hard to obtain good phase separation. To investigate the mixture's viscosity dependence on the phase separation, we observed phase separation process with change of temperature as 25°C, 35°C, 45°C, 55°C,

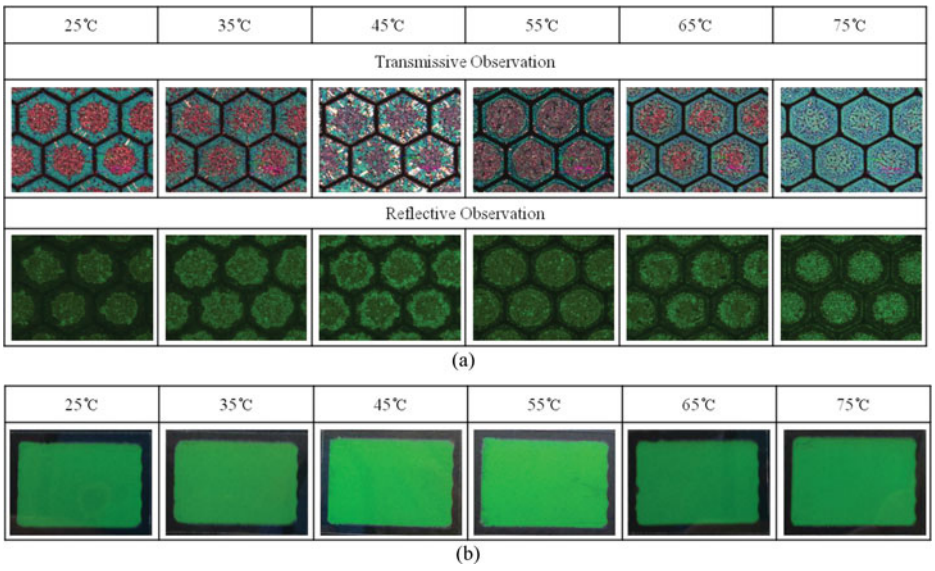

Figure 9. (a) POM images and (b) visual images of the Ch-LC cells irradiated at different temperatures.

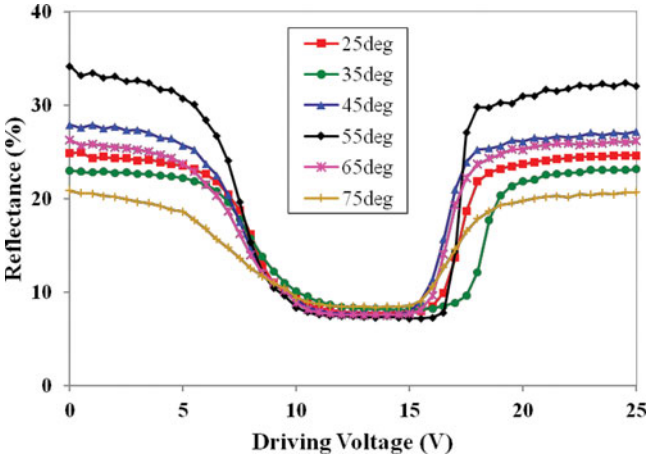

Figure 10. Reflectance vs. driving voltages of Ch-LC cells UV-irradiated at different temperatures.

65°C, and 75°C for fixed monomer concentration of 12.5 wt%. It is sufficient to investigate the temperature dependence of the viscosity of Ch-LC instead of that of mixture since it is dominant material and is much higher than that of monomer used in our experiment. Figure 8 shows the viscosity data of Ch-LC, CH100-550.

Figure 9 shows the POM and visual images of the cells irradiated at different temperatures. As shown in the images, polymer walls were clearer at phase separation temperature of 55°C than other temperatures. The planar texture near the polymer wall was not built well, which might be caused by large amount of polymer in LC-rich region. The planar alignment degrees were relatively higher in the cells phase-separated at 55°C than at other temperatures, so that the reflective brightness of the cell phase-separated at 55°C showed highest among all the cells. The electro-optical characteristics of the cells are shown in Figure 10, which was measured by luminance meter. Driving voltages of the cells were around 20 V independent on phase separation temperature. These results imply that the viscosity of Ch-LC was needed to be controlled for the best phase separation and reflectance.

From the above results, it was found out that the optimum material and process parameters for phase separation and electro-optical properties in our system were as follows: (1) monomer concentration = 12.5 wt% (2) phase separation temperature = 55°C (3) UV exposure energy = 9 J/cm^2.

3.2 Color Rendering of the Ch-LC Cells

To make color Ch-LC devices, we added the PSCD to the mixture of Ch-LC materials and monomers. When it is added into the Ch-LC mixtures, the strong dipole-dipole

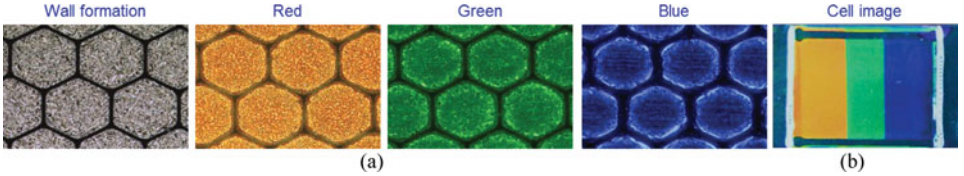

Figure 11. (a) POM images of RGB unit and (b) visual image of color Ch-LC cells.

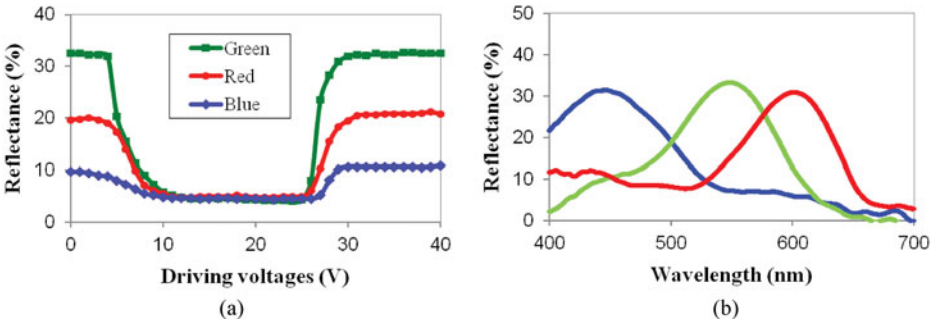

Figure 12. (a) Reflectance vs. driving voltages and (b) reflection spectra of Ch-LC RGB unit cells.

force between the ester (C═O) group and the liquid crystal (LC) molecules occurs, and the Wander Waals force between cinnamoyl group and the LC molecules results in the decrease of the helical twisting power, and thus the chiral pitch of the Ch-LC mixtures increases. The PSCD concentration ratio was chosen as 3.3 wt% to set the initial selective reflection wavelength of the mixture be 450 nm for blue. The helical twisting power of the PSCD decreases as UV irradiation on it increases, so that the reflection wavelength of PSCD doped Ch-LC cell increases as UV exposure energy increases. Using this property green and red cells were made by the irradiation of UV light with appropriate energies: 150 mJ/cm^2 for green and 3000 mJ/cm^2 for red in this experiment. Figure 11 shows the POM images of RGB unit and visual image of color Ch-LC cells. Figure 12 shows reflectance vs. driving voltages and reflection spectra of Ch-LC RGB unit cells. Polymer walls were formed well and color rendering for RGB cells was successfully carried out even though the red color was a little shifted to short wavelength. These results demonstrate that two step UV exposure method is an effective one to achieve flexible color Ch-LC displays.

4. Conclusion

We developed high performance flexible cholesteric LC displays using two-step UV exposure method: first exposure to form polymer walls by polymerization induced phase separation method and second exposure to get colors using photo-sensitive chiral dopant.

Through the extensive investigation of various parameter dependence on the phase separation and electro-optical properties of flexible cholesteric LCDs, it was found out that the optimum material and process parameters for clear phase separation and good electro-optical properties in cholesteric LC (CH-100 series) and di-acrylate monomer mixture system were as follows: (1) monomer concentration = 12.5 wt% (2) phase separation temperature = 55°C (3) UV exposure energy = 9 J/cm^2.

In addition, we achieved good RGB color cholesteric LCDs by doping a photo-sensitive chiral dopant, methyloxy-cinnamoylglucitol into the mixture of cholesteric LC and di-acrylate monomer and by irradiating UV light with appropriate energy, 3000 mJ/cm^2 and 150 mJ/cm^2 for rendering red and green colors from blue color respectively.

The experimental results demonstrated that two step UV exposure method is an effective one to achieve flexible color Ch-LC displays.

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