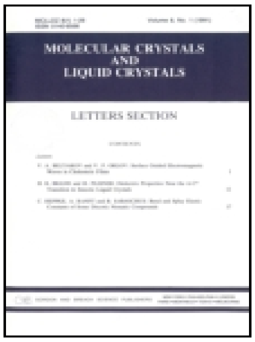

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The Investigation on the Reflective Properties for the Robust Flexible Cholesteric LCDs with Polymer Wall Structure

Y. JIN,[1] Z. HONG,[1,2] AND S.-B. KWON[2,*]

[1]Dept. of Display Engineering, Hoseo University, Chungnam, Korea
[2]NDIS Corporation, Chungnam, Korea

We developed robust flexible Cholesteric LCDs with polymer walls using polymerization-induced phase separation. It was found out that phase separation temperature in addition to monomer concentration and UV irradiation conditions affected not only the phase separation degree but also the reflective properties. We investigated the reflective properties of the Ch-LC cell with well separated polymer walls, particularly focused on the temperature dependence, resulting in the viewing angle dependence, of reflectance and reflection wavelength bandwidth. The experimental data for the viewing angle dependent reflection wavelength bandwidth were well fitted by a theoretical modeling with a parameter of α*, where* $\Delta\lambda(\theta) = \Delta\lambda/\cos(\alpha\theta)$*.*

Keywords Polymer wall; Flexible display; Cholesteric LCDs; Reflective properties; Phase separation

1. Introduction

Cholesteric liquid crystal (Ch-LC) has the selective reflection properties in planar texture due to its helical structure [1]. The reflection wavelength λ_0 of the Ch-LC material can be determined by $\lambda_0 = nP_0\cos\theta$, where n, P_0, θ are the average refractive index, the helical pitch, and viewing angle of the Ch-LC respectively. The reflection wavelength bandwidth $\Delta\lambda$ for normal incident light is ΔnP_0, where Δn is optical birefringence of the Ch-LC. The reflectance and color purity of Ch-LC cells are highly dependent on $\Delta\lambda$ as well. In order to know the viewing angle dependent reflective properties of Ch-LC cells, the viewing angle dependence of $\Delta\lambda$ should be found, the specific investigation of which was not carried out yet. The main purpose of this work is to investigate it in polymer wall type Ch-LC display.

For flexible Ch-LC displays, the mechanical stability should be secured. Polymer wall formation using phase separation between LC and polymer in LC layer was known for an effective way to achieve the mechanical stability. Extensive investigation into the polymer wall formation for nematic [1–2], smectic [3] and cholesteric [4–5] LC cells has been carried out. Our group achieved well configurated and solid polymer wall formation by the optimization of material and process parameters for the flexible Ch-LCDs [6].

*Address correspondence to S. B. Kwon, NDIS Corporation, Chungnam, 336-795, Korea. E-mail: sbkwon@hoseo.edu.

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When applying the polymer walls to the Ch-LC, the reflective properties, particularly the viewing angle dependent reflection may also change. The polymer walls and the remaining polymers inside the LC domains definitely influence the planar alignment of the Ch-LC, which is in connection with the reflective properties.

The LC layer in the polymer wall type Ch-LC cells in general has multi-domain structure as compared to the single domain structure of pure Ch-LC cell, so that the reflective properties depending on viewing angle are quite different from that of pure Ch-LC cell. The multi domain texture is formed depending on the various material and process parameters, one of which is the amount of remaining polymer existing inside LC-rich region. The remaining polymer quantity decreases as the phase separation degree increases, particularly in case of around 20 wt% and less monomer concentration. Key parameters such as monomer concentration, UV irradiation condition and phase separation temperature have to be controlled during polymerization induced phase separation process.

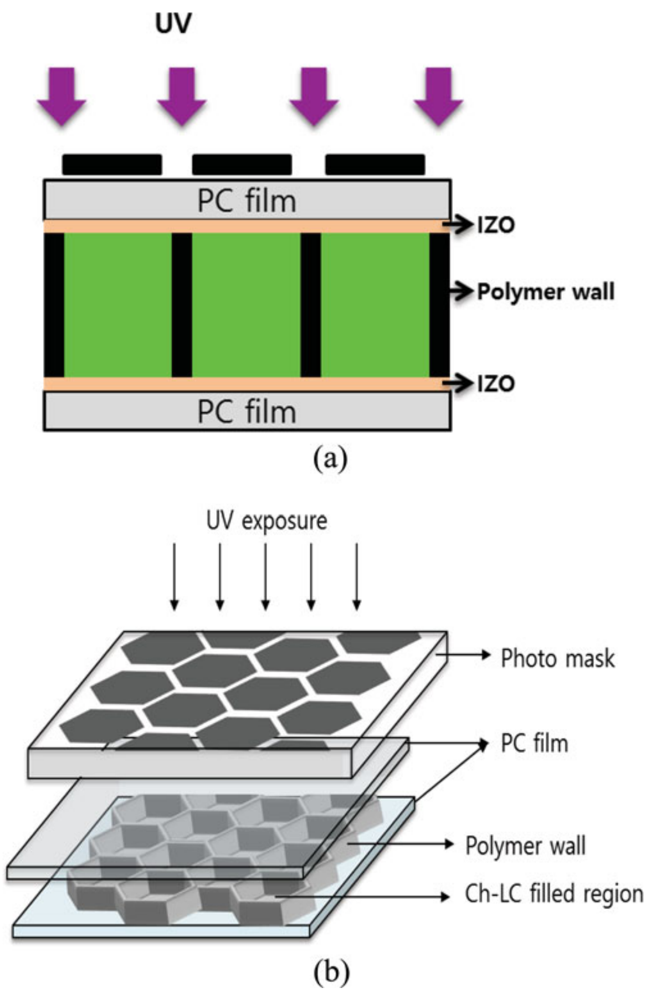

Figure 1. (a) Cross-sectional structure and (b) top view of the flexible Ch-LC cells.

Among these parameters, we mainly focused on the temperature dependence of the phase separation degree and reflective properties in this work.

2. Experimental

The main Ch-LC used in experiment was CH100-550 (Slichem Co.). The refractive indices of the materials were 1.66 for ne and 1.502 for no, and the dielectric anisotropy was 27.8. For the preparation of monomer mixture, acrylate monomer was blended with crosslinking agent and photo-initiator with a ratio of 90:9:1. After that, we mixed the Ch-LC and monomer mixture at room temperature with monomer concentration of 5 wt%, 10 wt%, 12.5 wt%, 15 wt% and 20 wt%.

LC cells were fabricated by using Indium Zinc Oxide deposited polycarbonate substrates. No alignment layer was coated here, and the cell gap was set 5μm. We simply coated the mixture of Ch-LC and monomers onto the bottom plastic substrate, and laminated the top substrate onto it. A halogen lamp was used as the UV source covering 365nm band effective for photo-polymerization. Figure 1(a) shows the cross-sectional structure of the flexible Ch-LC cells with polymer walls isolating the LC mixture pixilated. To form uniform polymer walls as a defined pattern, we designed the photo-mask with the optimized pixel size and wall width. With the photo-mask, the LC mixtures in the exposed region of the UV light will go through the polymerization induced phase separation process, and thus the walls will be formed as shown in Fig. 1. Due to the well-formed polymer walls, the mechanical stability against the external pressure was sufficiently high. Figure 1(b) was the top view of the flexible Ch-LC cells with polymer walls when applying the hexagonal shaped photo-mask during the phase separation process.

Figure 2 is the schematic drawing of the experimental set-up for the measurement of the reflective properties. The sample being loaded between the light source and the spectrometer can be rotated from 0 degree to 30 degrees, so that the viewing angle dependent reflective properties can be measured. We firstly measured the transmittance of the cell by using this experimental set-up, and then converted it to the reflectance curve.

3. Results and Discussion

In polymerization induced phase separation process, there are several parameters to be considered: monomer concentration, UV irradiation intensity, UV irradiation time and

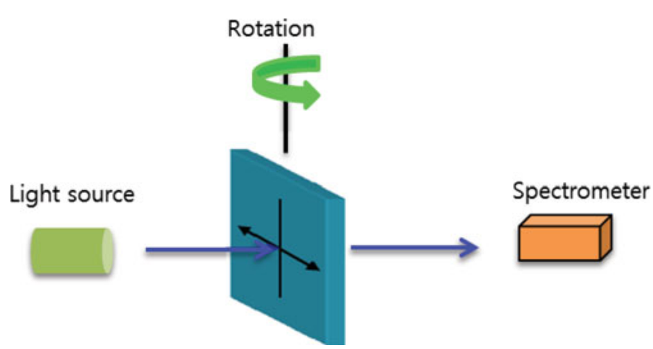

Figure 2. Experimental set-up for the measurement of reflective properties converted from transmittance measurement.

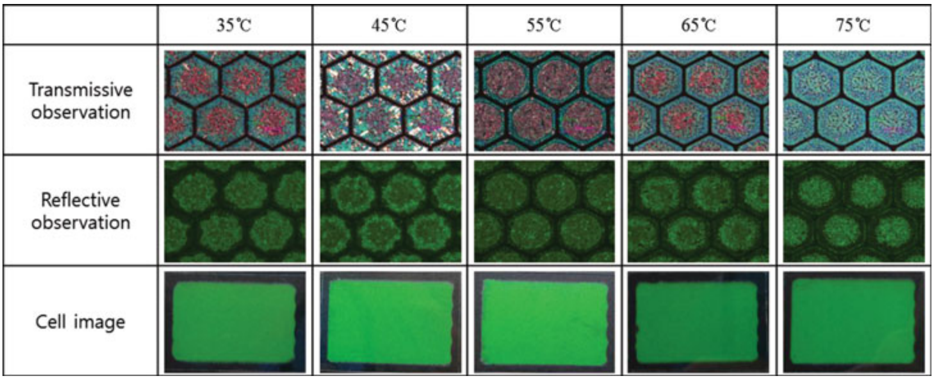

Figure 3. POM and visual images of the cells phase separated at different temperatures.

phase separation temperature. The overall description on the phase separation phenomena depending on the above parameters will be reported in detail in other paper [6]. It was noted in this work that the reflective properties of the flexible Ch-LC cells as well as the phase separation degree were influenced by these parameters.

To investigate 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 also cell fabrication process temperature. After the filling of the mixtures, all the cells were irradiated by UV light with the same intensity of 10mW/cm^2 through the same photo-mask for 15 minutes. 12.5 wt% showed the best monomer concentration from the reflectance and polymer wall formation point of view [7].

For the fixed monomer concentration, we observed the phase separation process with change of temperature as 25°C, 35°C, 45°C, 55°C, 65°C, and 75°C. Figure 3 shows the POM and visual images of the cells phase separated at different temperatures. As shown in the images, the planar alignment degree was relatively higher in the cells phase separated at 55°C than at other temperatures, so that the reflectance of the cell phase separated at 55°C showed highest among all the cells. The planar texture near the polymer wall was not formed well, which might be caused by the remaining polymer in LC area. Figure 4 was the reflectance vs. applied voltage curve. It was noted that the driving voltage was under 20 volts independent of the phase separation temperatures, and the reflectance of the cell phase separated at 55°C showed the highest reflectance among all the cells, which was in accordance with the result shown in Fig. 3. There are two factors affecting the phase separation dynamics: the viscosity of the LC mixture and the nematic ordering of the LC materials. In general, it is hard to obtain good phase separation when the mixture viscosity is too high. So with the increase of temperature until 55°C, which was lower than isotropic temperature of Ch-LC (60°C), the LC molecules separated well from the monomers, which resulted in better planar alignment for Ch-LCs. On the other hand, when both the LCs and monomers were in isotropic state (65°C and 75°C), the viscosity of the materials was low but the nematic ordering of the LC materials disappeared, which resulted in the insufficient phase separation. Thus, the reflectance decreased from 55°C to 75°C due to the lower planar alignment of LC molecules.

That is to say, the mixtures which has nematic ordering and relatively low viscosity are suitable for the phase separation.

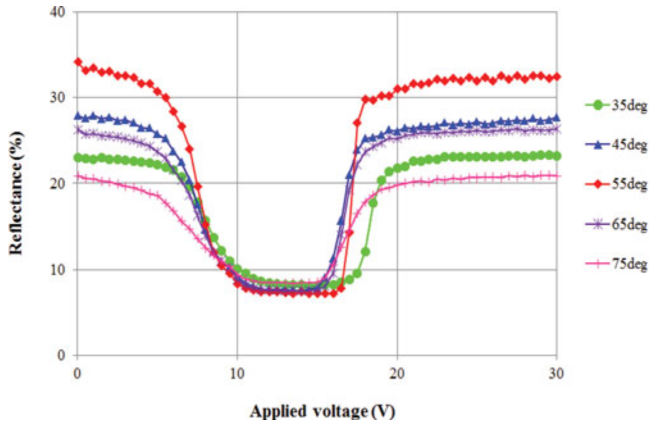

Figure 4. Reflectance vs. applied voltage curve of the cells phase separated at different temperatures.

As similar to the temperature dependence of reflectance, the selective reflection wavelength varied under different phase separation temperatures. The reflection wavelength of the Ch-LC used in our system was designed to reflect green color of 550 nm at 0 degree. Figure 5 illustrated the reflection wavelength depending on viewing angle from 0 degree to 30 degrees for pure and polymer wall type Ch-LC cells. At viewing angle of 0 degree, the peak wavelength of polymer wall type Ch-LC cells shifted to longer wavelength from that of pure cell, which was caused by the increase of the helical pitch of Ch-LC due to remaining polymer in LC-rich region. When light is obliquely incident at the angle θ to the Ch-LC cell, the reflection wavelength is given by $\lambda = nP_0\cos\theta$ [1]. When θ increases, the reflection wavelength is shifted to a shorter wavelength. It should be noted that the reflection wavelength shift of the cells at 35°C, 45°C, and 55°C showed nearly the same tendency: the value and decreasing rate of the reflection wavelength. However, for the cases of 65°C and 75°C, which are higher than clearing point of the Ch-LC, the tendencies were quite different from the above cases. For the cases of 35°C, 45°C, and 55°C, the cells phase

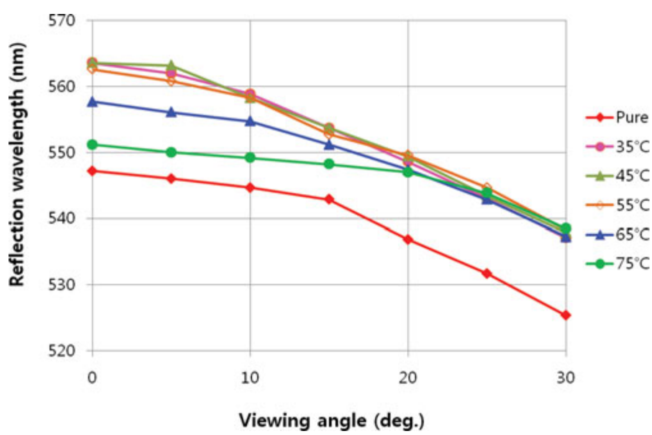

Figure 5. Reflection wavelength of cells for pure Ch-LC and polymer wall type Ch-LC irradiated at different temperatures depending on viewing angle.

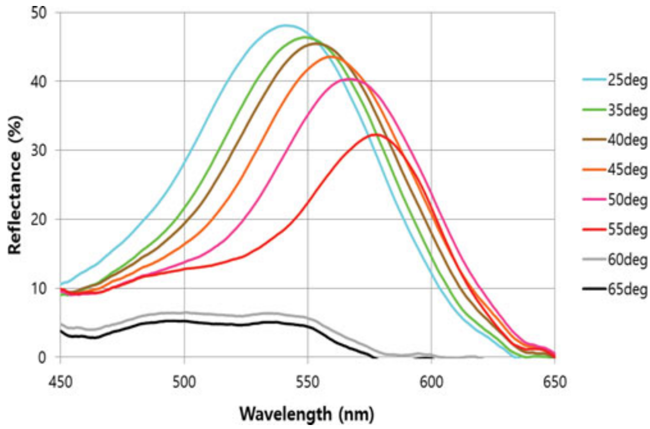

Figure 6. Reflection spectra of the pure Ch-LC cell with the increase of temperature.

separated relatively better than those for other two cases, where the remained polymer in LC rich region was very little, and thus the incident angle dependence of reflection wavelength for the cells showed nearly the same tendency. However, for the cases of 65°C and 75°C, the insufficient phase separation caused the quite different tendency.

Figure 6 shows the reflection spectra of the pure Ch-LC cell with the variation of temperatures from 25°C to 75°C, which is used for comparison with that of polymer wall type Ch-LC cells. With the increase of the temperature, the reflection wavelength shifted to longer wavelength, which was caused by the increase of helical pitch of Ch-LC. For the polymer wall type Ch-LC, the increase of the helical pitch of the Ch-LC molecules during the polymerization process at temperature 35°C, 45°C, and 55°C resulted in the increase of final helical pitch of the Ch-LC cells with polymer walls as compared to the pure Ch-LC cell. For the cells phase-separated at 65°C and 75°C, no typical selective reflection phenomena of Ch-LC cells happened as well because of non-liquid crystal phase.

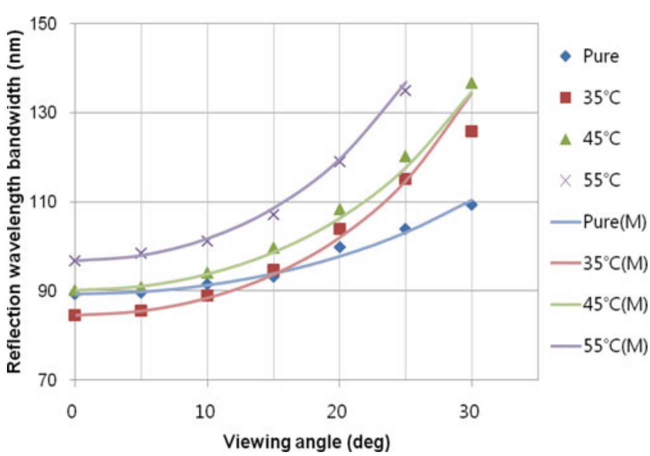

Figure 7. Reflection wavelength bandwidth of the Ch-LC cells with and without polymer walls: dots are the experiment data, and solid lines are simulation data.

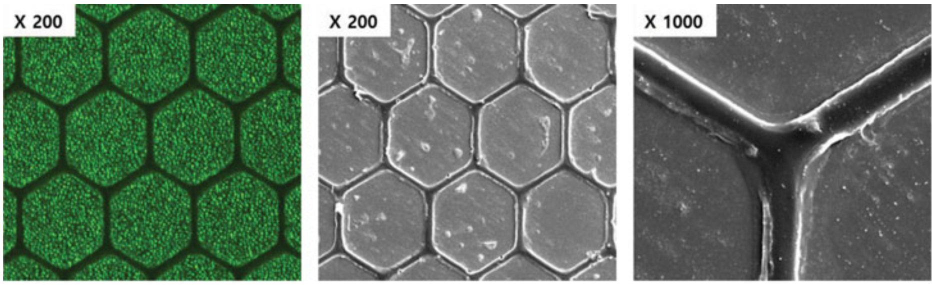

Figure 8. (a) POM image of the Ch-LC at planar state after polymer wall formation under 55°C; (b) and (c) SEM observation.

The reflection wavelength bandwidth of the Ch-LC cells with and without polymer walls was shown in Fig. 7. In the case of pure Ch-LC cell, the reflection wavelength bandwidth changed slowly, this implies that the deviation of helical axis normal to the cell surface is relatively small. For the cases of 35°C, 45°C, and 55°C, the reflection wavelength bandwidth changed rapidly, this implies that the deviation of helical axis normal to the cell surface is relatively large. The cells phase separated at isotropic state showed broader wavelength bandwidth at viewing angle of 0 degree, and the wavelength bandwidth increased to nearly 180 nm at viewing angle of 30 degrees, this implies that the deviation of helical axis normal to the cell surface is much larger inside the LC-rich region.

The experimental data for the reflection wavelength bandwidth were fitted by a theoretical modeling given by the following equation with a parameter α:

$$\Delta\lambda(\theta) = \Delta\lambda/\cos(\alpha\theta), \text{ where} \Delta\lambda = \Delta n P_0$$

The fitting parameter α was found by optimal fitting: $\alpha = 1.2$, 1.7, 1.6 and 1.8 for pure Ch-LC cell, polymer wall type Ch-LC cells phase separated at temperature of 35°C, 45°C, and 55°C respectively. The parameter α was presumed to be the parameter related to the variation of LC helical axis distribution induced by remained polymer. The precise analysis for the exact physical meaning of the parameter α remains as future work.

Figure 8 (a) was the POM image of the Ch-LC at planar state after polymer wall formation under 55°C. The polymer walls were clearly formed and very small micro-domains were formed by the influence of little remaining polymer inside the LC-rich region. Figure 8 (b) and (c) were the scanning electron microscopy (SEM) images of the Ch-LC cell with polymer walls. For the SEM observation, the cell was washed with isopropyl alcohol and coated with white gold particles. Polymer walls were formed normal to the cell surface, and were clearly expelled from LC molecules.

4. Conclusion

We developed robust flexible Cholesteric LCDs with polymer walls using polymerization-induced phase separation method. It was found out that phase separation temperature in addition to monomer concentration and UV irradiation conditions affected not only the phase separation degree but also the reflective properties of the cells: highest reflectance and phase separation degree obtained at temperature of 55°C for monomer concentration of 12.5 wt% and for UV irradiation condition of 10 mW/cm^2 and 15 minutes. The viewing angle dependent reflection wavelength and bandwidth were investigated. The reflection wavelength shift of the cells phase separated at 35°C, 45°C, and 55°C showed nearly the same tendency: the value and decreasing rate of the reflection wavelength. On the other hand, the reflection wavelength bandwidth of polymer wall type Ch-LC cells phase separated at 35°C, 45°C, and 55°C changed more rapidly than that of pure Ch-LC cell, which implies that the deviation of helical axis normal to the cell surface is relatively large for polymer wall type Ch-LC cells than for pure Ch-LC cell. The experimental data for the viewing angle dependent reflection wavelength bandwidth were well fitted by a theoretical modeling with a parameter of α, $\Delta\lambda(\theta) = \Delta\lambda/\cos(\alpha\theta) : \alpha = 1.2$, 1.7, 1.6 and 1.8 for pure Ch-LC cell, polymer wall type Ch-LC cells phase separated at temperature of 35°C, 45°C, and 55°C respectively.

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