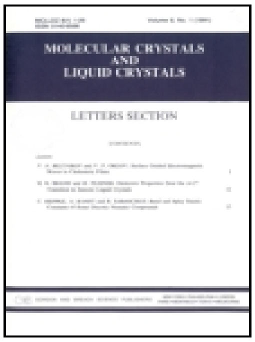

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Electro-Optical Properties of Robust Flexible VA LCDs Using Polymerization Induced Phase Separation

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We developed flexible VA LCDs with high electro-optical performance and thermal reliability for flexible display applications. It was achieved by applying the precise control of phase separation, forming well defined cylindrical liquid crystal domains surrounded by polymer matrix. The LC domains have uniform size and the LC molecules inside the domains were well aligned through the contact to vertical alignment layers coated on plastic substrates, so that low driving voltage, high transmittance and high contrast ratio were achieved. We fabricated 5-inch flexible VA LCD panel, showing good electro-optical properties and high mechanical stability.

Keywords Flexible Display; Polymerization Induced Phase Separation; VA LCD; Mechanical Stability; Low Driving Voltage

Introduction

Various liquid crystal modes for flexible displays have been investigated: ferroelectric [1–2], nematic [3–4], polymer dispersed liquid crystal (PDLC) [5–10], cholesteric [11–14]. The mechanical stability issue has not been clearly solved in the LC modes except for PDLC mode. Normal PDLC in general requires high driving voltage and cannot provide high contrast ratio property because LC molecule alignment cannot be controlled. Our group proposed a low voltage driven flexible vertical alignment LCD with high mechanical stability [15], where the cylindrical liquid crystal domains surrounded by polymer matrix were formed by polymerization induced phase separation (PIPS). The LC domains were not well controlled and had broad size distribution, so that the loss of the transmittance and contrast ratio of the LC cells occurred.

In this work, we investigated the phase separation phenomena for LC domain formation by varying UV exposure area with different size pattern photo mask. It was found that there was an optimum UV exposure pattern to provide uniform and clear LC domains. High transmittance and contrast ratio of the LC cells fabricated by using this optimum condition were achieved. The thermal and bending reliability of the LC cells were investigated.

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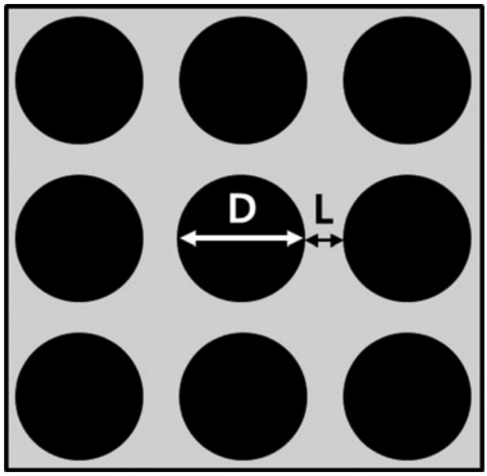


Figure 1. Photo-mask pattern used in polymerization process.

Experimental

The negative LC used in experiment was RTA-930 (HCCH), and the monomer mixture consisted of acrylate monomer, cross-linking agent and photo-initiator. The LC was blended with the monomer mixture with the ratio of 7:3 at room temperature. A polycarbonate plastic substrate was used for LC cell fabrication. The vertical alignment material (SE5300, Nissan) was coated onto the substrates, and then baked at 180°C for 1 hour. The mixture of the LC and monomer was injected into the cell and then irradiated by the UV light with the intensity of 10 mW/cm^2 for 10 minutes. The photo-mask pattern used in the photo-polymerization process is shown in Figure 1. The UV light was generated by a high pressure mercury lamp (SAN-EI) with peak intensity at 365nm. Schematic diagram of the flexible VA LCD made in this experiment is shown in Figure 2.

In order to find the shape of LC domains formed by the photo-polymerization process, scanning electron microscopy (SEM) observation was used.

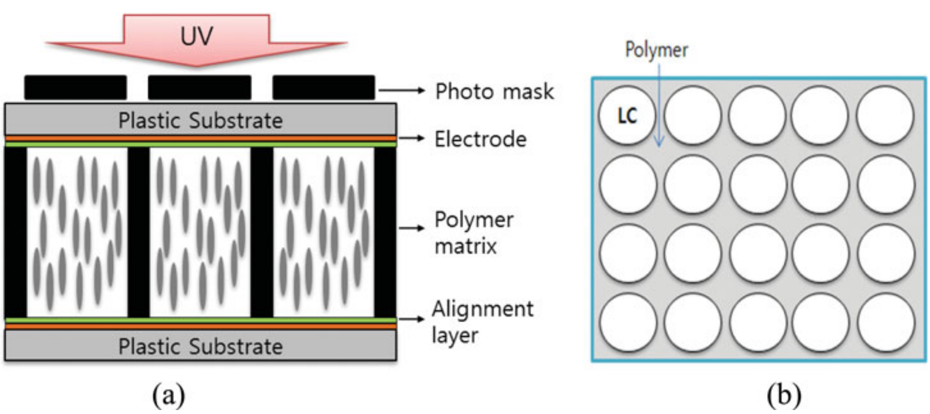


Figure 2. Schematic diagram of flexible VA LCD (a) side view and (b) top view.

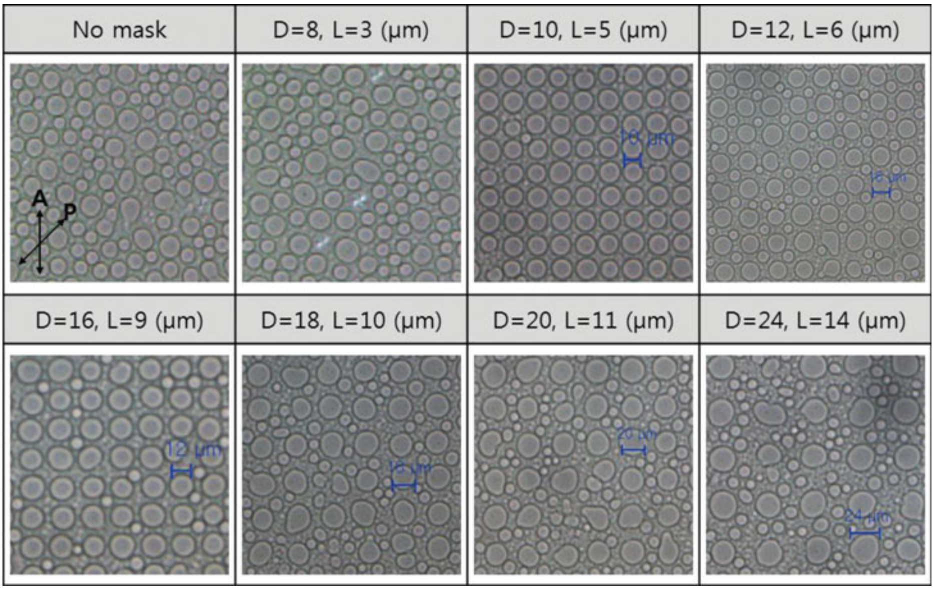


Figure 3. POM images of the cells after the phase separation using different photo-masks.

Results and Discussion

In order to find the condition for uniform polymer matrix, we applied various photo-masks with different design of D and L, where D was the diameter of the circle blocking UV light; L was the distance between the two adjacent circles as shown in Figure 1. Figure 3 shows the polarizing optical microscopic (POM) images of the cells for the phase separation using different photo-masks. To observe the LC domain formation clearly, we set the angle between polarizer and analyzer be 45 deg. In case of that D was larger than 10 μm and L was larger than 5 μm, the LC domains with smaller size than that of the LC domains formed UV expose region were formed in the UV unexposed region, which may result in the decrease of transmittance and increase of light leakage. On the other hand, in case of that D and L were smaller than 10 μm and 5 μm, ununiform LC domains were formed likely in the case of no mask. In the case of the monomer concentration was 30 wt%, the uniform LC domains were obtained with the photo-mask of $D = 10$ μm and $L = 5$ μm.

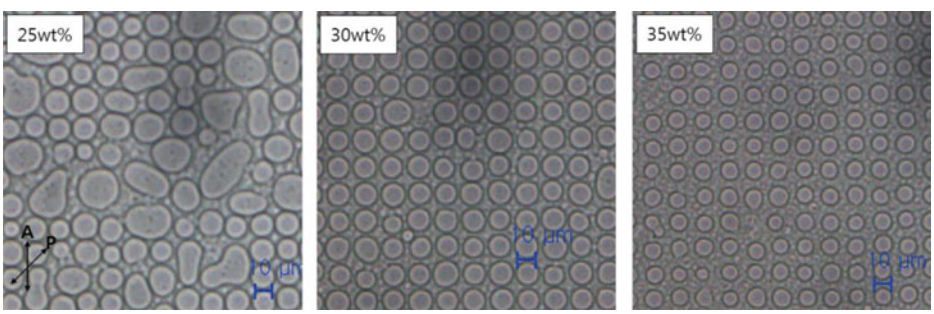


Figure 4. POM images of the cells with different monomer concentrations.

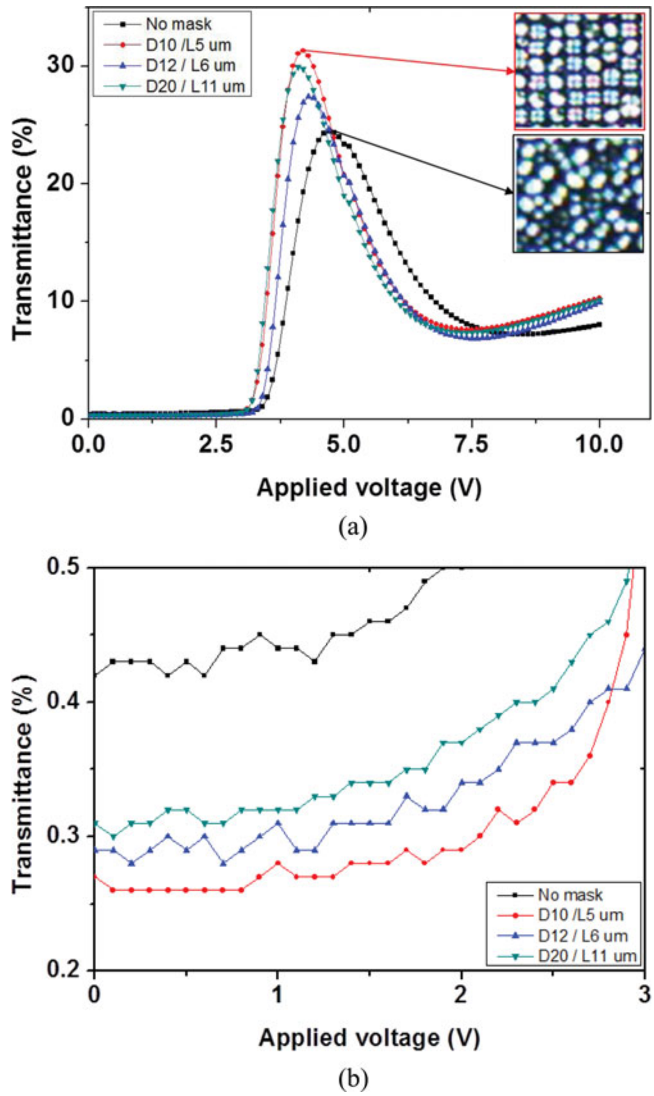


Figure 5. (a) Transmittance vs. applied voltage of the flexible VA cells with and without photo-masks; (b) dark level of transmittance.

Figure 4 shows the phase separation phenomenon with various monomer concentrations using the photo-mask of $D = 10\ \mu$m and $L = 5\ \mu$m. For the concentration of 25 wt%, the LC domains were randomly formed. For the concentration of 35 wt%, the uniformity of LC domains was fairly good, but the area of LC domain size decreased and thus the transmittance decreased.

Figure 5 shows the transmittance vs. applied voltage characteristics of the flexible VA LC cells with and without photo-masks. Maximum peak transmittance, 31.4% of the cells was obtained for the photo-mask of $D = 10\ \mu$m and $L = 5\ \mu$m, while that of the no-mask cells was 24.5%. Figure 5 (b) shows the dark levels of the transmittance. Minimum dark level transmittance, 0.27% of the cells was obtained for the photo-mask of $D = 10\ \mu$m

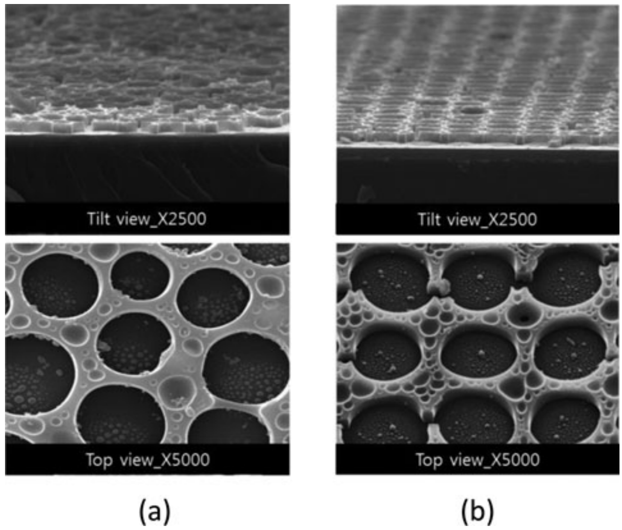


Figure 6. SEM images of the flexile VA LC cells made using (a) no photo-mask and (b) photo-mask.

and $L = 5$ μm, while that of the no-mask cells was 0.42%. This result implies that the precise control of the LC domains using appropriate photo-mask is crucial for achieving high transmittance and high contrast ratio of PIPS based flexible VA LC cells.

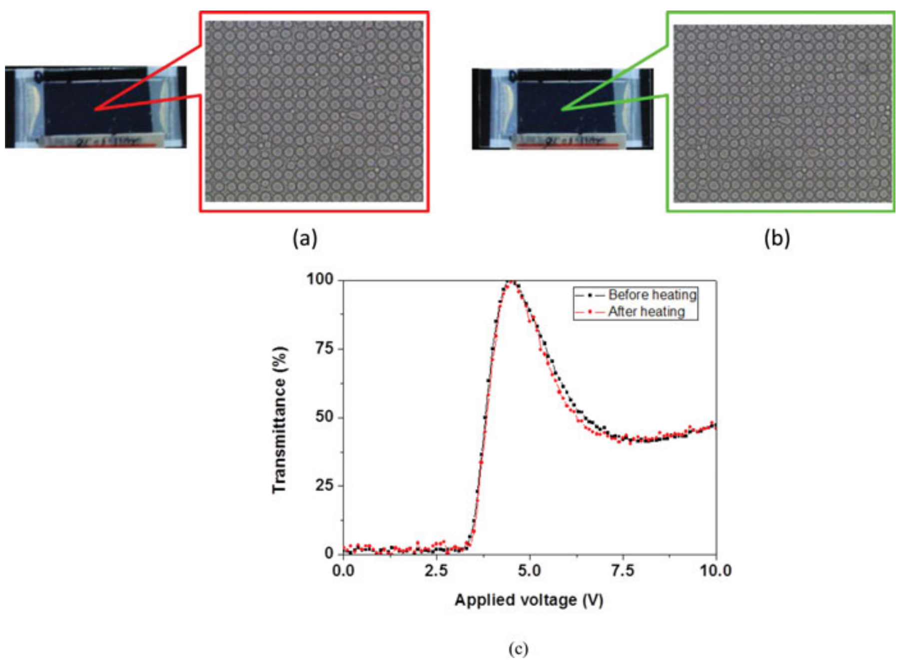
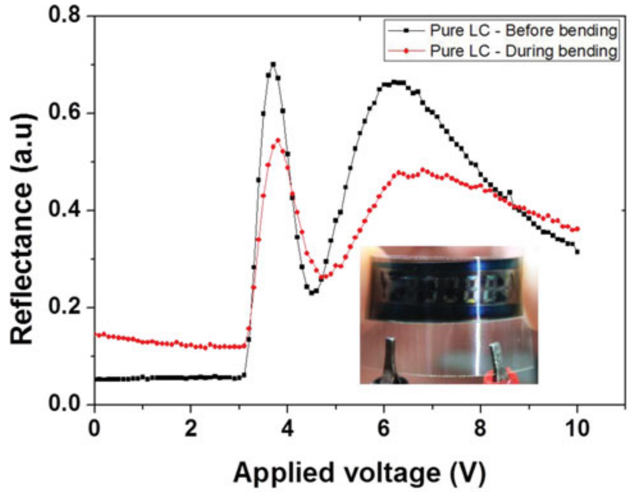
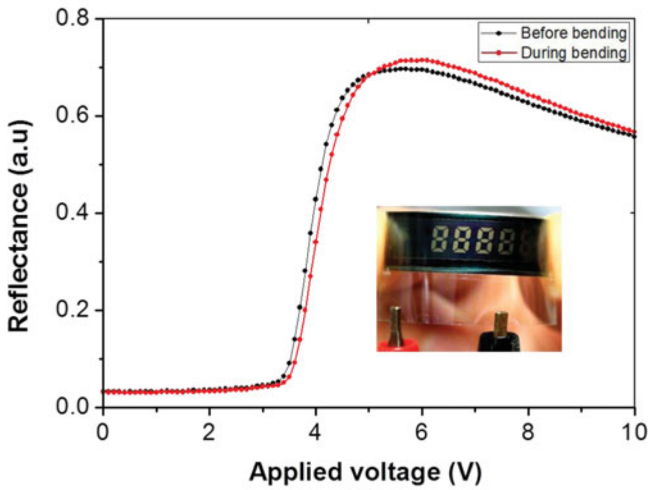


Figure 7. Thermal reliability test of the flexible VA LC cells: the cell images (a) before heating and (b) after heating; (c) transmittance vs. applied voltage curve before and after heating.



(a)



(b)

Figure 8. Reflectance vs. applied voltage curve before and after bending test for (a) Pure VA LC cell and (b) PIPS VA LC cell.

Figure 6 was the SEM images of the flexile VA LC cells made without and with photo-mask. In the case of no photo mask, the polymer matrix was randomly formed, so the LC domain size distribution was broad, while in case using photo mask the polymer matrix was uniformly formed and the LC domain size was around 10 μm similarly to mask size.

The thermal reliability of the flexible VA LC cells was investigated. Figure 7 (a) and (b) shows the image of the cells before and after heating, and (c) shows the transmittance vs. applied voltage curve before and after heating. The heating condition was heating the cells in oven at temperature of 70 degree for 24 hours. There was no damage of the LC domains and almost no change of electro-optical properties after heating.

Figure 9. The cell image of 5-inch flexible VA LCD panel.

We fabricated 1.5-inch reflective flexible VA LC cells with and without polymer matrix to compare the mechanical stability. As shown in Figure 8(a) the reflectance of pure VA LC cell decreased a lot during the bending of cell, and the cell was damaged. On the other hand, there was almost no change of the electro-optical properties of the cells with the polymer matrix during the bending test, and the cell was not damaged as shown in Figure 8(b).

A 5-inch flexible VA LCD was fabricated (Figure 9). It had low driving voltage of 5V, high contrast of 500: 1, good flexibility and high mechanical stability.

Conclusion

In order to achieve PIPS based high performance flexible VA LCDs, we investigated the phase separation phenomena for LC domain formation by varying UV exposure area with different size pattern photo mask. High transmittance and high contrast ratio were achieved for the LCD with uniform and clear LC domains, which was made in the condition of 30 wt% monomer concentration and the photo-mask with $D = 10\ \mu$m and $L = 5\ \mu$m and UV irradiation of 10 mw/cm^2 and 10 minutes. The flexible LCDs were thermally stable in the heating environment at 70°C for 24 hours and mechanically stable. We fabricated 5-inch flexible VA LCD panel, which shows low driving voltage (5V) and high contrast (500:1). This flexible VA LC mode would be suitable for the application to flexible displays.

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