56.2: *Invited Paper:* Pixel-Isolated Liquid Crystal Mode for Plastic Liquid Crystal Displays

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Abstract

We proposed a pixel-isolated liquid crystal (PILC) mode for enhancing mechanical stability of flexible display applications. Since the LC molecules in this mode are isolated in pixels by patterned or phase-separated microstructures, the LC alignment is stable against external pressure. Moreover, the cell gap of our structure is uniformly preserved against bending deformation of the plastic substrates since two substrates are tightly attached each other by the solidified polymer layer produced by photo-induced anisotropic phase separation. For flexible display applications, we have tested the mechanical stability of electro-optic properties in PILC structures with plastic substrates.

1. Introduction

In recent years, roll-up displays have drawn considerable attention for next-generation information displays because of their excellent portability such as light weight, thin packaging, and flexibility. Among several available technologies, it is expected that a liquid crystal display (LCD) using plastic film substrates is the most promising device because of its superior visibility with low power consumption over other displays such as organic light-emitting device or electrophoretic displays. However, there are still critical problems regarding the fabrication of commercially available plastic LCDs with current technologies based on the glass substrates. One of those problems is the instability of LC structures due to hydrodynamic properties of LCs at bending and another is the separation of two plastic substrates due to the flexibility of film substrates. Such problems do not exist in conventional glass-substrate-based LCDs since glass substrates can sustain a stable LC alignment condition against external bending or pressure.

To solve these problems, several types of polymer wall and/or network as supporting structures have been proposed and demonstrated [1]-[7]. These structures were fabricated using an anisotropic phase separation method from polymer and LC composite systems by applying a patterned electric field or spatially modulated UV intensity. However, these methods require high electric field to initiate the anisotropic phase separation or remain residual polymers in unexposed regions that reduce optical properties and increase the operating voltage of the devices.[5,6,9] Moreover, these methods are not appropriate to a cost-effective roll-to-roll process, which is essential to fabricate large area plastic LCDs. Thus, an alternate fabrication method should be developed for the plastic LCDs to be commercialized.

In this presentation, we propose various fabrication methods for enhancing the mechanical stability in the LC alignment and the adhesion of two substrates for the plastic LCDs with a pixel-isolated LC (PILC) mode. The proposed PILC structures for stable flexible LCDs are examined by measuring electrooptic (EO) properties under various mechanical stability tests.

2. Fabrication of PILC mode using patterned microstructures

We fabricated a PILC mode using patterned microstructures as shown in Fig. 1. In the proposed structure, the pixel-isolating polymer walls were made by a stamping method using durable elastomeric poly(dimethylsiloxane) (PDMS), which can be applicable to a roll-to-roll process for the mass production of large flexible LCDs.[11] The adhesion between the wall structure and the substrate was enhanced by a solidified thin polymer layer through an anisotropic phase separation process.

Fig. 2 shows the schematic illustration of procedures for fabricating our plastic LC device with a microtransfer molding method. The first step shown in Fig. 2(a) is to produce a master structure using the negative photoresist SU-8 (MicroChem) by a photolithographic method. On the master substrate, liquid PDMS is deposited and the excess liquid PDMS is removed by a PDMS block, as shown in Fig. 2 (b). The PDMS wall structure produced by the patterned master structure can be effectively transferred to the covered bare indium-tin-oxide (ITO) substrate by heating under pressure, as shown in Fig. 2(c). In our experiment, the heating condition for transferring and solidifying the PDMS structure was 100°C for 10 min. By peeling off the master substrate, the bottom substrate with the PDMS wall structures is prepared. Since PDMS provides a very low interfacial free energy and a good chemical stability, the master substrate can be easily detached without the degradation of the micro-structure on both substrates. Onto the prepared bottom substrate shown in Fig. 2(d), the homogeneous alignment layer RN1286 (Nissan Chemical Industries) is spin-coated and rubbed to promote a uniform LC alignment. After the mechanical rubbing process, the PDMS walls maintain the initial micropatterned structures attached to the ITO surface. After dropping a LC/prepolymer composite onto the substrate with the microstructure, a LC cell is prepared by covering a bare ITO substrate on the bottom substrate. However, within only these fabrication steps, the cell gap cannot be stably sustained at bending since two substrates are not tightly adhered to each other.

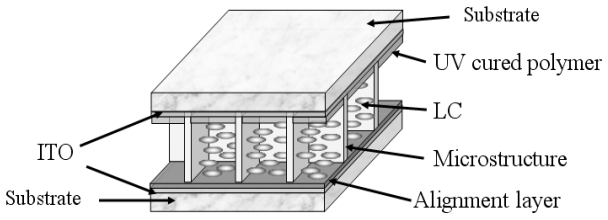

Figure 1 The schematic diagram of PILC structure made by patterned microstructures.

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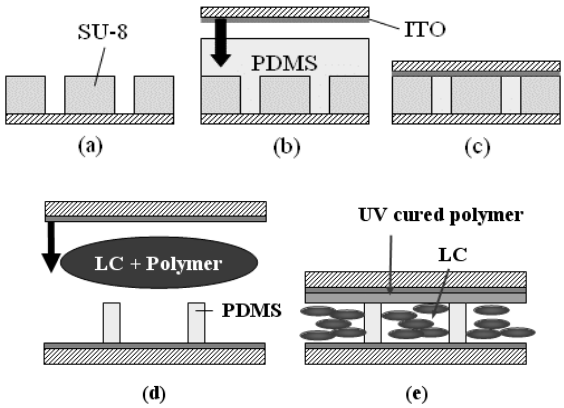


Figure 2 Schematic illustration of fabrication procedures with stamping method: (a) formation of micropatterned master structure, (b) fabrication of PDMS structure using the master substrate, (c) transferring the PDMS wall structure to a plastic substrate by baking under pressure, (d) forming LC alignment layer on microstructured plastic substrate, then dropping or injecting polymer/LC composites. The PILC structure is prepared by sandwiching the other plastic substrate. (e) The cross section of PILC structure after phase separation by UV exposure.

In our structure, such problems are eliminated by producing a uniformly solidified polymer layer on the bare ITO substrate using a complete anisotropic phase separation of the prepolymer/nematic LC (NLC) mixture by UV exposure. The materials used are E48 (Merck) for the NLC and the UV curable epoxy NOA-72 (Norland) for the prepolymer. A solution of the LC and prepolymer with a weight ratio of 95:5 is deposited on the substrate with the microstructure and covered by a bare ITO substrate, as shown in Fig. 2(d). The UV light is exposed to the bare ITO substrate. In our experiment, the source of the UV light is a Xenon lamp of λ=350 nm, operated at an electrical power of 200 W, and the exposure time for making the thin polymer layer fully cured is 20 min. The solidified polymer layer makes the patterned wall structures strongly attach to the opposite substrate and enhances the mechanical strength of the pixel-isolated LC device, as shown in Fig. 1.

Fig. 3(a) shows the SEM images of the master structure of SU-8 with a size of 100x300 μm^2 for the pixel area. The pattern-transferred PDMS structures are shown in Fig. 3(b). Using our microtransfer method, we could successfully and repeatedly fabricate the micropatterned wall structures. Figs. 3(c) and (d) show the microscopic textures of our cell under the polarizing microscope in dark and white state without applied voltage. The slight light leakage in Fig. 3 (c) indicates that the PDMS wall surface has weak LC anchoring. However, the overall transmittance behavior in the pixel area is not affected.

In applications of plastic LC devices, adhesion between two flexible substrates is of great importance. We observed the microscopic structure of PILC cell by scanning electron microscopy (SEM). Fig. 4 (a) shows the cross-sectional view of the PILC sample after opening the cell and removing the LCs. From Fig. 4(a), a uniform thin polymer layer can be observed. In SEM image of the top substrate surface (Fig. 4(b)), the areas where the polymer layer was attached to the microwall structures were obviously observed. The polymer layer acts as bonding

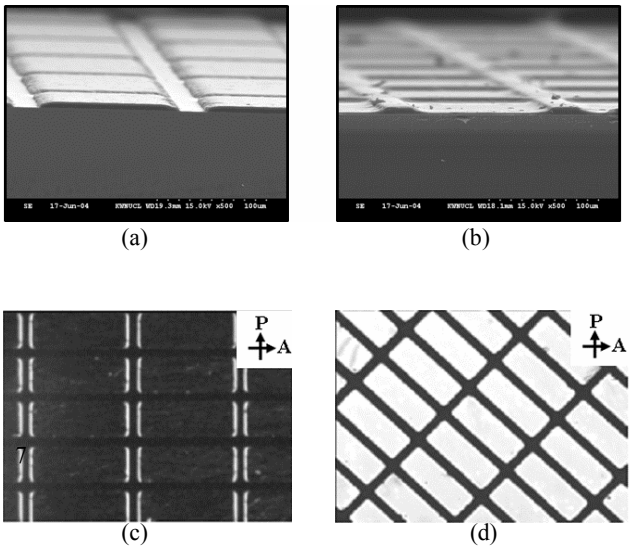


Figure 3 (a) and (b) are SEM images of the micropatterned SU-8 master substrate and the stamped PDMS structure, respectively. (c) and (d) are polarizing microscopic textures of the PILC cell obtained when the rubbing direction of the sample is parallel and 45°-rotated with respect to the polarizer in the absence of an applied voltage, respectively.

agent between the microwall structure and the top substrate. As a result, we can provide suitable adhesion between two plastic substrates. And we can obtain mechanical stability without cell gap variation under external bending pressure.

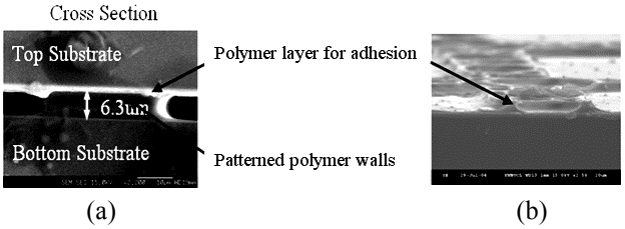


Figure 4 SEM images of (a) the cross-section and (b) the top substrate surface of PILC mode.

3. Fabrication of PILC mode using anisotropic phase separation

In this section, we will introduce the formation of inter-pixel wall structure by using anisotropic phase separation of LC/polymer mixture.

3.1 Microstructures from 3-dimensional anisotropic phase separation

We fabricated the pixel-isolating polymer wall structure by photo-polymerization induced phase separation from LCs and pre-polymer composite material. Using UV intensity variation and polymer wetting properties [8], the LC molecules in our structure could be isolated in pixels where LCs are surrounded by the inter-pixel vertical polymer walls and the horizontal polymer film. The fabrication process is shown in Fig. 5. One of the ITO-coated PES substrates was spin-coated with a homogeneous alignment layer

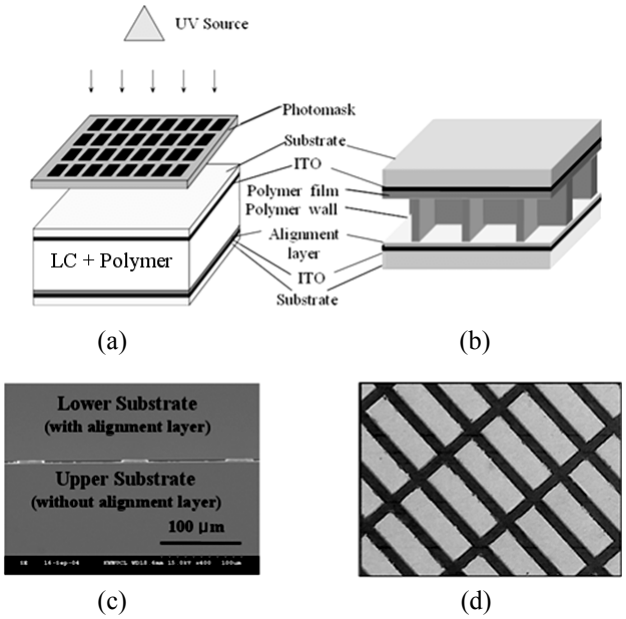


Figure 5 (a) Schematic diagram of PILC mode made by photo-polymerization induced anisotropic phase separation, (b) pixel structure after UV exposure, (c) the cross-sectional SEM image of PILC sample, and (d) the polarizing optical microscopic texture of the PILC cell.

and unidirectionally rubbed. A mixture of nematic LC (LC17) and photo-curable pre-polymer (NOA65, Norland) with a weight ratio of 75:25 was filled into the cell by capillary action at isotropic temperature. At the first UV exposure, the UV was illuminated onto the bare ITO-coated PES substrate through the photomask of pattern size of 100 μm x 300 μm for 90 minutes (Fig. 5(a)). The second UV exposure was performed without the mask for 10 minutes to fully harden the pre-polymers. During these first and second photo-polymerization processes, the anisotropic phase separation occurs in the horizontal and vertical direction, respectively, therefore vertical polymer walls and planar polymer layers were formed as shown in Fig. 5(b).

Fig. 5(c) shows the cross sectional SEM image of our PILC cell. The spatially distributed polymer walls formed by the first UV exposure act as supporting structures from external point pressure and bending distortion and maintain the cell gap of the plastic LC cell. The residual pre-polymers are completely expelled from the bulk LC layer by second UV exposure forming thin polymer layer onto the bare ITO-coated PES substrate. Due to this second step of UV exposure, our PILC mode can show a good EO properties and the enhanced mechanical stability with good adhesion of the plastic substrates and the polymer walls. Fig. 5(d) shows the polarizing optical microscopic image after UV irradiation. It is clear that inter-pixel polymer wall structures are formed and LC molecules are well aligned.

3.2 Polymer wall formation using patterned alignment layer

This method uses the phase separation between the LC and prepolymers induced by the difference of wetting property on a patterned surface. Fig. 6 shows the schematic diagram of fabricating a PILC mode using a phase separation depending on

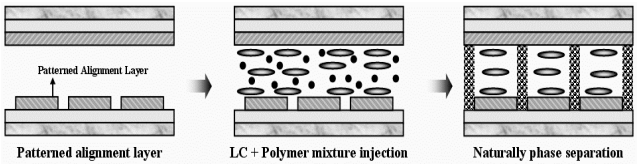


Figure 6 The schematic diagram of a PILC mode where phase separation is induced by surface wetting properties.

the surface wetting property. For spatially modifying the surface wetting condition to the LC/polymer mixtures, a homeotropic alignment layer (JALS684, JSR Co.) was patterned on one of the bare ITO-substrate by a micro-contact printing method. On the other substrate, JALS684 was uniformly coated. The mixture of negative NLC (MLC-6610, Merck) and photocurable prepolymer (NOA65, Norland) was introduced into the cell by capillary action at an isotropic temperature condition. After filling the mixture, the cell was cooled down slowly to room temperature. Because the wettability of the LC is higher than that of the prepolymer on the patterned alignment layer, phase separation between the LC and the prepolymer are promoted and the LC molecules are aggregated on the patterned alignment layers.

Fig. 7(a) shows the polarizing optical microscopic images of the phase-separated cell before UV exposure. Since the LC and the prepolymer were wholly phase-separated, there were no polymer dispersed LC droplets. Fig. 7(b) is the texture in the presence of an applied voltage before UV exposure. Within the intra-pixel regions on the patterned alignment layer, an axially symmetric LC reorientation was observed, which was originated by the symmetric boundary condition produced by the uncured prepolymer in inter-pixel regions. In this method, only one step of UV exposure is required for producing the PILC mode. To harden the prepolymers and to fix the separation pattern, we performed UV irradiation without photomasking. Fig. 7(c) shows the resultant texture in the absence of an applied voltage where the LC molecules are isolated polymer microwall structures.

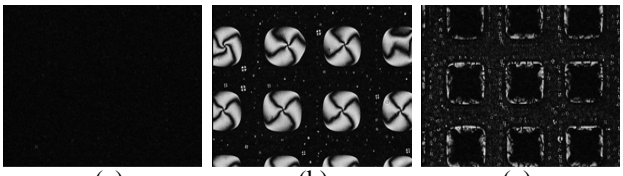
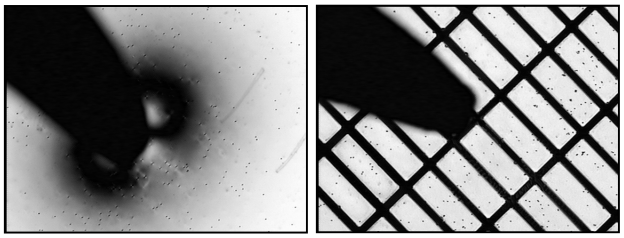


Figure 7 Polarizing optical microscopic images of PILC cell where the phase separation is induced by surface wetting properties of LC and polymer on the patterned alignment layer. Before UV exposure, (a) and (b) are obtained in the absence and presence of an applied voltage, respectively. (c) is obtained in the absence of an applied voltage after UV exposure.

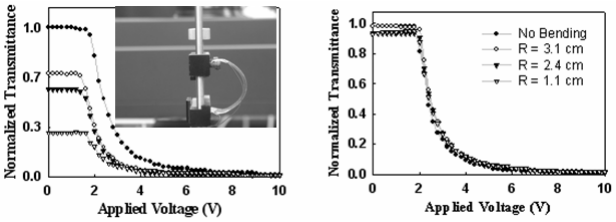
4. Electrooptic properties of a plastic LCD with the PILC mode

We tested the mechanical stability of the PILC cell against an external pressure and bending. Fig. 8 shows polarizing optical microscopic textures of a normal and the PILC samples prepared with plastic substrates in the presence of an external point pressure by a sharp tip. The alignment texture of the normal



(a) (b)

Figure 8 Alignment textures of (a) a normal sample and (b) a PILC sample fabricated using the plastic substrates. The polarizing microscopic textures are taken in the presence of an external point pressure with a sharp tip.



(a) (b)

Figure 9 EO properties of (a) a normal and (b) a PILC sample depending on degree of bending.

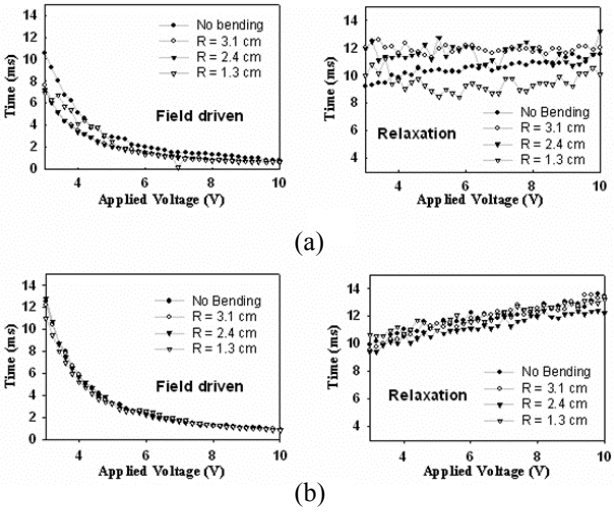
sample was severely degraded by the distortion of LC alignment due to the cell gap variation in a relatively large area as shown in

Fig. 8(a). However, that of the PILC sample showed no appreciable changes since the LC molecular reorientation was restricted and the cell gap was sustained by the polymer wall structure which was shown as a dark lines in Fig. 8(b).

Fig. 9 shows the EO properties of the normal plastic LC cell and the plastic PILC cell in the presence of an external bending pressure with a pair of linear stages. In Fig. 9, *R* represents the curvature of bending radius. As the bending stress on the normal plastic LC cell increases, the LC molecules are severely distorted and the cell gap is decreased, which resulted in the decrease of the transmittance as shown in Fig. 9(a). However, our PILC cell shows almost the same transmittance properties irrespective of the degree of the bending pressure in the whole operating voltages. Notice that the transmittances of Fig. 9(a) are degraded by about 70 % with respect to the initial transmittance condition.

Figs. 10(a) and (b) show the dynamic properties of field-driven and field-off relaxation times for the normal sample and the PILC sample depending on degree of bending, respectively. The dynamic properties of the PILC cell are much stable comparing with that of the normal sample since the cell gap of the PILC cell is not varied irrespective of the external bending distortion.

Fig. 11 shows a 3'' prototype sample of a plastic LCD with the proposed PILC mode. The resolution was 124 x 76 with a pixel size of 100 x 300 μ m^2 and polymer walls were well formed through the sample. A full color display was achieved by laminating a patterned color filter sheet on the top substrate. The



(a)

(b)

Figure 10 Dynamic properties of field-driven and field-off relaxation times for (a) a normal sample and (b) a PILC sample depending on degree of bending.

Figure 11 3" plastic LCD sample using PILC mode.

response time (field driven + relaxation time) was about 20 ms. The contrast ratio was about 130:1 even in bending distortion.

5. Conclusion

Mechanical stability is a key issue in the application of flexible LCDs using plastic substrates. To solve those problems, stabilization of LC mode and adhesion of two plastic substrates are essential. In this demonstration, we presented stability-

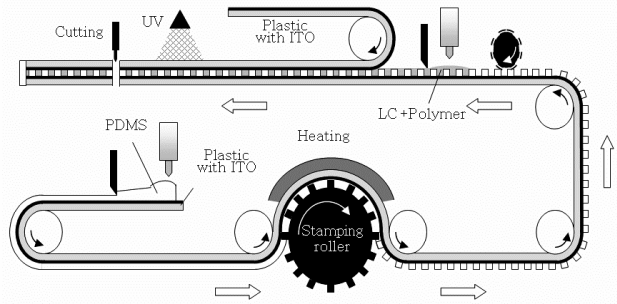


Figure 12 Schematic diagram of the continuous roll processing for fabrication of the plastic LCDs with the methods presented here.

enhanced LCDs using the PILC mode where LC molecules are isolated in pixels by both the horizontal polymer layer and the vertical polymer wall. The polymer wall acts as supporting structure from mechanical pressure and maintains the cell gap from bending. Moreover, the polymer layer acts as adhesive for tight attachment of two plastic substrates. Therefore, the plastic LCDs with the PILC mode show good EO properties against an external pressure and bending.

We presented various methods of fabrication of PILC structure using LC and polymer mixture. Among these methods, the fabrication of patterned wall structure using a stamping method is the most appropriate to be used in the mass production of plastic LCDs through continuous roll processing as shown in Fig. 12.

6. Acknowledgements

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7. References

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