

## Pixel-Isolated Liquid Crystal Mode for Flexible Display Applications

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We developed a new device using anisotropic phase separation from liquid crystals (LCs) and polymer composite materials using UV intensity variation and polymer wetting properties for flexible display applications. In the device, LC molecules are isolated in pixels where LCs are surrounded by interpixel vertical polymer walls and horizontal polymer films on the upper substrate. This device shows very good mechanical stability against external pressure. The electro-optic characteristics and the mechanical stability of the device are discussed in view of flexible display applications. [DOI: 10.1143/JJAP.43.4269]

KEYWORDS: polymer and liquid crystal composite, plastic LCD, anisotropic phase separation

### 1. Introduction

Liquid crystals (LCs) have been extensively studied and used for display applications because of their efficient light-control capabilities with low power consumption.<sup>1)</sup> These advantages come from hydrodynamic properties and high birefringence of LCs. In general, LC devices are prepared by sandwiching LC molecules between two glass substrates with transparent electrodes and alignment layers to obtain a specific configuration of the optic axis. One primary role of these substrates is supporting the LC molecular orientation from external bending or pressure, which alters the arrangement of LC molecules and diminishes the optical properties of the device.

In recent years, LC devices using plastic film substrates have drawn much attention for use in applications such as smart cards, PDA, and head mount displays because of their lighter weight, thinner packaging, flexibility, and lower manufacturing cost through continuous roll processing than other similar available devices.<sup>2–4)</sup> Different electro-optical modes have been proposed for use in plastic LCDs including twisted nematic, cholesteric, polymer dispersed LC (PDLC), and bistable ferroelectric LC (FLC) modes. However, it is clear that plastic substrates can not give a solid mechanical support for the molecular alignment of LCs between them. In particular, FLCs show very weak mechanical stability because of the presence of fragile smectic layers even between glass substrates. To overcome these problems, polymer walls and/or networks as supporting structures have been proposed and demonstrated.<sup>5–7)</sup> These structures were fabricated using an anisotropic phase separation method from polymer and LC composite systems by applying 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 an unexposed region that reduce optical properties and increase the operating voltage of the device.

In this paper, we propose a new method for fabricating a stable LC structure using anisotropic phase separation produced by contraction and surface wetting properties. In the structure, LC molecules are isolated in pixels surrounded by interpixel vertical polymer walls and horizontal polymer films on the upper substrate, namely, the pixel-isolated LC

(PILC) mode. This mode shows not only good mechanical stability but also almost the same optical behavior with respect to the normal mode without a polymer.

### 2. Experimental

The materials used in this study were commercially available nematic LC (NLC) E48 (Merck), FLC Felix 15-100 (Hoechst), and UV curable optical adhesive NOA72 and 73 (Norland), and SK 9 (Summers Laboratories) as prepolymers. These prepolymers were a mixture of a monomer, an oligomer, and a photoinitiator. For the alignment layers, we used Nylon 6 (Sigma Aldrich). The alignment layers were spin coated on one substrate followed by rubbing to achieve a homogeneous LC alignment. The thickness of the glass substrate was 0.7 mm. We note that the results of phase separation are greatly affected by the alignment layer and prepolymer. The cell gap was maintained using glass spacers of 4  $\mu\text{m}$ . A solution of the LC and prepolymer with weight ratios of 70 : 30 for FLC and 50 : 50 for NLC, was introduced into the cell by capillary action at a temperature higher than the clearing point of the LCs. The cells were exposed to UV light of  $\lambda = 350 \text{ nm}$  to initiate polymerization. The source of UV light was a Xenon lamp operated at an electrical power of 200 W. The photomask was placed on one of the glass substrates without the alignment layer.

Figure 1(a) shows the fabrication setup for a PILC. The cell with the LC+prepolymer mixture was irradiated with UV light for  $\sim 10 \text{ min}$ . A second exposure was performed without the mask for 5 minutes to fully harden the polymer. During this process, the LC molecules which remained in the polymer network after the first UV exposure were expelled from the polymerized volume. Figure 1(b) shows the resultant element after UV exposure. The LC molecules were isolated in the pixel surrounded by polymer layers which acted as supporting structures against external shock.

### 3. Results and Discussion

A complete theory of the anisotropic phase separation by UV exposure would describe the evolution of the PILC structure in terms of the spacial and temporal distributions of LCs, prepolymers, polymers, and all intermediate oligomers. It would also include the effects of a rubbed substrate surface on the induction of nematic ordering in otherwise isotropic LC mixtures and the polymer morphology. In our previous report,<sup>9)</sup> we developed a simple model to describe

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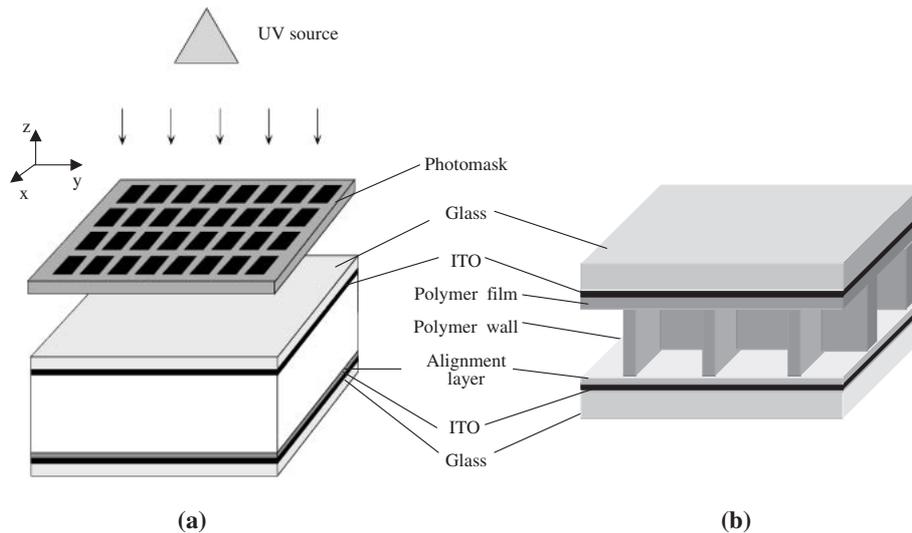


Fig. 1. Schematic diagrams of (a) the experimental setup and (b) resultant structure after UV exposure.

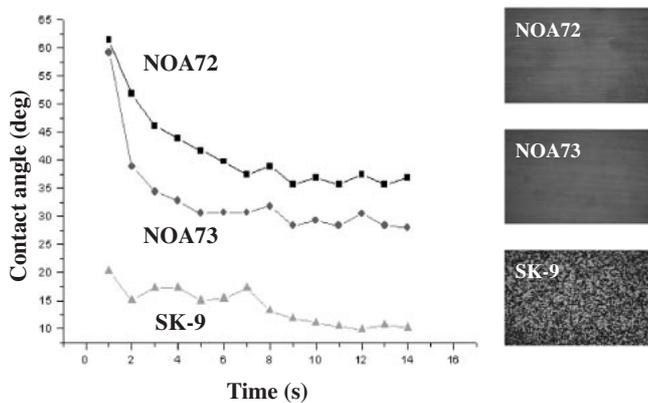


Fig. 2. Contact angles for different prepolymers on Nylon 6 as functions of time after dropping and alignment textures with E48 after phase separation.

the anisotropic phase separation due to the UV intensity gradient in the direction of sample thickness ( $z$ -axis) using the mean-field kinetic theory. According to the model, the LC molecules are expelled from the polymerized volume by the polymerization of the prepolymer by UV light, namely, the contraction effect. Now, we consider the effect of surface interaction between the LC/prepolymer and alignment layer on the anisotropic phase separation. Figure 2 shows contact angles on Nylon 6 for different prepolymers as functions of time after dropping and alignment textures with E48 after phase separation. In the data, the fluctuation of contact angles according to time is within the experimental error range. The contact angles of NOA 72 and 73 saturate at more than 30 degrees after 10 s. The contact angle of SK 9, however, saturates at 10 degrees. This indicates that SK 9 has a stronger correlation with N6 than with NOA 72 and 73. Since the LC materials used are fully wetted on the Nylon 6 alignment layer and dewetted on the ITO substrate, the interactions of LC and SK 9 with the surface alignment layers compete with each other and form network structures by UV exposure. With NOA 72 and 73, the LC molecules near the alignment layer respond to its anchoring potential

and align parallel to the rubbing direction. Oriented LC molecules determine the microscopic structure of the polymer-LC interface which becomes compatible with their alignment. Therefore, the presence of the alignment layer promotes the surface-induced anisotropic phase separation in the direction of sample thickness. As a result, we successfully fabricated a phase-separated composite organic film structure which has adjacent uniform polymer and LC layers using the UV intensity gradient in the  $z$ -direction and surface effect as shown in Fig. 2. The theoretical model including surface potential for understanding the anisotropic phase separation is now being developed and will be published elsewhere. The use of a suitable photomask during UV exposure produces additional intensity gradients on the ( $xy$ -) plane of the cell. Monomers in the high-intensity region near the UV source undergo polymerization first and those monomers in the low-intensity region diffuse to the high-intensity region to maintain their relative concentration, and join the polymerization reaction.<sup>10</sup> The LC molecules are immiscible in and are expelled from the polymer. Therefore, we can control the anisotropic phase separation in three dimensions using a suitable photomask and alignment layer. In our experiment, the PILC structure in which the LCs are isolated in the pixels surrounded by interpixel vertical polymer walls and horizontal polymer films on the upper substrate is fabricated for flexible display applications as shown in Fig. 1(b). We note that any LC modes such as nematic, ferroelectric, and cholesteric modes can be applicable.

Figure 3 shows the microscopic textures of the pixel-isolated NLC (PINLC) and FLC (PIFLC) cells at room temperature after UV exposure under a polarizing microscope. The pixels were rich in LCs with a uniform alignment and the interpixels were rich in polymers with few embedded LC molecules which generate light leakage in the dark state. Since the transition temperature of the LC obtained after complete phase separation [82.7°C] deviates from that of the original LC sample [83.1°C] by less than 0.5°C, we conclude that there are just few unpolymerized monomers in the LC region. This small change is most likely

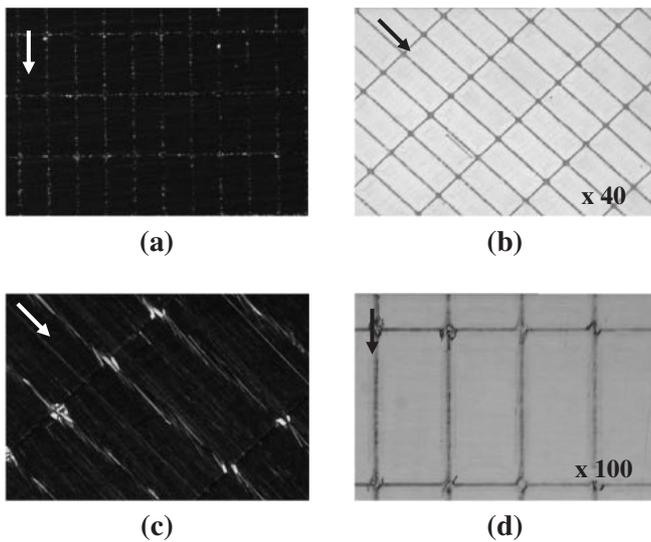


Fig. 3. Alignment textures of normal and PILC samples with NLCs [(a) and (b)] and FLCs [(c) and (d)]: The rubbing direction indicated by an arrow is rotated at 0° [(a) and (c)] and 45° [(b) and (d)] with respect to one of the crossed polarizers.

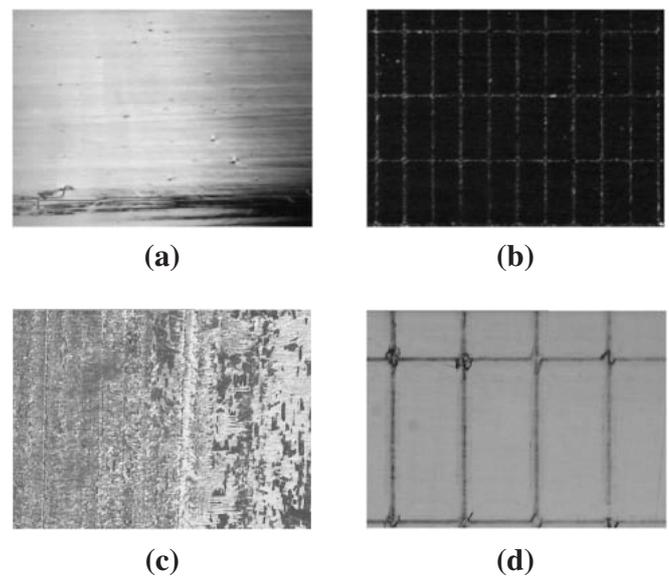


Fig. 5. Comparison of alignment textures for NLCs and FLCs caused by external pressures for normal and PILC samples: (a) and (c) are normal NLC and FLC, respectively. (b) and (d) are pixel-isolated NLC and FLC, respectively. We obtained the images during the pressure with a sharp tip for NLC samples and after removing the pressure for FLC samples.

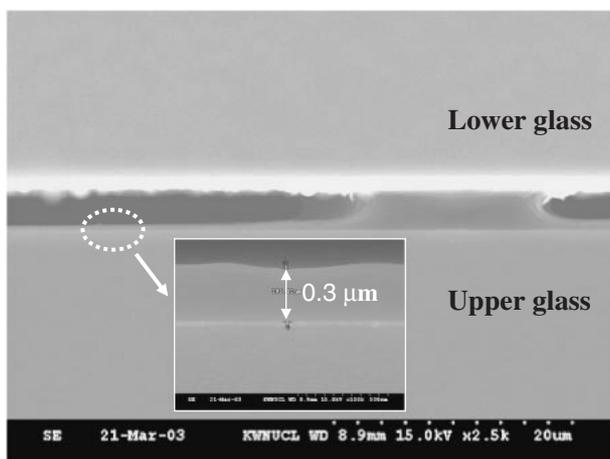


Fig. 4. Cross-sectional image of the PILC sample using a scanning electron microscope. The inset is the magnification of the dotted circle.

the consequence of an increase in impurity concentration resulting from the expulsion into the LC of unpolymerized monomers. We note that the LC molecules in the polymer can be controlled by the mixing ratio, UV intensity and exposure time, environment temperature, and sample thickness.

The cross-sectional image of PINLC obtained using a scanning electron microscope is shown in Fig. 4. Well-defined vertical polymer walls in interpixels and horizontal uniform polymer films on the upper glass substrate are observed. Therefore, the LC molecules are surrounded by polymers and isolated in pixels. The polymer walls act as supporting structures against external pressure and bending.

We now describe the alignment stability of PILC against external mechanical shock. Such mechanical stability has been one of the main problems in commercializing plastic LCDs, particularly those using FLCs. In Fig. 5, we compare the alignment textures for NLCs [(a) and (b)] and FLCs [(c) and (d)] caused by external pressures for normal and PILC

samples. The mechanical shock is produced by mechanically pressing the sample with a sharp tip. The area of the tip is about 0.7 mm<sup>2</sup>. For NLC samples, we observed alignment textures in the dark state during the mechanical pressure. In the normal sample, Fig. 5(a), we can see light leakages due to the reorientation of LC molecules by the mechanical pressure. It is very clear that there is no significant change in the PILC sample even with the mechanical pressure [Fig. 5(b)]. We note that the alignment textures for NLC samples recover after removing the pressure. For FLC samples, we observed the alignment textures after removing the mechanical pressure. The texture of the normal FLC sample, Fig. 5(c), that shows a crucial change due to the broken smectic layers, does not recover after removing the mechanical pressure, different from those of NLC samples. However, there are no significant structural change in the PILC sample [Fig. 5(d)], the same as in the NLC sample. From the results, we found that PILC is very promising for flexible display applications.

Figure 6 shows the electro-optic behavior of the normal and PINLC samples. In both samples, transmittance and response time show almost the same behavior except a slight increase in threshold voltage in the PINLC sample. This increase in threshold voltage is due to the polymer layers and increasing anchoring force at the polymer wall.

#### 4. Conclusions

We successfully fabricated a new device using a three-dimensional anisotropic phase separation method. In the device, LC molecules are isolated in pixels where LCs are surrounded by polymer layers. This device shows very good mechanical stability against external pressure. Its electro-optic characteristics are almost the same as those of a normal LC structure. We believe that the PILC mode will open a new generation of plastic LCDs in near future.

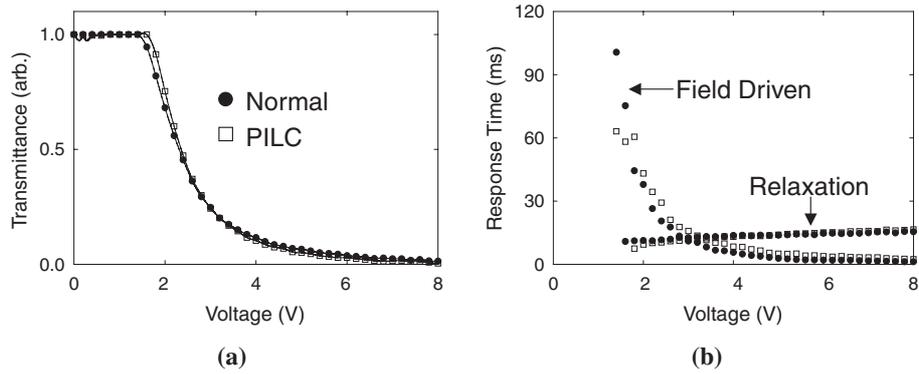


Fig. 6. Electro-optical properties of normal (circle) and PINLC (square) samples as functions of applied voltages: (a) the transmittance and (b) response time.

### Acknowledgements

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