Mechanical Stability of Pixel-Isolated Liquid Crystal Mode with Plastic Substrates

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We have fabricated a plastic liquid crystal display using the pixel-isolated liquid crystal (PILC) mode and characterized the mechanical stability of the sample against mechanical pressure and bending. Since the liquid crystal molecules are fully isolated in the pixels by the phase-separated polymer walls in the PILC mode, the electrooptic properties of the sample show good mechanical stability. In addition, a polymer layer formed on the upper substrate enhances the adhesion between two plastic substrates.   [DOI: 10.1143/JJAP.44.8547]

KEYWORDS: polymer/LC composite, plastic LCD, mechanical stability

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.[1] 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, PDAs, 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.[2–4] However, it is clear that plastic substrates cannot provide a solid mechanical support for the molecular alignment of LCs between them. To overcome these problems, polymer walls and/or networks as supporting structures have been proposed and demonstrated.[5–7] 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 a high electric field to initiate the anisotropic phase separation or retain residual polymers in an unexposed region that reduce optical properties and increase the operating voltage of the device.

More recently, we have proposed the pixel-isolated LC (PILC) mode for fabricating a stable LC structure using anisotropic phase separation produced by contraction and surface wetting properties.[8] Since LC molecules are isolated in pixels surrounded by interpixel vertical polymer walls and horizontal polymer films on the upper substrate in the structure, this mode shows not only good mechanical stability but also almost the same optical behavior with respect to the normal mode without a polymer.

In this paper, we demonstrated the PILC structure using plastic substrates and studied the mechanical stability of the sample in the presence of external pressure and bending.

2. Experimental

LC cells were fabricated using plastic substrates by the photopolymerization-induced anisotropic phase separation method. Two indium tin oxide (ITO)-coated poly(ether sulfone) (PES) films with a thickness of $200\,\mu m$ were used as substrates. The size of the cell was about $4.3 \times 7.6\,cm^2$. For the alignment layers, we used RN1199 polyimide (Nissan Chemical). The alignment layers were spin coated on one substrate followed by rubbing to achieve homogeneous LC alignment. Note that the results of phase separation are greatly affected by the alignment layer and prepolymer.[9] The other substrate was untreated to enhance anisotropic phase separation. The cell gap was maintained using glass spacers of $3.5\,\mu m$. A mixture of nematic LC (LC17) and photocurable prepolymer NOA65 (Norland) with a weight ratio of 75 : 25 was introduced into the cell by capillary action at a temperature higher than the clearing point of the LC. The cells were exposed to UV light of $\lambda = 350\,nm$ to initiate polymerization. The source of UV light was a Xenon lamp operated at $200\,W$ of electrical power. The photomask was placed on one of the plastic substrates without the alignment layer. The cell with the LC + prepolymer mixture was irradiated with UV light for $\sim 30\,min$. The polymer wall was formed around an area of $330 \times 130\,\mu m^2$, which is compatible to the size of a single pixel in normal liquid crystal displays (LCDs), and the width of the wall was $30\,\mu m$. A second exposure was performed without the mask for $10\,min$ to fully harden the polymer and to remove polymers from liquid crystal molecules. During this process, the LC molecules which remain in the polymer network after the first UV exposure were expelled from the polymerized volume.

3. Results and Discussion

When LC/monomer mixture is exposed to intensity modulated UV light, the monomers in the high intensity region 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. As a result, monomers move toward solidified polymers and LC molecules are expelled to the low intensity region, which results in the macroscopic phase separation of LC and polymer. At the first UV exposure with a square-patterned photomask, the UV intensity gradient is produced on the plane parallel to the substrate and the polymer walls are formed in the high UV
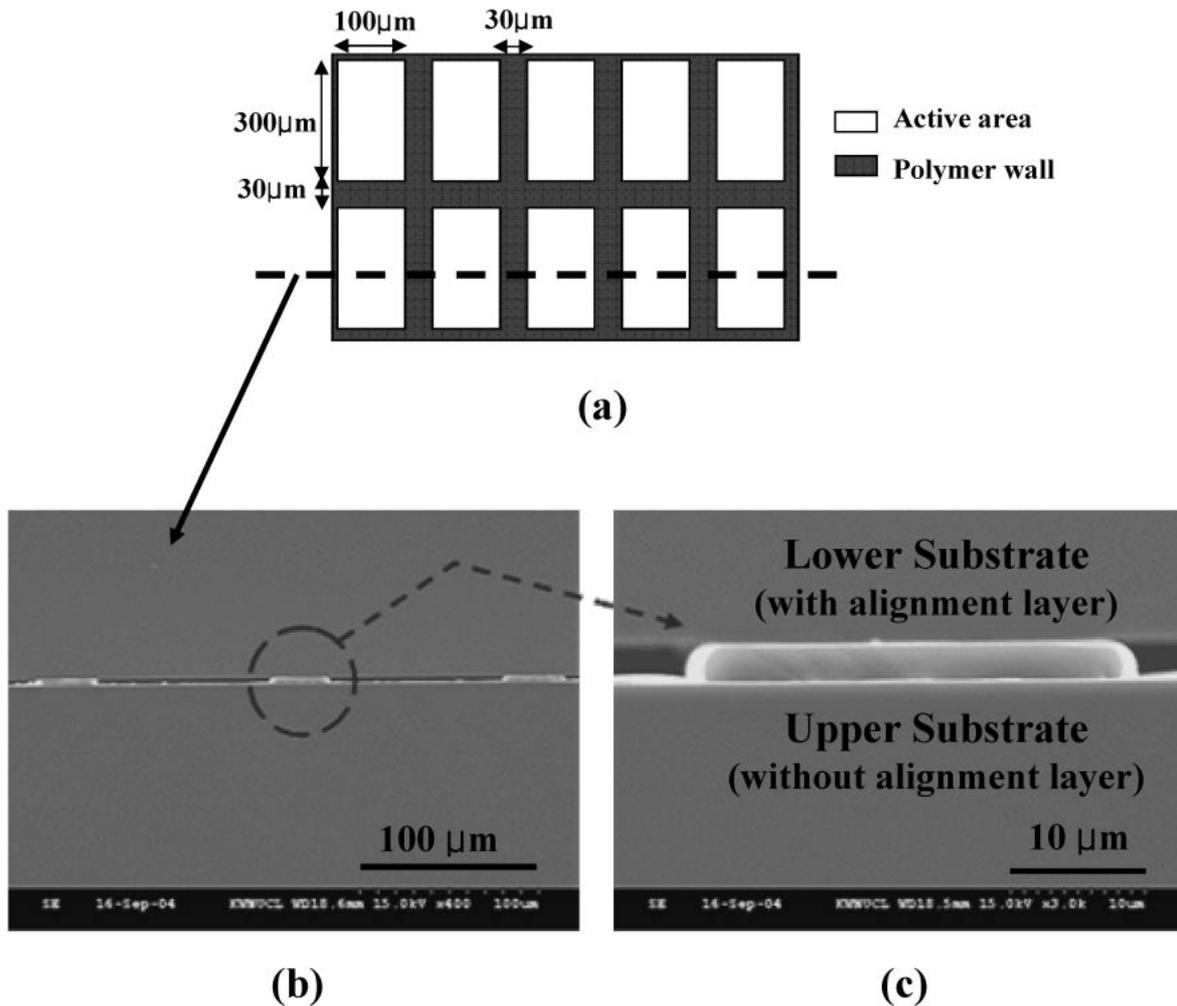
Fig. 1. Cross-sectional image of scanning electron microscopy of our PILC structure sample. (a) Schematic diagram of planar view of pixel structure; the dotted line indicates the cutting line for the cross-sectional view. (b) Cross-sectional view of polymer wall formed as shown in circle and (c) magnification of (b). The bottom substrate is ITO-only-coated PES film and we can see a uniform horizontal polymer layer, which is the white shiny layer on the bottom substrate.

intensity region. During this process LC molecules are expelled from the polymer. After removing the photomask, the second UV exposure is performed. Because the UV light is absorbed predominantly by LC molecules, UV intensity is higher near the illuminated substrate, which produces an intensity gradient normal to the substrate. Thus the polymerization starts from the illuminated surface and monomers near the surface region move to the surface by entropic driving. Therefore, anisotropic phase separation of the polymer layer and LC molecules occurs, and the polymer layer is formed on the illuminated substrate. The resultant texture of phase separation depends on the wetting properties of the prepolymer and liquid crystal on the alignment layer as we previously reported.[9]

By applying this two step UV exposure, the LC molecules are fully isolated in pixels by the formation of interpixel vertical polymer walls and horizontal polymer layer formed by the first and second UV exposure, respectively. Figure 1 shows the cross-sectional images of the polymer structure in the PILC cell obtained using scanning electron microscope (SEM). It is clear that the polymer walls are formed periodically between the two substrates. These polymer walls separate the LC from neighboring pixels and act as

patterned spacers, which promote the mechanical stability of the cell. The residual pre-polymers are completely expelled from the bulk LC by the second UV exposure and form a thin polymer layer on the ITO-coated PES substrate without an alignment layer; such a layer is also formed in the vicinity of polymer walls. The cured polymers near a polymer wall can enhance the adhesion of the wall and the lower substrate. Due to this double exposure of UV, the PILC mode can show enhanced mechanical stability with good adhesion between two substrates.

We tested the alignment stability of the PILC cell against an external mechanical shock and bending. We prepared a normal LC cell under the same fabrication conditions except mixing with monomer to compare with the PILC cell. In the normal LC sample, the cell gap is maintained only by spacers. Figures 2(a) and 2(b) show polarizing microscopic textures of the normal and PILC cells in the presence of an external point pressure with a sharp tip, respectively. Under the same amount of pressure, the alignment texture of the normal sample [Fig. 2(a)] was severely distorted due to the cell gap variation. This means that spacers between two substrates in the normal cell do not resist LC molecular reorientation induced by the pressure. The distortion of LC
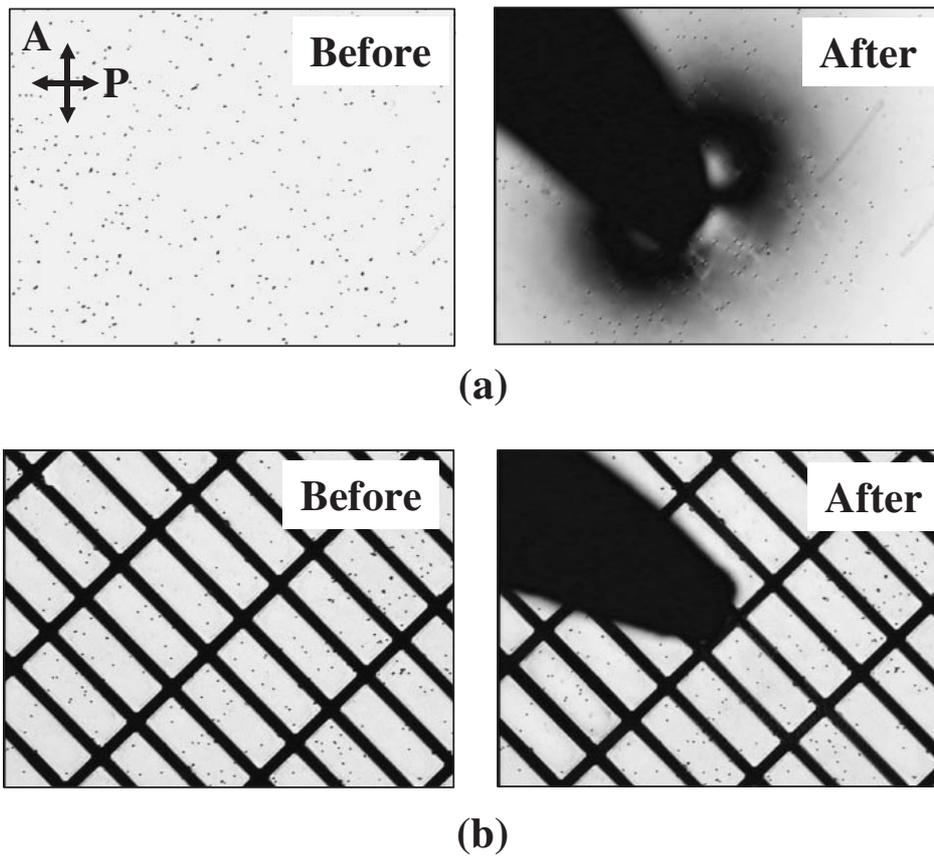
Fig. 2. Microscopic textures of normal plastic cell and PILC structure on plastic substrates (a) before and after point pressure on normal cell and (b) before and after point pressure on PILC cell. The pixel pitch is $330 \times 130\,\mu m^2$ and the wall width is $30\,\mu m$. Hence, the active area is $300 \times 100\,\mu m^2$. The small dots are glass spacers.
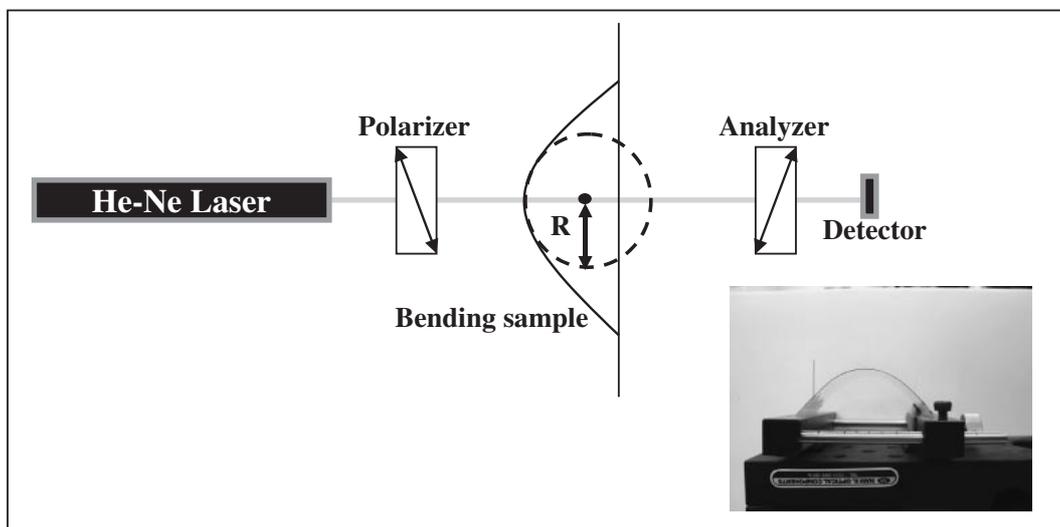

Fig. 3. Electrooptic measurement setup with external bending stress. With a pair of linear stages we can apply the bending stress. To obtain the radius of curvature as a measure of bending stress, we took photographs and made a fit to a circle as shown in the inset.

molecular orientation propagates over a sufficiently large area as shown in the figure and degrades the display quality. However, the PILC cell showed no appreciable changes since the LC molecular reorientation is restricted in pixels by the vertical polymer wall and horizontal polymer layer [Fig. 2(b)]. These polymer walls act as supporting structures to maintain the cell gap from external pressure and bending.

The dispersed small dots in the figure are glass spacers.

To investigate how the above results affect the display qualities, we measured electro-optic properties of the normal and PILC cells under external bending. Figure 3 shows a schematic diagram of our measurement setup. The cell is bent using a pair of linear translation stages and placed between two crossed polarizers. We measured transmittance
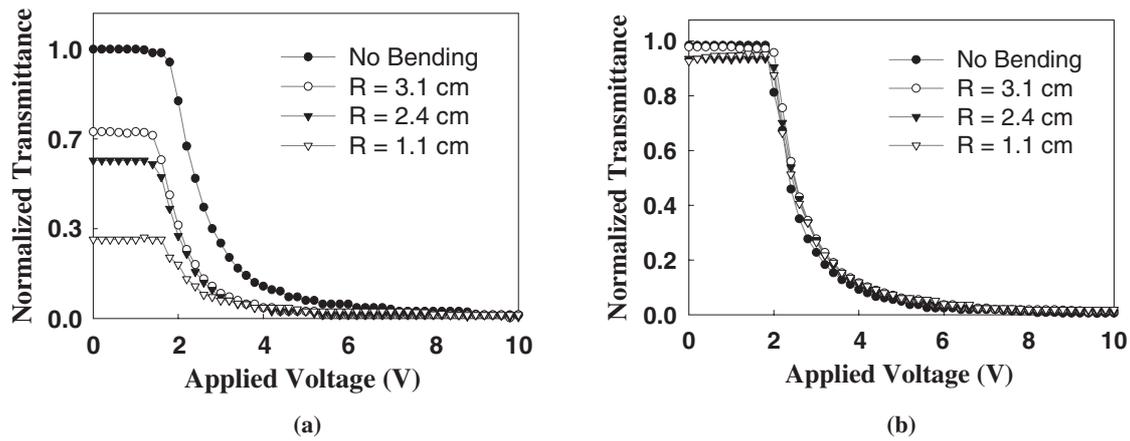
Fig. 4.   Transmittance curves vs applied voltage (a) for normal cell and (b) for PILC cell at various bending states. We used the radius of curvature as a measure of the degree of bending.
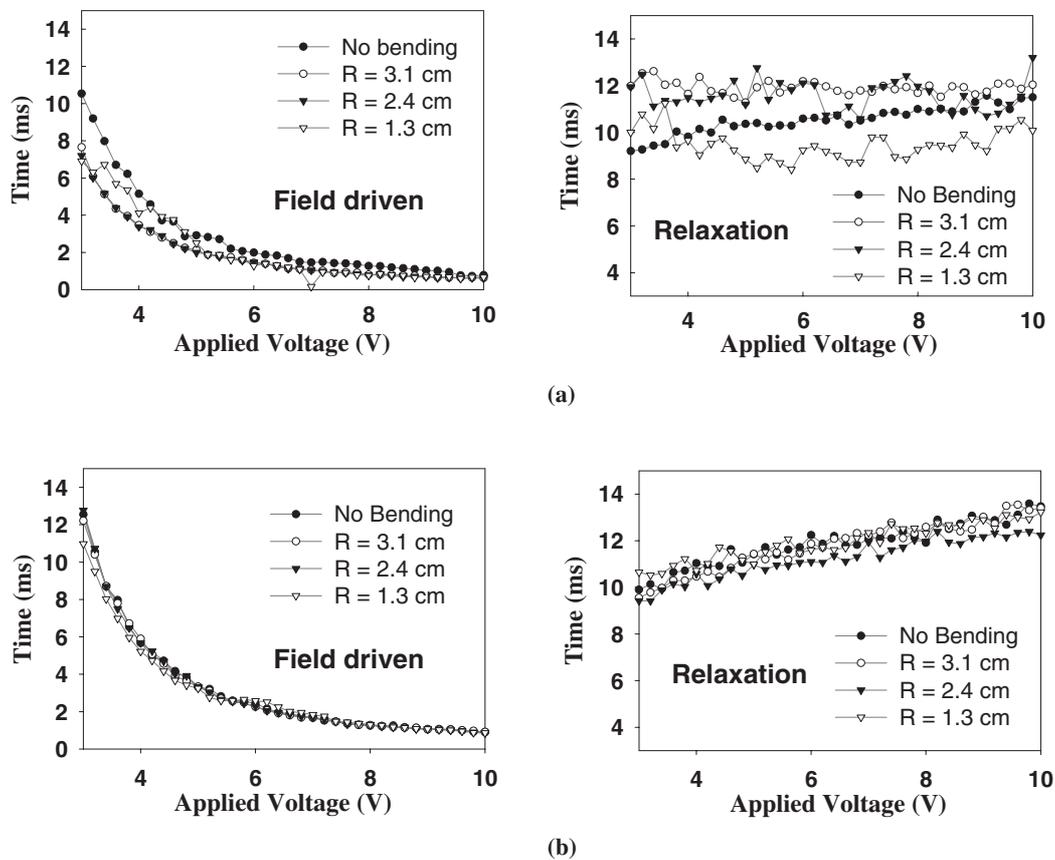

Fig. 5.   Measured response times (field-driven and relaxation times) vs applied voltage (a) for normal cell and (b) for PILC cell at various bending states. The radii of curvature are the same as those in Fig. 4.

and response time as functions of applied voltage with various degrees of bending as shown in Figs. 4 and 5, respectively. The degree of bending is represented by the curvature of the cell (R) as shown in Fig. 3. Decreasing R means increasing the degree of bending. For the normal plastic LC cell, as shown in Fig. 4(a), decreasing R decreases the transmittance at 0 V. At the maximum degree of bending ($R \sim 1.1$ cm) the transmittance decreases to 70% with respect to that of the unbent sample. The contrast ratio decreases to $1/3$ ($75 : 1 \rightarrow 25 : 1$) with decreasing R. However, the PILC cell shows almost the same behavior except for a minor decrease in the low voltage regime. The

contrast ratio of $133 : 1$ in the unbent cell decreases to $75 : 1$ in the bent cell with $R = 1.1$ cm. It is clear that LC molecular orientational distortion due to bending stress is effectively suppressed in the PILC structure with respect to the normal plastic cell. Moreover, the PILC sample has no appreciable shift of the threshold voltage different from the polymer network or dispersed structures in which the threshold voltage increases as polymer concentration increases.[10]

Figure 5 shows the response time of both samples with various degrees of bending. The field-driven response of the normal sample in the low voltage regime is slightly faster
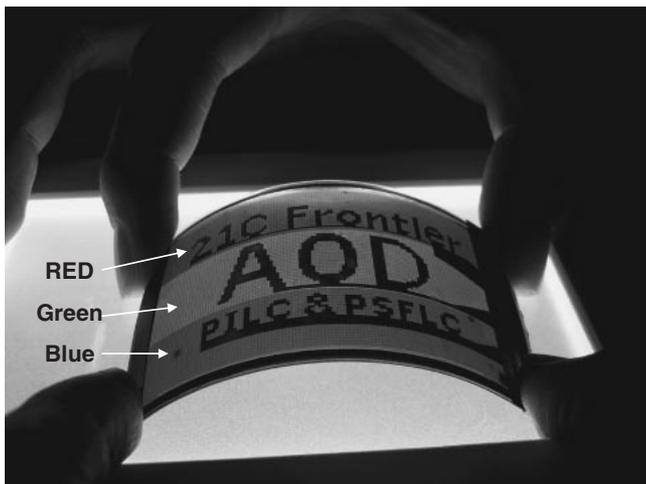
Fig. 6.   Three-inch-size LC sample using plastic substrates with pixel-isolated liquid crystal structure.

than that of the PILC cell. This is probably due to the surface interaction of LC molecules in the PILC cell with the polymer wall and layer. Since the cell gap decreases with R (i.e., increasing degree of bending) in the normal cell, the field-driven time decreases. This is probably due to the decrease in cell gap. In contrast, the relaxation time usually increases with decreasing R because of LC molecular orientational distortion due to the cell gap variation as shown in Fig. 2(a). Since the relaxation time depends on both the cell gap and elastic properties of the LC alignment, the variation is not clear. In the case of the PILC cell, electroopic responses exhibit an almost uniform distribution due to supporting structures. From the results, we found that the PILC structure provides not only good mechanical properties but also stable LC molecular dynamics.

Figure 6 shows a prototype sample of a 3-in. plastic LCD with the PILC mode in a bending state. The resolution is 124×76 with a pixel size of $500 \times 500\,\mu m^2$ and polymer walls are well formed throughout the sample. The electrodes on the lower substrate were patterned. To make a full-color display device, red, green and blue color filters were formed on the upper substrate.

4.   Conclusions

We successfully fabricated a PILC cell using plastic substrates. By applying a two-step UV exposure with/without a photomask, the liquid crystal molecules are fully isolated in the vertical polymer walls and uniform horizontal solidified polymer layer. We compared mechanical stabilities for both a normal plastic and the PILC cell using plastic substrates. Through microscopic observation and EO measurements, we found that the PILC structure can provide a mechanical supporting structure for liquid crystal molecules, which results in stable and good EO properties under external stresses. Moreover, the adhesion strength of two plastic substrates is also enhanced due to the solidified horizontal polymer layer, which is one of the main problems in the fabrication of large plastic LCDs. Therefore, it is expected that the PILC structure and the fabrication methods presented in this paper will be suitable for solving current main problems in plastic LC devices.

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