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Pixel-Isolated Phase-Separated Composite Organic Film for Flexible Ferroelectric Liquid Crystal Display Applications

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We have studied a pixel-isolated phase-separated composite organic film (PI-PSCOF). This PI-PSCOF is used for anisotropic phase separation from ferroelectric liquid crystals (FLCs) and prepolymer materials using an appropriate UV intensity variation. In this device, the FLC molecules are isolated in the pixels where FLCs are surrounded by the interpixel vertical polymer walls and the horizontal polymer films on the upper substrate. These devices show very short response time and very high mechanical durability against external pressure. We also compared the pure FLC, conventional phase-separated composite film (PSCOF) and PI-PSCOF mode in terms of their electrooptic characteristics and X-ray layer structure measurements. Compared with the PSCOF mode, PI-PSCOF exhibits good electrooptical behaviors. Consequently, we achieved an excellent device scheme suitable for flexible substrates, using the PI-PSCOF mode and expect that this PI-PSCOF scheme will be one of the powerful and promising new FLC display modes, particularly applicable to flexible FLC display modes. [DOI: 10.1143/JJAP.47.2195]

KEYWORDS: ferroelectric liquid crystal, polymer wall, pixel isolation, phase-separated composite organic film, flexible display

1. Introduction

Since the discovery of ferroelectric liquid crystals (FLCs) from rod-shaped liquid crystals with a chiral molecular structure by Meyer in 1975,[1)] many manufacturing companies have practically applied such crystals to the fabrication of displays, such as surface stabilized ferroelectric liquid crystal (SSFLC) and anti-ferroelectric liquid crystal (AFLC), which exhibit short response time and wide viewing angle. However, mass production of SSFLC display (SSFLCD) and AFLC display (AFLCD) had been terminated because there were many serious problems to be solved for LCD application, such as difficulties in achieving high contrast ratio due to "zig-zag" defects[2,3)] and mechanical durability. Among alternatives, FLC modes, such as twisted FLC, deformed helix FLC (DHF), polymer-stabilized FLC, V-shaped switching AFLC, and polymer separated composite organic film (PSCOF) are commonly used.[4,5)] In the PSCOF mode, a polymer layer domain is formed at the upper part of the cell and LC molecules are moved down to form LC layers by UV cure-oriented phase separation. A pixel-isolated liquid crystal (PILC) had already been researched by many researchers.[6–8)]

Nowadays, next-generation LC devices require various features, including light weight, flexibility, low manufacturing cost, and simple processes.[9,10)] In particular, flexible displays have drawn much attention from many major display suppliers in the world. Therefore, studies on the LC devices in conjunction with plastic films have been carried out by many researchers.

However, FLC molecules have intrinsically serious problems, such as mechanical shock and low alignment reliability. In this study, we applied a new display concept, namely, two-step UV curing, using a polymer wall as a supporting structure.[11,12)] In other words, we applied a conventional PSCOF scheme to the pixel-isolated display mode to obtain mechanical flexibility and superior optical characteristics at the same time. We then compared three FLC display modes, i.e., pure FLC, phase-separated composite film (PSCOF), and PI-PSCOF mode, in terms of their electrooptic characteristics, spontaneous polarization, stability of mechanical shock and X-ray measurement.[13)] As a result, we achieved an excellent and promising new display mode using the PI-PSCOF scheme.

2. Experiment

The technique used to construct the PI-PSCOF cell is shown in Fig. 1; this technique is similar to that of fabricating polymer-dispersed liquid crystal (PDLC) devices. A pair of substrates coated with transparent electrodes of indium tin oxide (ITO) was, prepared to construct the cell. One of the substrates was coated with commercially available polyimide (RN1286) and then rubbed to ensure LC alignment. The other substrate was bare glass. The cell gap between the substrates was controlled at $\sim$5 μm. For a LC–polymer binary mixture, we used a commercially available photocurable prepolymer (NOA-65) from Norland Optics Inc. and liquid crystals (Felix-016/100) from Clariant. The ratios of the photocurable prepolymer NOA-65 and FLC used were 30 : 70, 40 : 60, and 50 : 50. Two components were mixed for two days to prepare a homogeneous binary mixture, and then the mixture was introduced into the cell by capillary action at a temperature well above the clearing point of the LC. Phase separation was carried out at a temperature above 100 °C by conventionally exposing the cell to UV light on the substrate without the polyimide-coated PSCOF mode.[4)] The photomask was then placed on one of the glass substrates without the alignment layer. The first exposure was performed with the mask for 20 min. A second exposure was performed without the mask for 10 min to harden the polymer. During this process, the FLC molecules remaining in the polymer network after the

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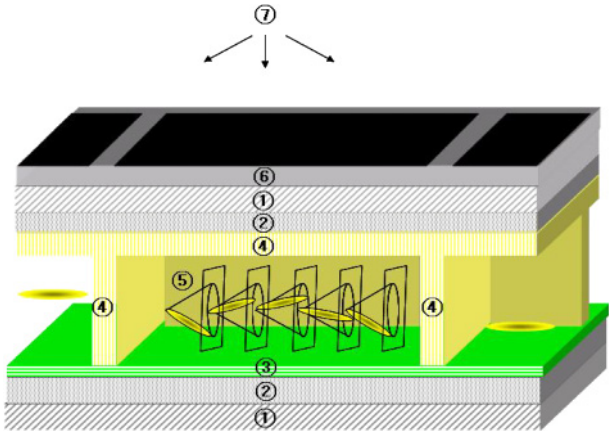


Fig. 1. (Color online) Schematic of structure of a PI-PSCOF cell. (1) Glass substrates, (2) electrodes, (3) alignment layer, (4) polymer region, (5) FLC region, (6) photomask, and (7) UV source.

first UV exposure at $\lambda = 365\,\text{nm}$ were expelled from the polymerized volume. The FLC molecules were isolated in the pixel surrounded by polymer pillars, which also serve as supporting structures against external shock. After constructing the PI-PSCOF cell, we attempted to develop a very thin glass cell (below 100 µm thickness) by hydrofluoric acid etching to minimize X-ray absorption to the glass. We then carried out X-ray scattering measurements on the PI-PSCOF cell for the layer structural studies. The phase transition sequences of FLC (Felix-015/100 and Felix-016/100) that we used are as follows: I–(86 °C)–N–(83 °C)–Sm A–(72 °C)–Sm C* for Felix-015/100 and I–(94 °C)–N–(85 °C)–Sm A–(72 °C)–Sm C* for Felix-016/100.

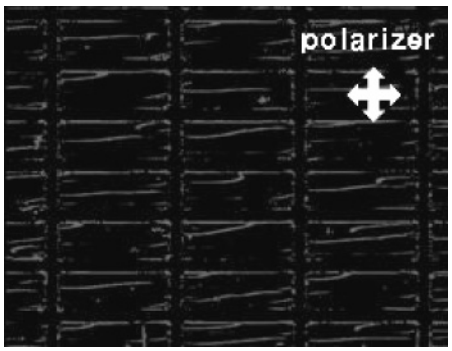
3. Results and Discussion

The PI-PSCOF cell texture was observed under crossed polarizers using a polarizing microscope (Olympus BX50). One of the polarizers was orientated to be parallel to the rubbing direction to align FLC molecules along the rubbing direction for maximum contrast.

Both PI-PSCOF and PSCOF cells were monostable. The PSCOF mode formed at the upper part of the cell was a polymer film and that at the lower part was LC. The cell was sufficiently thick (under 5 µm) such that no bistability was observed as in SSFLC. PI-PSCOF was also similar to PSCOF with additional polymer walls formed in the interpixel region. We applied UV light to the cell with the patterned mask to form a polymer wall in the interpixel region, and subsequently, we performed UV exposure without the mask to form a polymer composite film in the upper part of the cell as in a conventional PSCOF cell. Figure 2(a) shows clearly the phase separations of FLC–polymer regions and near-interpixel regions in bright states. The pixels in PI-PSCOF were rich in FLC with uniform alignment, whereas the interpixels were rich in polymer with a small amount of embedded FLC molecules.

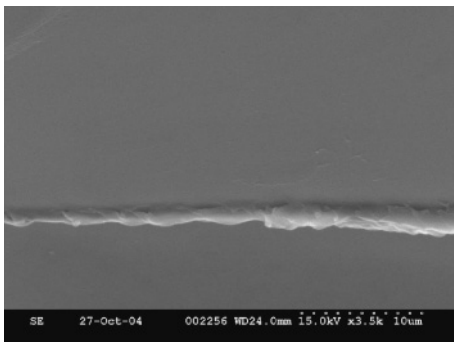
The images of PSCOF and PI-PSCOF obtained by scanning electron microscopy (SEM) are shown in Figs. 3(a) and 3(b). We observed the polymer film on the upper substrate as in the PSCOF mode in Fig. 3(a). In Fig. 3(b), a well-defined vertical polymer wall in the interpixels and a horizontal polymer film on the upper substrate can be observed as in the PI-PSCOF mode. FLC molecules are

(a)

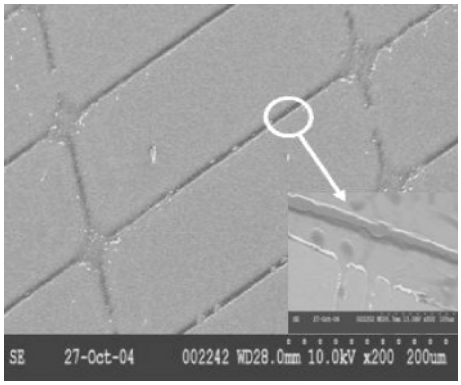


(b)

Fig. 2. Alignment texture of PI-PSCOF cell: (a) normally white, and (b) normally black under polarizing microscope (×40, ×500).



(a)



(b)

Fig. 3. SEM images of (a) PSCOF and (b) PI-PSCOF cells.

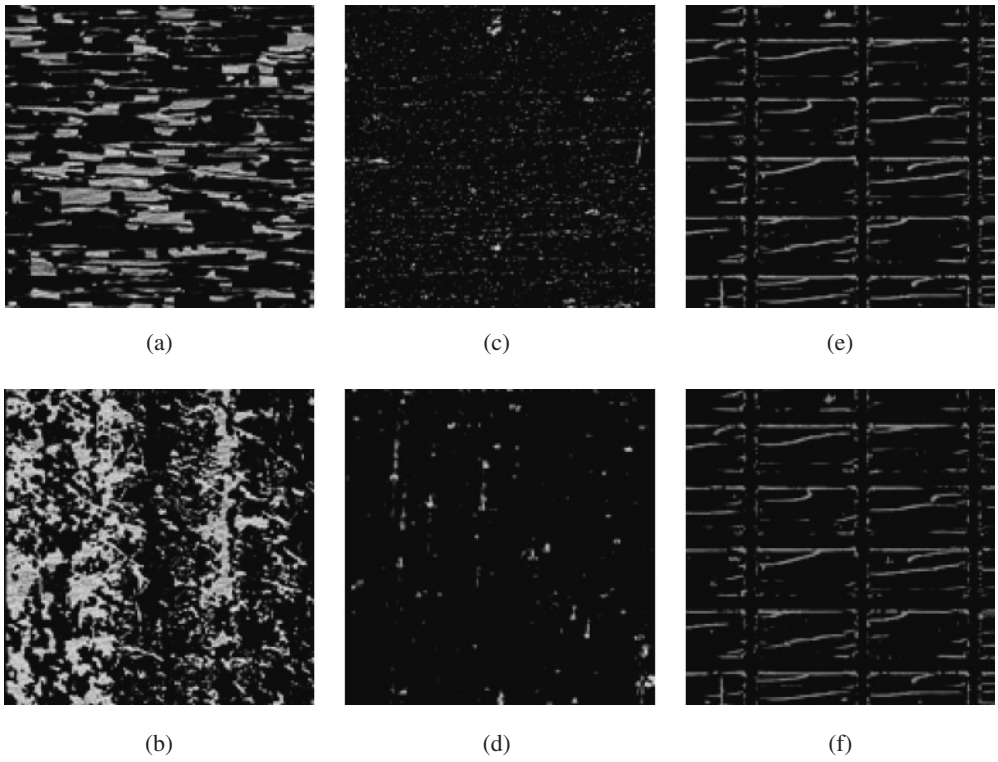


Fig. 4. Mechanical stabilities of FLC modes: (a) pure FLC, (b) pure FLC after external pressure application, (c) PSCOF cell constructed using mixture of Felix-016/100 : NOA65 = 70 : 30, (d) PSCOF after external pressure application, (e) PI-PSCOF cell constructed using mixture of Felix-016/100 : NOA65 = 50 : 50, and (f) PI-PSCOF after external pressure application.

surrounded by polymer walls and isolated into the pixels. Therefore, we confirmed that polymer walls act as supporting structures against external pressures.

We showed the alignment stability of PI-PSCOF against external mechanical shock with a sharp tip. The possible forces pressing the samples were higher than $10\,N/cm^2$. Such mechanical stability has been one of the main bottlenecks for the realization of FLC displays. In Fig. 4, we compared the alignment textures of the pure FLC, PSCOF, and PI-PSCOF on glass substrates by applying external pressures. In a pure FLC [Figs. 4(a) and 4(b)] cell, the texture showed a crucial change, that is, damage due to the reorientation of FLC molecules by mechanical pressure. Furthermore, the texture of the normal FLC was not reversed after removing external pressure due to the broken smectic layers. In PSCOF [Figs. 4(c) and 4(d)] cells, PSCOF alignments were slightly degraded by external shock. When one sees the texture carefully, one can tell the difference in the texture of PSCOF after pressing, as shown in Figs. 4(c) and 4(d). Finally, no appreciable structural changes were observed in PI-PSCOF, as shown in Figs. 4(e) and 4(f). Therefore, we believe that the PI-PSCOF mode exhibits the highest mechanical stability among these three FLC modes. To study the electrooptic properties, the FLC cell was placed between crossed polarizers and illuminated with He–Ne laser light of 633 nm wavelength. Figure 5 and Table I show the electrooptical characteristics of the pure FLC, PSCOF and PI-PSCOF samples. From the dynamic response time of the ferroelectric liquid crystal, the voltage applied to the liquid crystal layer was determined to be a rectangular voltage with a frequency of 60 Hz using a function generator (Stanford Research D340) and a power amplifier (FLC 20A). The response time was the average value of the measured

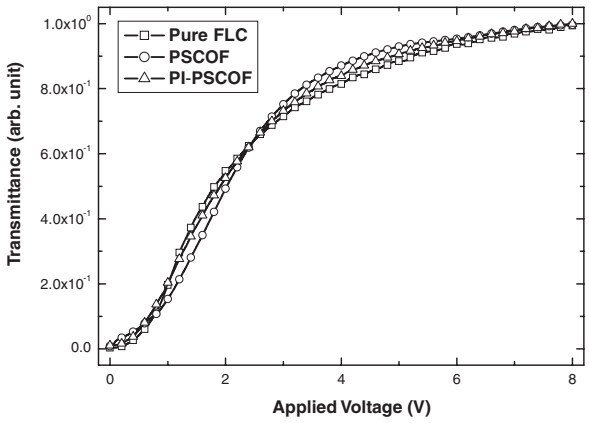


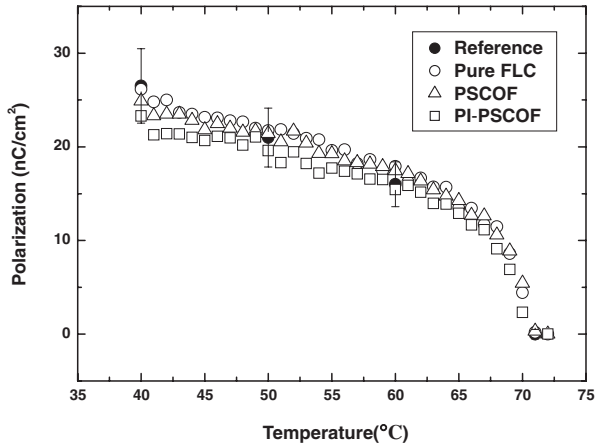
Fig. 5. Transmittances of pure FLC, PSCOF, and PI-PSCOF modes.

Table I. Comparison of electrooptic characteristics of FLC, PSCOF, and PI-PSCOF modes.

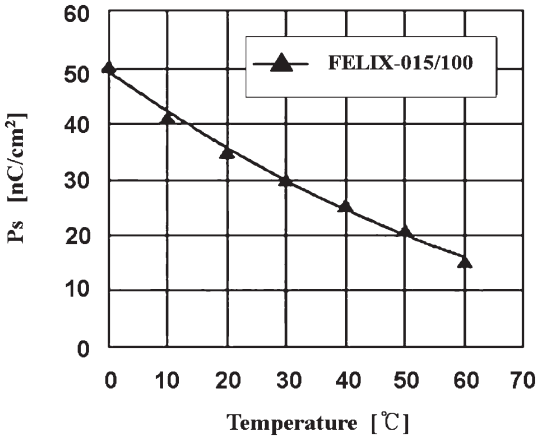
	Pure FLC	PSCOF	PI-PSCOF
Threshold voltage (V)	0.75	0.83	0.8
Saturation voltage (V)	5.5	4.6	5.0
Response time (ms)	0.465	0.378	0.612

rising time (10 to 90% of transmittance) and falling time (90 to 10%). In these three samples, transmittance and threshold voltage were similar, as shown in Fig. 5. The general trend of the V–T curve and the response time were also similar, i.e., they were below 1 ms.

As reported earlier in the literature,[4] the PSCOF mode has advantages over a pure FLC cell with a slightly shorter response time and the polymer-rich region is well separated from the LC-rich region. However, it is considered that the



(a)

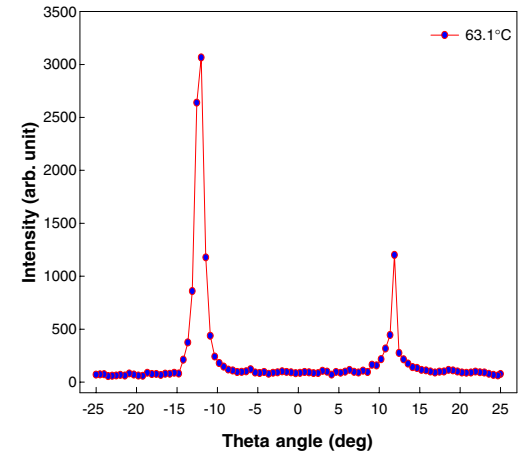


(b)

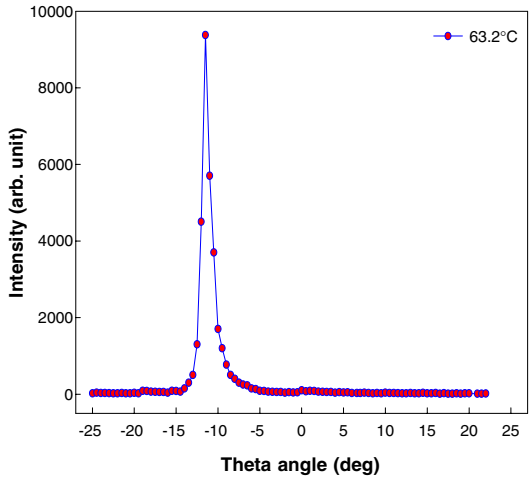
Fig. 6. Spontaneous polarizations of pure FLC, PSCOF, and PI-PSCOF modes. (a) Measured values and (b) references from maker.

FLC molecules near the polymer walls in the PI-PSCOF cell interact with each other and slightly affect the electrooptic properties of the FLC cells. The response time in PI-PSCOF is slightly longer (0.612 ms); However, it is still below 1 ms, probably caused by the polymer-wall-FLC interactions near interpixel areas.

Figure 6(a) shows the measured spontaneous polarizations of the three cells. Figure 6(b) shows reference polarization values from the material maker, and it seems that spontaneous polarization is independent of the polymer structures in the FLC–polymer systems, i.e., the three modes. Therefore, the measured Ps is in good agreement with the reference within a certain experimental error. For further systematic studies on the FLC layer structures in FLC–polymer binary structures, we carried out X-ray scattering experiments. Figure 7(a) shows the X-ray θ-scan of the typical pure FLC chevron structure, with two peaks at symmetric locations at a certain scattering angle. Figure 7(b) shows the obtained theta scan at 63.2 °C using the PSCOF cell constructed using the binary mixture of 70 wt % with the FLC Felix-016/100 and 30 wt % with the prepolymer NOA65. There is only one peak that appears in the theta scan. The strong peak near -12° means that the layer structure of the FLC cell in the PSCOF mode is a very uniform tilted-bookshelf structure. As in the PSCOF mode, the PI-PSCOF cell is a tilted-bookshelf structure with a



(a)



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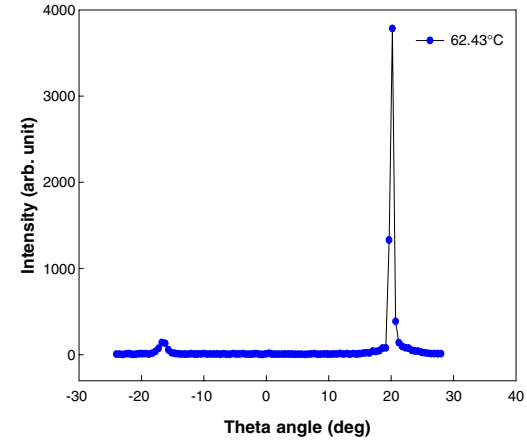

(c)

Fig. 7. (Color online) (a) θ scan of SSFLC cell constructed using pure Felix-016/100 FLC at 63.1 °C. (b) θ scan of PSCOF cell constructed using mixture of Felix-016/100 : NOA65 = 70 : 30 at 63.2 °C. (c) θ scan of PI-PSCOF cell constructed using mixture of Felix-016/100 : NOA65 = 50 : 50 at 62.43 °C.

strong peak position at about 20°. The tilt angle of the bookshelf structure is the same as the layer tilt angle, as shown in Figs. 7(b) and 7(c), because of the compensation of layer buckling. Further detailed X-ray studies of the pure FLC, PSCOF, and PI-PSCOF modes are now in preparation for publication.

We, from these results, learned that FLC molecular layer structures and electrooptical properties in terms of polymer composition can be controlled using the mixing ratio, UV intensity, UV exposure time, environmental temperature, and sample thickness. The new noble display mode we described above, that is, PSCOF-combined PILC mode, turned out to be an excellent promising display mode that, particularly, has potentials in flexible FLC display applications in the near future.

4. Conclusions

We successfully obtained a new PI-PSCOF mode by a noble pixel-isolated phase separation method. In this device, the FLC molecules are isolated in interpixels, where FLCs are surrounded by polymer layers. The PI-PSCOF cell shows an operation voltage below 5 V and a response time below 1 ms. Electrooptic characteristics of the PI-PSCOF mode similar to those of the pure FLC and PSCOF modes. It was also found that the PI-PSCOF mode is a uniform tilted-bookshelf structure by X-ray scattering. However, it is likely that the polymer wall-FLC interactions lead to a slight increase in the response time of the FLC. One of the strong advantages of such devices is that they exhibit very high mechanical stability against external pressures and are feasible and promising display modes. In the near future, we expect that the PI-PSCOF mode will become a new FLC display mode, particularly for the flexible FLC displays. We will further study on its optical characteristics and switching dynamics for fast image performance.

Acknowledgements

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