

Fast-Switching Stratified Polymer-Stabilized Liquid Crystal for Flexible Display Applications

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Abstract: A new liquid-crystal device for flexible display applications was developed using twofold polymerization process. The cell was fabricated from a homogeneous mixture of a liquid crystal and a polymer-forming material. Caused by the spatially nonuniform rate of polymerization and wetting properties, large-scale anisotropic phase separation of the liquid-crystal blend and the polymer precursor leads to a stratified structure of a solidified film of polymer on the UV-illuminated substrate and a nematic liquid-crystal film with an *in-situ* reduction of the cell gap on the alignment layer. A second step of UV exposure from the other direction allows the residual monomer in the liquid crystal to polymerize, forming a typical polymer network-stabilized liquid crystal underneath the hard polymer coating. In comparison with the Paintable liquid-crystal display technology or the pixel-isolated liquid-crystal mode, such a stratified polymer-stabilized liquid crystal requires only a very simple processing procedure for manufacturing and is demonstrated to be fast-switching, exhibiting a response time of the order of 1 ms. This innovation, taking the advantages of a phase-separated composite film as well as a polymer-stabilized liquid crystal, can be applied to flexible display technology with a reasonable mechanical stability.

Keywords: liquid crystals; phase separation; polymer-stabilized liquid crystals; flexible displays.

Introduction

The structured binary material as a composite comprising liquid crystal (LC) and polymer holds great promise for optoelectronic applications in the area of liquid-crystal display (LCD) and flexible information display [1]. By polymerization-induced isotropic or anisotropic phase separation from a homogeneous blend of a LC substance and a polymer precursor, the polymeric material provides mechanical support to the substrate(s), rendering the LC confined in a cell mechanically rugged, as such LC cells fabricated on flexible substrates become possible and even durable. Polymer-dispersed LC (PDLC) films, which are heterogeneous systems consisting of dispersed or continuous LC phases in various matrices, have attracted much attention since their first introduction in the 1980s [2, 3]. In comparison with a PDLC, polymer-network LC (PNLC), containing higher LC content ranging from 70–90 wt.%, requires a relatively lower driving voltage. A polymer-stabilized LC (PSLC), which is also known as a LC gel, contains LC of more than 90% or even 95% by weight and requires lowest operation voltage for display and light-control devices.

Recently, novel innovations involving the formation of controlled structures by means of photopolymerization-induced *anisotropic* phase separation have brought about the realization of *in-situ* reduction of the cell gap via the phase-separated composite film (PSCOF) technique [4–6] as well as the improved stratification and stratified box array of crosslinked polymeric containers filled with a switchable LC phase based on the Paintable technology [7–9]. Most recently, a plastic LCD with the pixel-isolated LC (PILC) mode has been demonstrated [10–13]. In this structure, LC molecules are isolated in pixels defined by interpixel vertical polymer walls and horizontal polymer films on the upper substrate. Moreover, the microstructure can be produced by a stamping method [11].

In this paper, we propose a new concept pertaining to the fabrication of a low-cost LC device by using a two-step photopolymerization process as an alternative to a PSCOF. The fabrication procedure requires no patterned photomask. Instead of a thinned or encapsulated *neat* LC layer in the above-mentioned architectures for flexible display applications, this device allows some residual monomers in the LC layer to polymerize, forming a PSLC or PNLC, referred to as stratified PSLC (SPSLC) or PNLC (SPNLC) in the lower layer covered by a polymeric sheet. The electro-optical characteristics of a SPSLC are compared with that of a typical PSCOF.

Experiment

To fabricate a PSCOF [4] for comparison, we mixed 50 wt.% photopolymerizable monomer NOA65 and 50 wt.% commercial nematic LC mixture E7, which exhibits a positive dielectric anisotropy. By capillary action at a temperature well above the nematic–isotropic phase transition, the blend was introduced into an empty cell consisting of a pair of transparent, electrically conductive glass substrates. Only one of the substrates was spin-coated with a thin film of polyimide as the alignment layer. The cell gap was controlled by $\sim 5.4\text{-}\mu\text{m}$ ball spacers. In order to obtain a smoothly layered structure, phase separation was initiated by shining the cell with a collimated beam of ultraviolet (UV) light through the untreated substrate at a very low UV intensity ($\sim 0.1\text{ mW/cm}^2$). The sample was kept at 90 °C using a hot stage during the 30-min exposure. After photocuring, the cell was cooled to the room temperature slowly. Polarizing optical microscopy and scanning electron microscopy were exploited to characterize the internal configuration, confirming the double-layer structure. Figure 1 shows the schematic of the PSCOF structure and its one-step polymerization process. The production

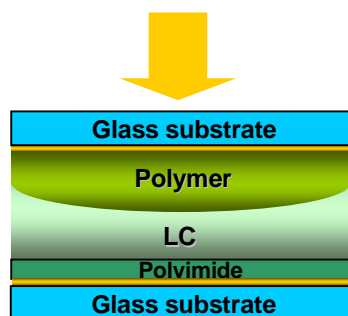


Figure 1. Formation of a phase-separated composite film for liquid crystal displays

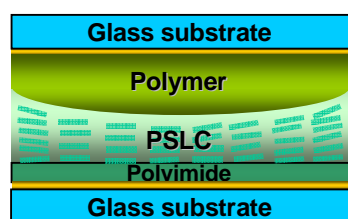


Figure 2. Schematic of the internal structure of a stratified polymer-stabilized liquid crystal

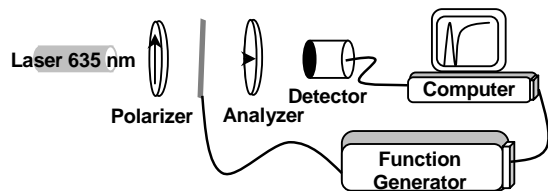


Figure 3. Setup of electro-optical measurement

of our SPSLC, which requires an extra UV exposure at a higher intensity of 3 mW/cm^2 on the other side of the sample for 30 min at the room temperature, is depicted in Fig. 2. Note that the second step was performed one day after the completion of the first UV exposure to promote the alignment of polymeric fibrils along the planar-aligned LC directors.

Results

In order to understand the electro-optical properties of a LC device with the SPSLC structure, a typical setup was constructed, enabling one to acquire the transmittance as a function of the ac voltage and to obtain the associated response curve (see Fig. 3). The voltage was in the form of a square wave at 1 kHz.

Comparisons of the electro-optical (EO) characteristics between a $5.4\text{-}\mu\text{m}$ SPSLC with a $2.7\text{-}\mu\text{m}$ -thick PSLC layer and a $5.4\text{-}\mu\text{m}$ PSCOF device with a LC thickness of $2.7 \text{ }\mu\text{m}$ are illustrated in Figs. 4 (for the turn-on response)

and 5 (for the turn-off response). The rise time τ_{on} and decay time τ_{off} were measured for 90% change in total transmission as the electric field was applied and removed, respectively. The total switching time τ , defined as the sum of the rise and decay times ($\tau_{\text{on}} + \tau_{\text{off}}$), is 3–4 ms, depending on the external voltage applied. It is clear from the figures that the EO performance of the SPSLC in terms of the response speed is superior to that of the PSCOF counterpart. The obvious drawback of a SPSLC, however, is its relatively lower contrast ratio as indicated by the numerical values in Figs. 4 and 5. It is worth mentioning that, due to the diameter of ball spacers to be $\sim 5.4\text{ }\mu\text{m}$ used in this study, the thickness of the (PS)LC layer formed via phase separation was still too thick for the wavelength of 635 nm of the diode-laser probe beam to exhibit a submillisecond response. In accordance with the parameters of the nematic LC E7, a planar-aligned LC layer of $\sim 1.5 \text{ }\mu\text{m}$ in thickness, which gives a maximal phase retardation [14] of $\sim \pi$, can function as a half-wave plate. In addition, the driving voltage could be further lowered for a SPSLC or PSCOF cell with a thinner polymeric layer. Because of the restriction on the reduction of thickness of the LC layer with a clear boundary with polymer, ball spacers with smaller diameters are needed if one wants to demonstrate faster switching of the SPSLC device with a lower operation voltage.

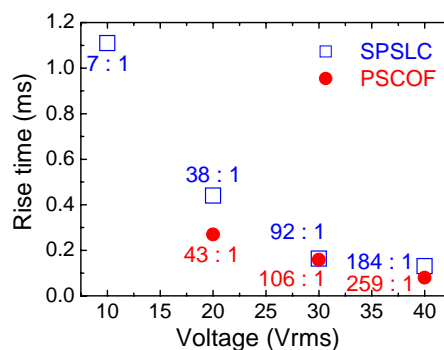


Figure 4. Rise time as a function of voltage

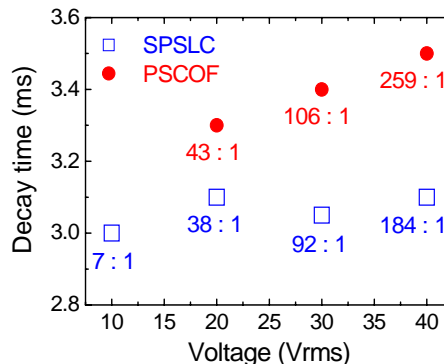


Figure 5. Voltage-dependent decay time

Conclusion

In summary, we have demonstrated that nematic LC cells prepared with two-step photopolymerization-induced phase separation of LC and polymer can easily attain a polymer-PSLC bilayer structure, taking advantages of a PSCOF as well as a PSLC. The photoinduced phase separation method allows one to fine-tune the LC film thickness and the polymer content in the LC bulk. Our preliminary results imply that a low-cost SPSLC or SPNLC device as an alternative to a PSCOF counterpart can be realized for applications in flexible display or in fast-response LC devices such as televisions and videos. Experimental details including the materials, sample preparation and characterization and further experimental results will be published elsewhere [15].

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