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Submillisecond switching of nematic liquid crystal in cells fabricated by anisotropic phase-separation of liquid crystal and polymer mixture

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Liquid crystal (LC) cells consisting of a very thin (submicrometer) nematic LC layer switch with time response smaller than 1 ms. The total response time, i.e., sum of the *turn-on* and *turn-off* times, can be made as small as 1.3 ms. Such devices were prepared by a photoinduced anisotropic phase separation of mixtures of the LC and prepolymer. The formation of the LC–polymer bilayer in these devices was confirmed by polarized light microscopy and scanning electron microscopy. The phase separation method permits one to fine-tune the LC film thickness by varying the LC concentration in the mixture. This technique can be used to fabricate fast LC devices for TV and video applications. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1861120]

Nematic liquid crystal (LC) displays are widely used in portable information devices and monitors for laptop and desktop computers due to their low power consumption, light weight, good gray levels capability, and low driving voltages. However, the response time of nematic liquid crystal displays (LCDs) is still not sufficiently fast for TV and video applications where fast moving objects and images are more common. The nematic LC materials used in these devices have slow response time from one gray level to another. This so called *gray-to-gray* (GTG) response results in smearing and blurring for rapidly moving video images.[1,2]

The response time of nematic LCD is determined by the physical properties of the LC material, cell configuration, and applied field.[3] By using the most advanced nematic LC materials, the response time from *on* to *off* state of nematic LCDs has been improved to around 16.7 ms, a single refresh cycle duration (for 60 Hz frame rate).[4] However, a recent report shows that a response time of 0.3 ms is needed for a 256 gray level display in order to completely remove the blurring of fast-moving objects.[5] By employing a fast display mode, known as optically compensated bend (OCB)[6] mode, the response time can be lowered to ~ 5–10 ms. However, OCB cells need a long transition time from the initial splay state to the operating bend state. Overdrive methods[7] employ a much higher voltage to achieve faster GTG response time. It requires more complicated driving schemes accompanied by higher manufacturing costs. Xiang *et al.* reported a three-electrode structure[8] to produce two directional electric fields alternately to obtain fast turn-on and turn-off times. However, the introduction of a third electrode (to provide lateral electric field) also adds to the manufacturing cost and lowers brightness due to the smaller aperture ratios.

For a homogeneous aligned Fredericks cell, the response times, both τ_{on} and τ_{off}, are directly proportional to d^2 (d is the LC film thickness)[3]

$$\tau_{\text{on}} = \frac{\eta_1 d^2}{\pi^2 k_{11}} \left(\frac{\Delta \varepsilon}{\pi^2 k_{11}} V^2 - 1 \right)^{-1}, \quad \tau_{\text{off}} = \eta_1 d^2 / \pi^2 K_{11}.$$

Here, the times τ_{on} and τ_{off} measure the switching speed when the electric field is applied (the *on* state) and after its removal to let the system relax back to its ground (or, *off*)

state. For a 5 μm thick cell filled with a typical nematic LC having the viscosity coefficient $\eta_1 \sim 0.1$ kg m^2 s, the splay elastic constant $K_{11} \sim 10^{-11}$ N, then $\tau_{\text{off}} \approx 25$ ms. If the LC layer thickness can be reduced to $\leqslant 1$ μm, then the relaxation time should become ~ 1 ms or faster. However, the fabrication of uniform cells less than 1 μm has so far remained a big challenge.

Recently, Vorflusev and Kumar developed a new method to fabricate cells containing bilayer structures of LC and polymer by anisotropic phase-separation of a mixture of LC and prepolymer.[9] This phase-separated composite films (PSCOF) method, provides a simple approach to prepare thin LC films without requiring spacers of that size. Here, we demonstrate that cells containing very thin nematic LC film (< 1 μm) can be prepared by the PSCOF method and that they undergo very fast switching with total response time (τ_{on} plus τ_{off}) of less than 1.3 ms.

We used nematic LC E7 (E-Merck) and a photocurable monomer NOA65 (Norland Products). The monomer and LC materials were mixed in ratios ranging from 25:75 to 75:25 by weight. The empty cells were constructed with glass substrates coated with transparent electrodes of indium-tin-oxide. Only one of the substrates was spin-coated with a thin film of polyimide (PI), RN1286 (Nissan Chemical Ltd.). After the hard-bake, the PI film was rubbed with a velvet cloth to induce LC alignment. The cell gap was maintained with 3-μm-diameter glass fiber spacers. The LC+monomer mixture was filled into empty cells by capillary action at a temperature well above the nematic–isotropic transition. Phase-separation was initiated by exposing the cells to a collimated beam of UV light through the untreated substrate at a very low level (~ 0.1 mW/cm^2) of UV intensity in order to obtain smooth polymer layer structure.[10,11] The sample temperature was kept at 90 °C using a Mettler FP-82HT hot stage during the 20 min exposure. After completion of the phase-separation, the cells were cooled to room temperature.

Polarized light microscope (PLM) and scanning electron microscope (SEM) were employed to characterize the internal polymer structure obtained. Under the PLM with crossed polarizers, the alternating bright and darks states observed during rotation of the cell confirmed uniform and homogeneously LC alignment (Fig. 1) along the rubbing direction of the PI layer. This revealed that the LC layer was formed next to and in contact with the PI alignment layer. Several cells

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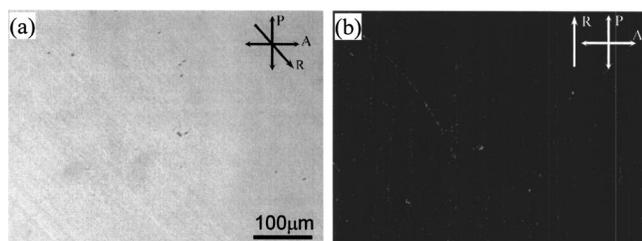
FIG. 1. A PSCOF cell under an optical microscope with crossed polarizers, LC molecules are homogeneously aligned along the rubbing direction **R**. (a) Bright state: **R** is at 45° to the fast axis (**P**) of the polarizer; (b) dark state: **R** is parallel to **P**.

were opened and washed with hexane to remove the LC for SEM studies. After depositing a thin (~50 Å) layer of gold, the substrates were placed into the vacuum chamber of the SEM. The polymer layer was found to form on the untreated substrates, which was closer to the UV source. The PLM and SEM results established the formation of parallel layers of LC and polymer in these cells.

The mechanism responsible for the formation of PSCOF structure is the anisotropic phase-separation, i.e., spatially nonuniform polymerization[12] of monomers. This is due to an intensity gradient along the cell normal caused by strong absorption of UV by LC molecules at wavelengths near 350 nm.[11] The polymerization for the NOA-65 monomers near the substrate close to the UV source proceeds faster, depleting the monomer concentration. Consequently, more monomers diffuse to this region to equalize their concentration. The LC molecules, expelled from the polymerized volume, move toward the second substrate [Fig. 2(a)] eventually resulting in a complete phase separation of the mixture. This yields adjacent and uniform layers of the LC and polymer parallel to the substrate [Fig. 2(b)].

Three cells, with 25, 50, and 75 wt % of the monomer NOA-65, were prepared using 3 μm spacers under the same polymerization conditions. The SEM pictures [Figs. 3(a)–3(c)] show that a uniform polymer layer was formed and that its thickness monotonically increased with the concentration of NOA65. The SEM results show that the PSCOF method provides an exceptionally easy control of the device's optical path length through the concentration of the mixture. This is a great advantage in preparing very thin and uniform cells, using much larger spacers, to achieve fast response times.

Optical transmittance of two PSCOF cells with 50% and 35% LC loading measured as a function of the applied electric field is shown in Fig. 4. The light source was a He–Ne laser ($\lambda_0 = 633$ nm) and the sample was placed between a

FIG. 3. SEM pictures of polymer layers formed in PSCOF cells. The polymer content was (a) 25 wt %, (b) 50 wt %, and (c) 75 wt %. The thickness of the polymer film monotonically increased from ~0.8 to ~2.6 μm as the polymer content increases.
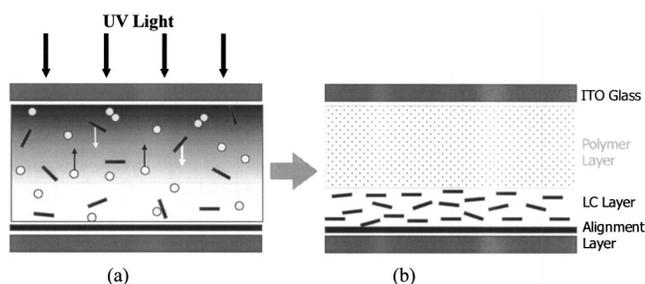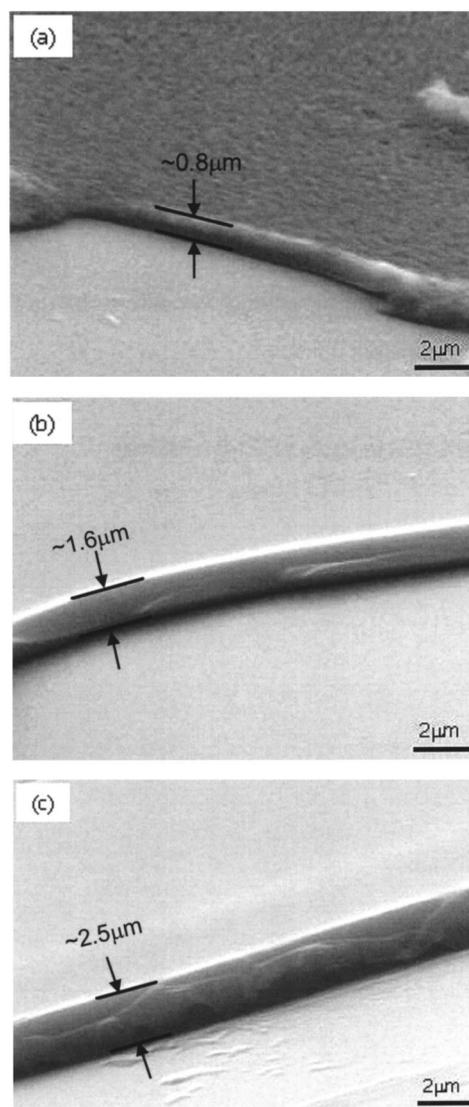

FIG. 2. Schematic diagram for the formation of PSCOF structure. (a) Diffusion of small molecules caused by nonuniform polymerization. (b) The bilayer structure of a PSCOF cell after phase-separation.

pair of crossed polarizers with the cell's rubbing direction at 45° to the fast axis of the polarizer. The transmission versus voltage characteristics show a good gray scale capability. The driving voltages were ~15 V for the cell with 50% LC and ~20 V for 35% LC cell. These voltages are much higher than needed for a regular LC cell, i.e., without polymer, which typically require less than 5 V. This increase is due to the presence of the polymer layer inside these devices with smaller dielectric constant ($\varepsilon_p = ~4$ for NOA65) than that of the LC (E7: $\varepsilon_\parallel = 5.2$, $\varepsilon_\perp = 19.0$ at 1 kHz) causing most of the voltage drop to appear across the polymer layer. This effect becomes more serious as LC molecules reorient toward homeotropic orientation and the effective dielectric constant of the LC increases. However, it should be possible to reduce the driving voltage to $\leqslant$10 V by selecting a polymer with high ε_p.

Transmission in the *off* state of the cell with 35% LC is much lower than the cell with 50% LC. Net light transmission ($T_\perp$) through a homogeneous cell between crossed polarizers, with fast axis oriented at 45° to the alignment direc-

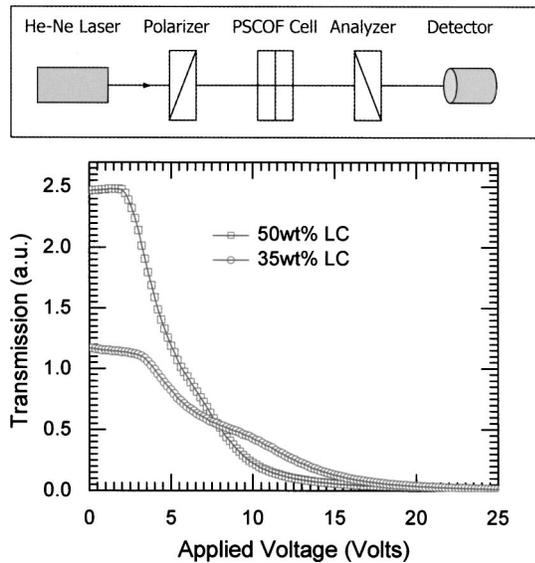FIG. 4. Experimental setup to measure the transmission as a function of applied voltage and the results for cells with the 35 wt % and 50 wt % LC.

FIG. 6. The optical transmission vs time (channel 1) under a 50 ms rectangular-wave pulse (channel 2) with amplitude of (a) 15 V, and (b) 20 V for cells with 50 wt % and 35 wt % LC.

tion, is determined by its optical retardation Δnd_{LC} and can be written[3] as

$$T_\perp = I_0 \sin^2\left(\pi \frac{\Delta nd_{LC}}{\lambda_0}\right).$$

Here, I_0 is the intensity transmitted by the polarizer, d_{LC} is the LC layer thickness, and Δn is the birefringence ($\Delta n = 0.225$ for E7). For the cell with 35% LC, the LC layer is so thin that the total retardation in the field-off state is much smaller than $\lambda_0/2$, required for the first maximum transmission. Hence, a high birefringence LC material ($\Delta n > 0.35$) is needed to achieve high transmission in the *off* state. A sectional SEM view of this cell in Fig. 5 shows a uniform gap of 0.9 μm.

Fast switching in cells with 50% and 35% LC was recorded with an oscilloscope, Fig. 6. The amplitudes of the applied rectangular wave were 15 and 20 V, which were the saturation voltages for the two cells, respectively. The times τ_{on} and τ_{off} were measured for 90% change in total transmission as the electric field was applied/removed. For the 50%

LC cell, the total switching time ($\tau_{on} + \tau_{off}$) is $\sim$3 ms with $\tau_{on} = 0.37$ ms and $\tau_{off} = 2.59$ ms. In comparison, the thickness of the LC layer is even thinner in the cell with 35% LC. Switching speed for this cell is even faster, with ($\tau_{on} + \tau_{off}$) $\sim$1.3 ms and individual times in the submillisecond range; ($\tau_{on} = 0.301$ ms and $\tau_{off} = 0.995$ ms). The total switching time of a PSCOF cell can be reduced even further by lowering the LC concentration to make the LC layer thinner. However, if the LC layer is thinner than 1 μm, the total optical retardation becomes too low for optimum transmittance for E7.

To conclude, we have demonstrated that nematic LC cells prepared with anisotropic phase-separation of LC and polymer can switch at *submillisecond* speeds. The bi-layer structure of PSCOF cells provides us with the ability to precisely fine-tune the LC layer thickness and, thereby, the total optical retardation without actually using small spacers. This method will prove to be extremely valuable for TV and video applications, where fast response times are essential. Our future work will focus on selecting a new photocurable prepolymer with high dielectric constant and a LC material with $\Delta n > 0.35$, to optimize the device performance.
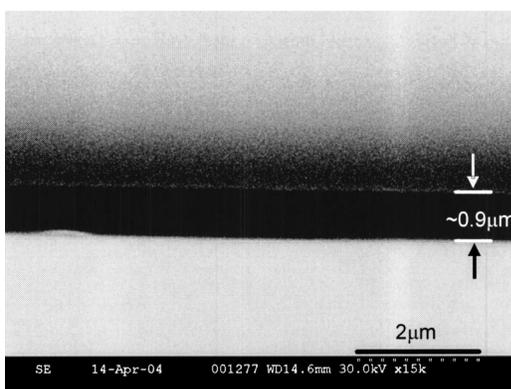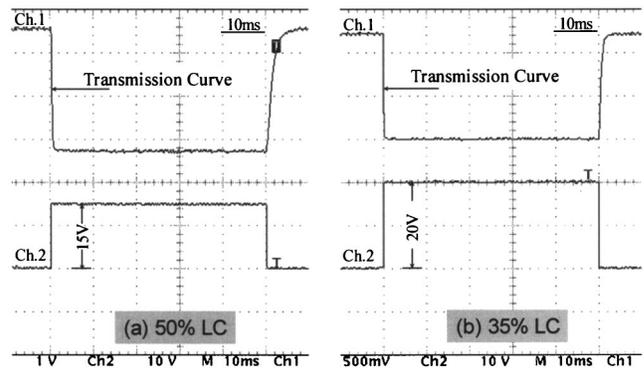
FIG. 5. Sectional SEM view of a PSCOF cell with 35 wt % LC shows a uniform gap of 0.9 μm formed between the polymer layer (bottom) and the substrate with rubbed PI film (top).

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