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Enhancement of electro-optic stability in the vertical configuration of a deformed-helix ferroelectric liquid crystal

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Abstract

We propose a reliable vertical configuration of a deformed-helix ferroelectric liquid crystal (DHFLC) mode in a transverse electrode structure by introducing reactive mesogens (RMs) into the DHFLC material. Polymerized RMs remember the direction of the DHFLC molecules in the absence of an applied voltage and suppress the bending and breaking of the smectic layer under a strong electric field. In this DHFLC mode with polymerized RMs, reliable switching characteristics are obtained in the vertical configuration.

(Some figures may appear in colour only in the online journal)

1. Introduction

Liquid crystal displays (LCDs) with fast response times have attracted considerable interest for a long time to enhance the dynamic image quality, apply to field-sequential LCDs with a high optical throughput [1, 2] and three-dimensional displays with shutter glasses [3, 4]. In most nematic-based LCDs, however, the response time is still insufficient for realizing an excellent dynamic image. Ferroelectric LCs (FLCs) with a spontaneous polarization show intrinsically fast response characteristics due to large electric field coupling [5–10]. In spite of the fast response feature of FLCs, the achievement of a stable and uniform alignment in a large area remains a challenge for display applications [5–7]. To obtain a uniform alignment in FLCs, the vertical configuration of a deformed-helix FLC (DHFLC) was proposed in a transverse electrode structure [8–10]. In the configuration of vertical alignment of the DHFLC, the helix is perpendicular to the substrates. In this situation, the average optic axis is parallel to the helix and thus a completely dark state is easily obtained since the helical pitch of the DHFLC is shorter than the wavelength of visible light. Also, two domains were achieved due to the polarity of the electric field in the in-plane electrode without any process for multi-domain. However, this led to the bending of a smectic (Sm) layer near the electrode edges due to a strong vertical

electric field [11]. The Sm layer broke under a strong applied electric field and remained unrecovered in the absence of the applied field. This unrecovered broken layer produces light leakage at a dark state.

In this work, we propose a reliable DHFLC mode in the vertical configuration that protects against the Sm layer breaking, by introducing reactive mesogens (RMs) into the DHFLC material. The RM monomers are polymerized by ultra-violet (UV) exposure at the FLC phase. The polymerized RMs remember the direction of the FLC molecules in the absence of an applied voltage. In this situation, the layer bending and breaking are suppressed by the polymerized RMs under the strong electric field, and the Sm layer is kept parallel to the two sandwiched substrates. In the DHFLC mode with the polymerized RMs in the vertical configuration proposed here, reliable switching characteristics including response time are obtained.

2. Experimental

The DHFLC sample with polymerized RMs was made using glass substrates, only one of which was sputtered with indium tin oxide (ITO). Inter-digital electrodes of width 10 μm , separated by 15 μm , were patterned on the ITO-sputtered

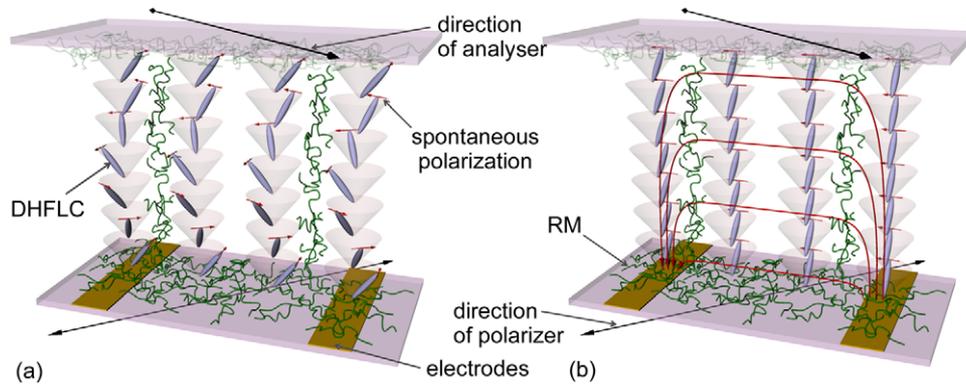


Figure 1. Schematic diagram of the vertical configuration of DHFLC structure with the polymerized RMs (a) in the absence of an applied voltage and (b) in the presence of an applied voltage. The ellipses and the red arrows on the ellipses represent the liquid crystals and the dipoles showing a helical structure confined on cones, respectively.

substrate to produce a transverse electric field. A polyimide layer of AL1H695 (Japan Synthetic Rubber Co.) was coated on two substrates to promote a homeotropic alignment. Note that no rubbing process was carried out. The cell gap was maintained at $4\ \mu\text{m}$ using glass spacers, which were dispersed in an optically curable adhesive epoxy (NOA 61, Norland Inc.).

The FLC material used here was KC-FLC3 (Kingstone Chemicals Ltd). The phase transition sequence of the KC-FLC3 is as follows: isotropic \rightarrow (115°C) \rightarrow N^* \rightarrow (96.5°C) \rightarrow $Sm\ A$ \rightarrow (82.0°C) \rightarrow $Sm\ C^*$. The spontaneous polarization and the molecular tilt angle are $P_s = 23\ \text{nC cm}^{-2}$ and $\theta_t = 22^\circ$, respectively. To reduce the helical pitch to shorter than the wavelength of visible light ($\leq 0.2\ \mu\text{m}$) and stabilize the Sm layer, DHFLC material with a short pitch was prepared with a mixture of KC-FLC3 (95 wt%), a chiral dopant (4 wt%) and the RM (RM257, 1 wt%). The DHFLC mixture with the RM was introduced into the sandwiched substrates by capillary action at the isotropic phase of the DHFLC mixture (about 180°C). The polymer-stabilized DHFLC sample was obtained by UV exposure ($0.027\ \text{mW cm}^{-2}$ at $365\ \text{nm}$) of the DHFLC mixture for 4 h at about 60°C ($Sm\ C^*$ phase). The electro-optic (EO) switching behaviour was observed using a polarizing optical microscope (Nikon E600W POL) with a frame-grabbing system (Samsung SDC-450) and an arbitrary function generator (Stanford Research System DS345). The EO transmittance was measured using a He-Ne laser ($633\ \text{nm}$), a digitized oscilloscope (Tektronix TDS745D) and a photodetector. The direction of the striped electrodes was rotated 45° from one of the two crossed polarizers. The polymerized structures were observed using a field-emissive scanning electron microscope (FESEM; Hitachi S-4800) after washing off the FLC with hexane for about 2 h. All measurements were carried out at room temperature.

3. Results and discussion

Figure 1 shows the structure and operating principle of the DHFLC sample with polymerized RMs in the vertical configuration. Here, the ellipses confined on the Sm cones and the arrows around the ellipses represent the DHFLC molecules and the dipole moments, respectively. In the vertical

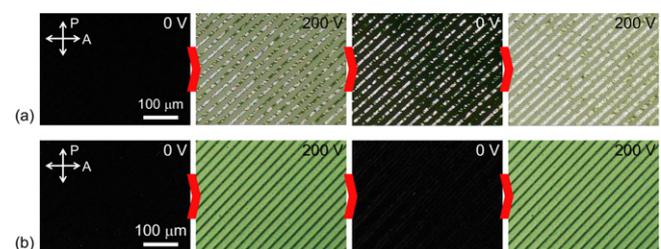


Figure 2. Microscopic textures of (a) the conventional DHFLC cell without the polymerized RMs and (b) the proposed DHFLC cell with the polymerized RMs under crossed polarizers. The applied voltage was repeatedly switched between 0 and 200 V in both cells.

configuration of the DHFLC cell, since the Sm layers are parallel to the substrates and the pitch of the DHFLC is shorter than the wavelength of visible light, a completely dark state is obtained under no applied field, as shown in figure 1(a) [8–11]. In the presence of an applied field, the helix of the DHFLC is unwound on the Sm cone and the dipole moments are aligned parallel to the electric field, as shown in figure 1(b). In the conventional DHFLC sample without the polymerized RMs, the strong vertical field near the electrode edges gives rise to the breaking of the Sm layers and thus unrecoverable defects are observed. In the DHFLC sample with polymerized RMs, however, no defect is observed under the applied field since the polymerized RMs enhance the Sm layer's robustness against the strong vertical field.

Figure 2 shows the polarizing optical microscopic images of the conventional DHFLC without the polymerized RMs and the proposed DHFLC samples with the polymerized RMs for switching under an applied voltage. In principle, the incident light cannot resolve the helical structure of the DHFLC because its pitch is shorter than the wavelength of visible light. In the vertical configuration, the Sm layers are parallel to the substrates and thus the average optic axis is normal to the substrates. As a result, both DHFLC modes look like a vertically aligned nematic LC (NLC) mode, and show a completely dark state in the absence of an applied voltage [8–11]. In the conventional DHFLC sample without the polymerized RMs, defects were observed near the electrode edges under an applied voltage of 200 V, and

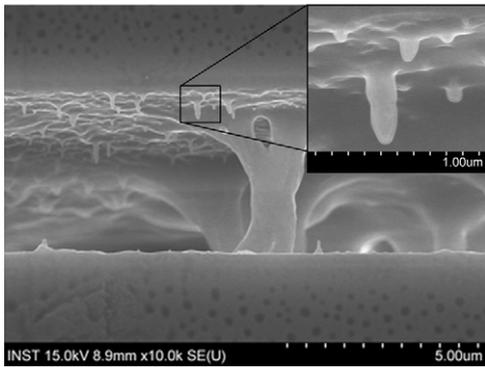


Figure 3. FESEM images of the polymerized RMs in the proposed DHFLC cell observed across the cell.

they were not eliminated even though the applied voltage was removed, as shown in figure 2(a). Also, transmittances at the same applied voltages were significantly changed during the repeated switching voltage due to the defects. These defects originated from the breaking of the Sm layers due to the strong vertical field near the electrode edges, and they were eliminated after heating up to an isotropic phase and cooling down [11, 12]. In the proposed DHFLC sample with the polymerized RMs, however, no defect was observed at 200 V, and a good dark state was obtained after removing the applied voltage, as shown in figure 2(b). The polymerized RMs remember the direction of the DHFLC molecules in the absence of the applied voltage and enhance the Sm layer’s robustness against the strong vertical field. These functions of the polymerized RMs were widely observed in NLC systems [13–17]. As a result, reliable EO characteristics were obtained against breaking of the Sm layers.

The FESEM image of the polymerized RMs in the proposed DHFLC sample is shown in figure 3. The stalactiform protrusions of the polymerized RMs are observed from the cross-section of the cell. Various dimensions of the stalactiform protrusions were observed, ranging from tens of nanometres to a few hundred nanometres, which might have originated from the high viscosity of the DHFLC material. Because of the high viscous DHFLC, it is difficult for the RM monomers to be in a well-mixed state. The large protrusions of a few hundred nanometres give rise to light scattering and thus slightly degrade the EO properties of the DHFLC mode with the polymerized RMs.

Figure 4 shows the EO transmittances of the conventional DHFLC cell without the polymerized RMs and the proposed DHFLC one with the polymerized RMs during repeated switching of the applied voltage (200 V). The bright state of the DHFLC with the polymerized RMs is lower than that of the conventional DHFLC without the polymerized RMs, since an effective voltage applied to the DHFLC layer is reduced due to the polymerized RM structure and the large protrusions scatter the incident light. In the conventional DHFLC without the polymerized RMs, however, the brightness was varied and the dark level gradually increased with the repeated switching of the applied voltage since the defects near the electrode edges were unrecovered at 0 V and expanded by the repeated switching. On the other hand, the bright state and dark level

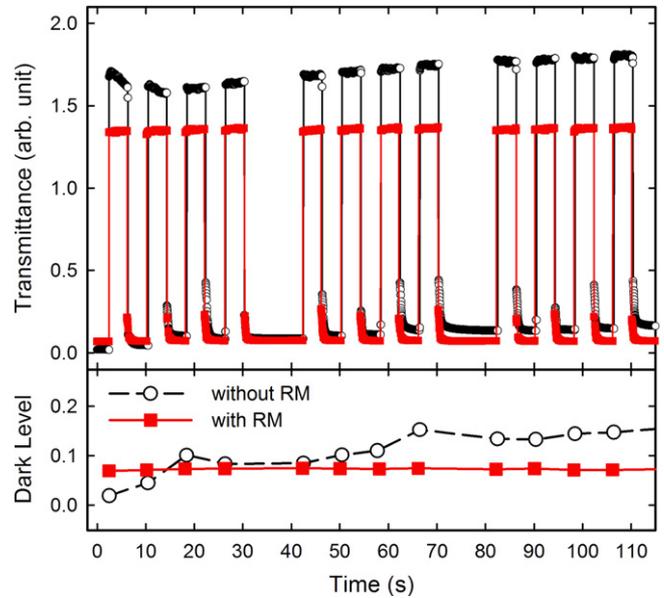


Figure 4. Transmittances and dark levels of the conventional DHFLC cell without the polymerized RMs (open circles) and the proposed DHFLC one with the polymerized RMs (filled squares) during repeated switching of the applied voltage.

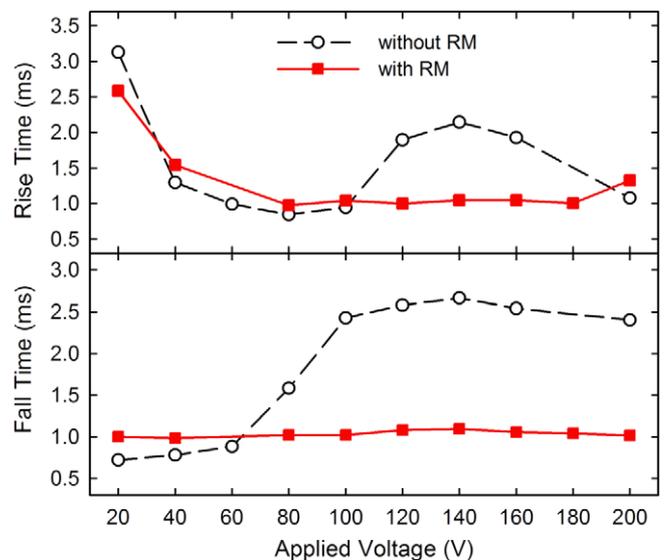


Figure 5. Rise and fall times of the conventional DHFLC cell without the polymerized RMs (open circles) and the proposed DHFLC one with the polymerized RMs (filled squares) as a function of the applied voltage.

in the DHFLC with the polymerized RMs were consistently maintained irrespective of the repeated switching, and thus reliable switching characteristics were obtained by introducing the polymerized RM structure.

Figure 5 shows the EO response times of the conventional DHFLC cell without the polymerized RMs and the proposed DHFLC one with the polymerized RMs as a function of the applied voltage. In general, the rise time is gradually decreased with an increase in the applied voltage. In the conventional DHFLC cell without the polymerized RMs, however, the rise time abnormally increased in the range from 80 to 160 V. Similarly, in the fall time, an abnormal response time was

observed from 80 V. These abnormal response times could be attributed to the defects originated from the Sm layer breaking. The breaking of the Sm layer is considered to appear at about 80 V. For the electrode interval of 15 μm , the electric field breaking the Sm layer in the in-plane electrode was calculated to be about 5.3 $\text{V}\mu\text{m}^{-1}$ which matched with the order of magnitude of the breaking electric field in the previous work [11]. Specifically, a slow fall time was observed after the breaking of the Sm layer, since the defects cause a decrease in the restoring force in the relaxation process. In the DHFLC cell with the polymerized RMs, the rise time was gradually decreased with increasing applied voltage, like normal EO behaviour. The fall time in the DHFLC with the polymerized RMs was consistently maintained, irrespective of the applied voltage. The polymerized RMs enhanced the Sm layer stability against a strong vertical field, suppressed the layer breaking, and thus realized reliable switching characteristics in the DHFLC mode in the vertical configuration.

4. Conclusion

We demonstrated a reliable DHFLC mode in the vertical configuration with Sm layer stability against a strong vertical field by introducing a polymerized RM structure. To generate the polymer structure, the DHFLC mixture with RM monomers was exposed to UV light at the ferroelectric liquid crystalline phase. The polymerized RMs remembered the direction of the DHFLC molecules in the absence of the applied voltage and suppressed the Sm layer breaking under a strong electric field. From the polarizing optical microscopic observation, reliable switching characteristics without defects were confirmed during repeated switching of the applied voltage. Also, from the EO measurements, a stable dynamic response was obtained in the DHFLC mode in the vertical configuration proposed here.

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