Flexible LCDs with Columnar Spacers for Fast Response and Wideviewing

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Abstract

We report on a high speed flexible display based on a deformed helix ferroelectric liquid crystal (DHFLC) in a vertically aligned configuration. The mechanical stability of the flexible DHFLC display was achieved using a periodic array of columnar spacers formed directly on the top sides of in-plane electrodes by the photolithography technique. Several unique features of display performances such as flexibility, uniform alignment, fast response, and gray scale capability were obtained.

1. Introduction

Flexible displays have several important features of light-weight, thinner packing, bending capability, and portability. These features are suitable for many applications such as a wearable display, a smart card, a personal information assistant, and an electronic book. Especially, a flexible display based on a liquid crystal (LC) has been extensively studied and widely used because of low power consumption.

For flexible LC displays, the mechanical stability and the uniform cell gap between two plastic substrates are critical factors of retaining the long-term LC alignment against external perturbations such as pressure, a bending distortion, and a mechanical shock. Recently, a variety of the LC-based [1-9] with polymer walls, polymer networks, or structured spacers on flexible plastic substrates have been investigated. In the case of the FLCs with polymer walls and/or networks [1,2] the residual polymers cause to significantly increase the operation voltage and to reduce the electro-optic (EO) modulation. Moreover, the polymer walls and/or networks do not fully guarantee the uniform alignment of the FLC molecules in large area against a mechanical bending force. Due to such problems, an anisotropic phase separation of a nematic LC[3] was suggested although the fast response was sacrificed. In the case of structured spacers on a substrate[4,5], the EO performances are deteriorated by the spacers formed in optically active areas since the LC distortions are inevitable occurred around the spacers. Therefore, a new type of a flexible LCD having the uniform cell gap, the mechanical stability, and excellent EO characteristics is needed for practical applications.

In this work, we propose a high speed flexible display based on a deformed helix ferroelectric liquid crystal (DHFLC) in a vertically aligned (VA) configuration[10] with a periodic array of columnar spacers on top sides of in-plane electrodes. This VA-DHFLC allows for the uniform alignment of both the FLC molecules and the smectic (Sm) layers in large

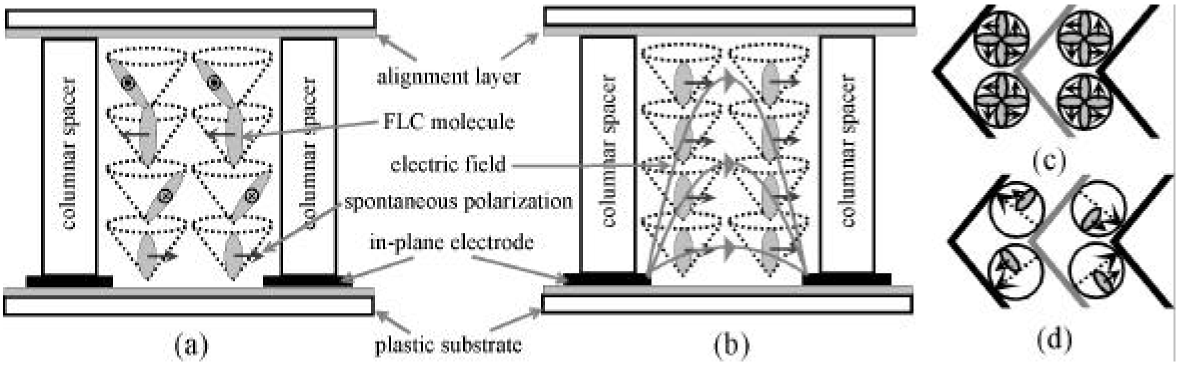

Figure 1. The schematic diagrams and the operation principle of our flexible VA-DHFLC cell. The solid arrows and dotted arrows in (c) and (d) represent the spontaneous polarization and an applied electric field, respectively. (a) and (c) under no electric field; (b) and (d) under and applied electric field.

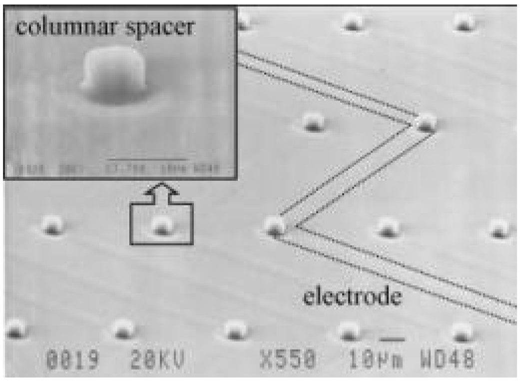

Figure 2. The SEM image of columnar spacers arrayed regularly on in-plane electrodes. The in-plane electrodes are 8.8 µm wide and 26.5 µm long. The columnar spacers, one of which magnified in the inset, are 8.0 µm thick and 5.5 µm high on average.

area without employing any additional alignment process. Particularly, the alignment of smectic layers is extremely stable against an external bending force, compared to conventional planar FLC cases, so that the analog gray scales are well preserved by using a periodic array of columnar spacers formed directly on in-plane electrode regions.

2. Operation Principle

The driving scheme of our VA-DHFLC cell is provided by in-plane electrodes. Figure 1 shows the schematic diagram and the operation principle of our flexible VA-DHFLC cell. Arrows shown in Fig. 1(a)-1(d) represent the polarization direction when the FLC molecules rotate on the smectic C* cone.

In the absence of an applied electric field, the average optic axis is perpendicular to the substrate because the helical pitch of the FLC is short (≤ 0.2 µm) compared to the wavelength of visible light. This initial state in Fig. 1 (a) and 1 (c) corresponds exactly to a vertically aligned nematic structure, and therefore complete extinction is obtained under crossed polarizers.

When an electric field is applied to our flexible VA-DHFLC, the molecules rotate on the Sm C* cone and the helix becomes deformed. As a consequence, the average optic axis of the VA-DHFLC cell becomes continuously tilted away from the surface normal and reaches the maximum value of the Sm C* tilt angle as the electric field increases. Therefore, under crossed polarizers, the transmitted intensity through the cell produces analog gray scale capability. Moreover, four different domains are spontaneously formed because the chevron type in-plane electrodes generate four types of the electric field directions. This multidomain structure provides wide viewing characteristics.

3. Experiments

Aluminum (Al) in-plane electrodes were fabricated on the polyethersulfone (PES) plastic substrate by thermal evaporation. Note that, chevron type in-plane electrodes were used for obtaining wideviewing characteristics. The in-plane electrodes make angles of ±45 °C with respect to the input polarizer. The width, the length, and the thickness of each electrodes are 8.8 µm, 26.5 µm, and 1000 Å, respectively. In order to maintain the uniform cell gap against a mechanical bending force, an array of the columnar spacers were produced on the in-plane electrodes by the photolithography technique. The columnar spacers are 8.0 µm thick and 5.5 µm high on average as shown in Fig.2. For the homeotropic alignment of the DHFLC molecules, we coated the polyimide (PI) layer of JALS-203 (Japan Synthetic Rubber Co.) on inner sides of the two PES plastic substrates, followed by thermal curing at 160 °C for one hour. The PES substrate used in this work has low optical retardation ($\leq$10 nm) with high softening temperature (200 °C) suitable for flexible LCDs.

The FLC material used was FLC-10817 of Rolic Ltd. The phase transition sequence is as follows: isotropic → (64.5 ~ 62.4 °C) → cholesteric → (62.4 ~ 61.5 °C) → Sm C*. Material parameters such the spontaneous polarization, the tilt angle, and the helical pitch are P_s = 115 nC/cm^2, q_t = 34°, and $p_0 \leq 0.2$ µm, respectively. The FLC material was introduced into our flexible DHFLC cell by capillary action in the isotropic state. For the uniform alignment of smectic layer, the cell was cooled down at a rate of 5 °C /min into the Sm C* phase under no electric field. In general, the electric field treatment is required for a planar DHFLC cell.

4. Results and Discussion

Figure 3 shows microscopic textures observed under crossed polarizers in the presence of the applied electric fields of (a) 0.0 V/µm and (b) 5.3 V/µm. In contrast to the SSFLC and a conventional DHFLC, our VA-DHFLC configuration provides the uniform alignment in large area without using any additional

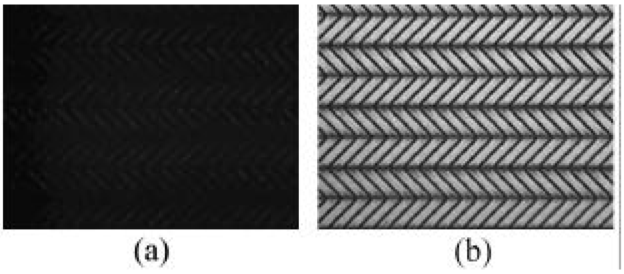

Figure 3. Microscopic textures of our flexible VA-DHFLC cell observed under crossed polarizers in the presence of the applied voltages of (a) 0.0 V/μm and (b) 5.3 V/μm.

process such as the rubbing process and/or the electric field treatment. Fig. 3(a) shows a completely dark state in the absence of an electric field. In this state, the DHFLC layer behaves as an optically isotropic medium.

When an electric field is applied, the helix of the FLC molecules is unwounded on the Sm C* cone and thus the molecules tend to align along the electric field direction. Therefore, the optical birefringence is produced.

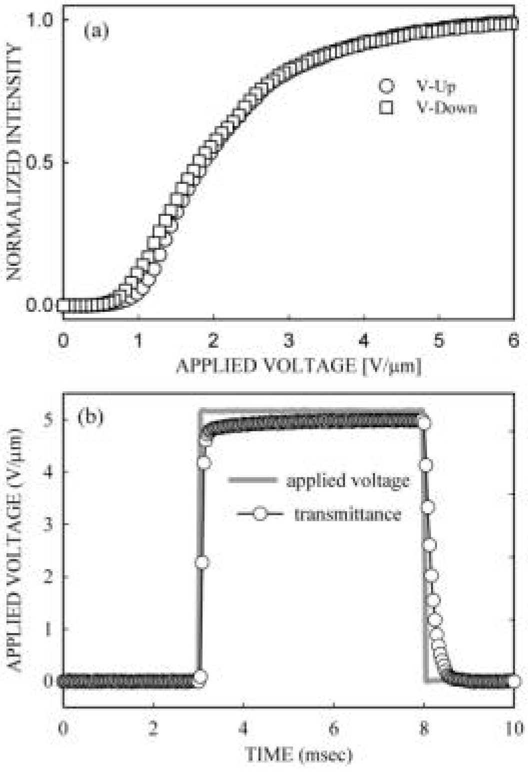

Figure 4. (a) The EO transmittance through our flexible VA-DHFLC cell as a function of the applied electric field under crossed polarizers. The open circles and squares correspond to the rising and falling field. (b) The dynamic EO response to the electric field of a unipolar square waveform at 100 Hz. The solid line and open circles represent the driving electric field and the dynamic EO response.

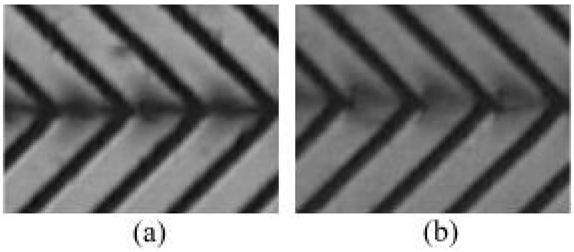

Figure 5. Microscopic textures of our flexible VA-DHFLC cell observed under crossed polarizers (a) in a flat state and (b) in a bent state of the substrate.

The analog gray capability of our flexible VA-DHFLC cell is shown as a function of the applied electric field in Fig. 4(a). A bipolar square waveform of 100 Hz was applied to the cell to measure the EO transmittance under crossed polarizers. As shown in Fig. 4(a), the hysteresis is essentially negligible due to the continuous nature of the helix unwinding process in our case.

Figure 4(b) shows the dynamic EO response to the applied electric field in a unipolar square waveform at 100 Hz. The solid line and opened circles represent the driving electric field and the dynamic EO response, respectively. The rising time, τ_{on}, was found to be about 110 μsec and the falling time, τ_{off}, was about 320 μsec. The switching times of the order of 100 μsec are suitable for high speed LCDs with no image sticking effect. The reorientation of the FLC molecules from the unwound state to the helical state depends on their helical power, and thus the falling time is relatively slower than the rising time.

Figure 5 shows microscopic textures of the flexible VA-DHFLC cell on the mechanical bending under crossed polarizers in the presence of an applied electric field. The mechanical bending of the smectic layers does not affect the optical transmission through the cell since the smectic layers are parallel to the surface as shown in Fig. 5(a) and 5(b).

5. Concluding Remarks

We report on a new type of a fast flexible display based on the VA-DHFLC. The mechanical stability of uniform cell gap was guaranteed by a regular array of columnar spacers. The formation of columnar spacers on in-plane electrode regions dose not affect the optical performances. The difficulty of uniform alignment in large area in conventional FLC cases is easily removed by employing vertical alignment of the FLC molecules in the in-plane electrode geometry. The gray scale capability with good linearity and the fast response of our flexible LCD seem to be suitable for dynamic image processing.

Acknowledgements

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