Defect-free deformed-helix ferroelectric liquid-crystal mode in a vertically aligned configuration (Invited Paper)

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Abstract — A novel deformed-helix ferroelectric liquid-crystal (DHFLC) mode in a vertically aligned (VA) configuration is described. In this configuration, several unique features of display performance such as uniform alignment, fast response, and analog gray-scale capability are obtained. Particularly, this VA-DHFLC mode allows for the defect-free uniform alignment of both the FLC molecules and the smectic layers over a large area without employing additional processes such as rubbing or electric-field treatment that are generally required for planar FLC modes. Based on the VA-DHFLC mode, a transflective display having a single-gap geometry with in-plane electrodes on two substrates in the transmissive regions and on one substrate in the reflective regions is described.

Keywords — Uniform alignment, fast response, deformed-helix ferroelectric liquid crystal, transflective display.

1 Introduction

Liquid-crystal displays (LCDs) that are typically based on nematic liquid crystals (NLCs) have several attractive features such as light weight, small size, and low power consumption. Recently, the electro-optic (EO) characteristics have been much improved and have made it possible to produce large-sized LCD TVs. Due to the intrinsic nature of a dielectric coupling with an external electric field in the NLCs, however, the dynamic response is limited. Since the discovery of ferroelectricity in a tilted chiral smectic phase (Sm C*), ferroelectric liquid-crystals (FLCs) have been extensively studied because of their fast EO response, resulting from a direct coupling of the spontaneous polarization with an applied electric field, and wide viewing property. Thus far, most of the FLC devices have been realized in a planar alignment (PA) configuration including a surface-stabilized FLC (SSFLC) mode. The SSFLC structure can be produced by removing the energy degeneracy of the Sm C* state in a thin cell gap compared to the helical pitch of the FLC. However, for practical applications, this SSFLC mode is known to have several problems such as non-uniform alignment due to zigzag defects, associated with two chevron structures (C1 and C2), and lack of gray-scale capability because of intrinsic bistability. In contrast, a deformed-helix FLC (DHFLC) mode with a short helical pitch compared to the wavelength of visible light is expected to possess many desirable properties such as fast response, analog gray scale, and wide-viewing properties. However, the PA-DHFLC configuration has a low contrast ratio resulting from the existence of striped domains.

In this paper, we describe a defect-free DHFLC mode in a vertically aligned (VA) configuration with in-plane electrodes. In addition to fast response, analog gray-scale capability, and wide-viewing characteristics, this VA-DHFLC mode provides high uniformity in the alignment of both the FLC molecules and the smectic layers over a large area without additional processes such as the rubbing and/or electric field treatment required for the PA-DHFLC mode. Based on the VA-DHFLC mode, we demonstrate a transflective display with a single-gap geometry having in-plane electrodes on two substrates in the transmissive regions and on one substrate in the reflective regions.

2 DHFLC mode

2.1 Operation principles of the PA- and VA-DHFLC modes

Figure 1 represents the schematic diagrams of the PA- and VA-DHFLC configurations where two types of molecular reorientation are shown. The small arrows (black) on the FLC molecules, red arrows, blue arrows in the insets, and θ represent the dipole moments $P_i$ of the FLC layers $\mathbf{n}_i$ projected in the $x$-$y$ plane, the direction of the polarizer, and the tilt angle, respectively. The angle between the average optic axes $n_i$ and the front polarizer is denoted by $\alpha_i$ (i.e., $\alpha_i$). Here, “p” and “v” represent the planar and vertical structures, respectively.

Since the twisting power is very high in a short-pitch FLC, the DHFLC behaves as an optically uniaxial medium along the helical axis. In the absence of an external electric field, the macroscopic spontaneous polarization is zero. For the PA-DHFLC configuration, the smectic layers are formed in the $x$-$z$ plane and the average optic axis $\mathbf{n}_p$ projected in the $x$-$y$ plane is parallel to the $y$-axis as shown in Fig. 1(a). Thus, this initial state resembles a homogeneously aligned nematic structure along the $y$-axis. In contrast, in the VA-DHFLC configuration shown in Fig. 1(c), the helical axis is perpendicular to the substrate and the average

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Journal of the SID 16/9, 2008 947
optic axis \( \mathbf{n}_p \) lies along the \( z \)-axis. This corresponds to a homeotropically aligned nematic structure.

Under an external electric field, the FLC molecules become rotated along the electric-field direction on the \( \text{Sm C}^* \) cone through a direct coupling between the spontaneous polarization and the external electric field. As a consequence, the helix becomes deformed as shown in Figs. 1(b) and 1(d). The average optic axis of the FLC layer \( \mathbf{n}_i \) projected in the \( x-y \) plane, the direction of the polarizer, and the tilt angle, respectively. The angle between the average optic axis and the front polarizer is denoted by \( \alpha_i \) (\( i = p, v \)). Here, \( "p" \) and \( "v" \) represent the planar and vertical structures, respectively.

### 2.2 Sample preparation of the PA- and VA-DHFLC cells

The FLC material used in our PA- and VA-DHFLC cells was FLC-10817 from Rolic Technologies Ltd. The phase-transition sequence is as follows: isotropic \( \rightarrow (64.5-62.4^\circ C) \rightarrow \text{chiral nematic (N*}) \rightarrow (62.4-61.5^\circ C) \rightarrow \text{Sm C*}. \) The average optical anisotropy of the material in a helical structure is about 0.09 at a wavelength of 633 nm. The spontaneous polarization, the tilt angle, and the helical pitch are \( P_s = 115 \text{ nC/cm}^2, \) \( \theta_t = 34^\circ, \) and \( p \leq 0.2 \mu \text{m}, \) respectively. The PA-DHFLC cell was made using two glass substrates coated with indium-tin-oxide (ITO). The planar alignment layer, AL16139 (Japan Synthetic Rubber Co), was coated on the inner surfaces of the cell and both substrates were rubbed unidirectionally to promote planar alignment. The cell gap was maintained using glass spacers 3 \( \mu \text{m} \) thick. For the VA-DHFLC cell, aluminum in-plane electrodes were fabricated on one of two glass substrates by thermal evaporation and photolithography techniques. The width and the thickness of each electrode were 10 \( \mu \text{m} \) and 1000 Å, respectively. The separation between in-plane electrodes was 30 \( \mu \text{m}. \) For the vertical alignment, AL1H659 (Japan Synthetic Rubber Co) was coated on the inner surface of glass substrates and glass spacers 6 \( \mu \text{m} \) thick were used to maintain the cell gap. The FLC was injected into the PA- and VA-DHFLC cells by capillary action in the isotropic state and cooled down at a rate of 1°C/min into the \( \text{Sm C*} \) phase. Note that in the PA-DHFLC cell, the electric-field treatment of 2 V/\( \mu \text{m} \) at 30 Hz was carried out in the vicinity of the N*-Sm C* phase transition for the enhancement of the alignment uniformity.

### 2.3 Alignment properties of the PA- and VA-DHFLC modes

The schematic diagrams of the PA- and VA-DHFLC cells and the corresponding microscopic textures, taken under crossed polarizers, are shown in Fig. 2 under the electric fields of \( E = 0 \) and \( E \neq 0. \) Two insets in Fig. 2(a) of the PA-DHFLC cell represent the top view of the smectic layer structures (left) and the microscopic texture prior to the electric-field treatment (right). Here, small arrows (black) on the FLC molecules and long arrows (gray) represent the spontaneous polarization and the external electric field, respectively.

For the PA-DHFLC cell, the smectic layers are perpendicular to the substrates, and the average optic axis is parallel to the rubbing direction in the absence of the birefringence, which is the optical anisotropy averaged over the helical structure, is denoted by \( \Delta n. \) As is clearly shown in Eq. (1), \( I \) is proportional to \( \sin^2(2\alpha_i) \) in terms of \( \alpha_i. \) In the PA-DHFLC configuration, the transmission is relatively low since the maximum angle \( \alpha_p \) is limited by the tilt angle, typically smaller than 45°, while in the VA-DHFLC configuration can be obtained at an angle \( \alpha_v = 45^\circ. \)

\[
I = \sin^2(2\alpha_i) \sin^2 \left( \frac{\pi d \Delta n}{\lambda} \right). \tag{1}
\]

Here, \( d \) and \( \lambda \) are the thickness of the FLC layer and the wavelength of incident light, respectively. The effective
applied electric field as shown in Fig. 2(a). Compared to the microscopic texture prior to the electric-field treatment (2.0 V/µm at 30 Hz) shown in inset, the alignment uniformity was found to be substantially enhanced. However, the complete dark state was not observed due to the existence of striped domains. The striped domains are associated with two different horizontal chevron structures with different small inclination angles, δ1 and δ2, away from the rubbing direction13,14 as shown in the left inset of Fig. 2(a). As a result, the contrast ratio is relatively low in this PA-DHFLC configuration.

When a bipolar electric field of 3.5 V/µm at 60 Hz was applied to PA-DHFLC cell, the average optic axis was rotated from the helix axis and a bright state was observed as shown in Fig. 2(b). In this case, the maximum angle αp between the average optic axis n∥ and the front polarizer was the tilt angle of the FLC molecules, θt = 34°.

In the case of the VA-DHFLC cell, the smectic layers are parallel to the substrates and the complete dark state is obtained as shown in Fig. 2(c). This structure corresponds to an optically isotropic medium which resembles a homeotropically aligned nematic structure. It should be noted that in the VA-DHFLC cell, the defect-free uniform alignment of both the FLC molecules and the smectic layers can be obtained without additional processes such as rubbing and electric-field treatment.

Under a bipolar electric field of 3.0 V/µm at 60 Hz, the helical structures of the FLC in the VA-DHFLC cell was unwound by the molecular orientation on the Sm C* cone so that the optical anisotropy (birefringence) appeared. As a result, a bright state was then obtained as shown in Fig. 2(d). Here, the periodic dark lines denote the in-plane electrodes.

### 2.4 EO characteristics of the VA-DHFLC mode

We measured the EO characteristics of the VA-DHFLC cell using a He–Ne laser of 632.8 nm as a light source. All measurements were carried out at room temperature. In the absence of an applied electric field, no light can be transmitted through the cell, and thus excellent contrast can be achieved. As shown in Fig. 3, the active area becomes bright by increasing the electric field for the two polarities of the electric field, which is similar to the PA-DHFLC mode.12 Figure 3(a) shows the analog gray-scale capability of the VA-DHFLC cell as a function of the electric field which is a bipolar square waveform at 60 Hz. As shown in Fig. 3(a), a nearly linear relationship between the EO transmittance and the applied electric field was obtained. Figure 3(b) shows the dynamic EO response of the VA-DHFLC cell to a bipolar electric field of a square waveform at 60 Hz. The solid line and open squares represent the applied electric field and the dynamic EO response, respectively. It is clear that the symmetric EO property was obtained in our VA-DHFLC cell as shown in Fig. 3(b). It was found that the rise time τon = 120 µsec and the fall time τoff = 45 µsec. These response times (on the order of hundreds of microseconds) are suitable for high-speed LCDs with no image-sticking effect.

### 3 Transflective display based on the VA-DHFLC mode

Transflective LCDs17–20 are promising for mobile applications due to their superior performances, including low power consumption and good readability in both indoor and
outdoor environments. The transflective LCDs, consisting of two subpixels of transmissive (T) and reflective (R) regions, typically adopt dual-cell-gap structures to compensate the optical-path difference (OPD) between the T and the R regions. However, the dual-cell-gap structures require complex fabrication processes for precise optical compensation. In addition, NLC-based transflective LCDs suffer from slow response, and thus a new type of a transflective LCD having fast response in a single-gap geometry is needed for video-rate applications.

Here, we demonstrate a fast-response transflective display with a single gap in the VA-DHFLC configuration. To compensate the OPD between the T and the R regions, we used in-plane electrodes on two substrates in the T regions and on one substrate in the R regions. The phase retardation in the T region was adjusted to be twice as that in the R region.

Figure 4 shows the operational principle of our transflective VA-DHFLC cell in a single-gap geometry. It is composed of two crossed polarizers, the upper and the lower quarter-wave plates (QWPs) and the DHFLC layer. The small (black) and curved (gray) arrows in the FLC layer denote the dipole moments of the FLC molecules and the electric-field directions, respectively. The R region has in-plane electrodes only on the top substrate while the T region has in-plane electrodes on both the top and bottom substrates. The thickness of our transflective VA-DHFLC cell was maintained using a glass spacer 6.5 μm thick.

Under no applied electric field, in the R regions, linearly polarized light by the upper polarizer becomes circularly polarized light after passing through the upper QWP. This circularly polarized light passes through the DHFLC layer twice, forward and backward, without retardation and passes the upper QWP again. The polarization state of the light is then a linear polarization state perpendicular to the transmission axis of the upper polarizer. In this case, a dark state is obtained. In the presence of an electric field, the phase retardation appears due to the reorientation of the FLC molecules. If the phase retardation through the DHFLC layer is λ/4, the combination of the upper QWP and the reoriented DHFLC layer results in a half-wave-plate (HWP). The reflected light, passing through the HWP twice, has a linearly polarized state parallel to the transmission axis of the upper polarizer, and thus a bright state is obtained. In the T regions, the polarization state of the light arriving at the upper polarizer becomes the same as the polarization state of the light passing through the lower polarizer in the absence of an applied electric field. This is because the retardation of two QWPs whose optic axes are crossed with each other is zero. Thus, a dark state is obtained. If the phase retardation through the DHFLC layer is λ/2 under an applied electric field, a bright state is obtained.

The induced phase retardation, the transmittance, and the reflectance of our transflective VA-DHFLC cell are shown as a function of the applied electric field in Fig. 5. Figures 5(a) and 5(b) show the polar plot of the induced phase retardation at the electric fields of 1.5 and 2.0 V/μm, respectively. The magnitude of the phase retardation was given by the radius of the circle in radians, and the cell was rotated counterclockwise from 0° to 360°. Here, triangles and rectangles denote the experimental EO results of the T and the R regions under a bipolar electric field of a square
waveform at 60 Hz, respectively. As shown in Figs. 5(a) and 5(b), the induced phase retardation in the T region is nearly twice as that in the R region because the effective transverse electric field in the T region with in-plane electrodes on two substrates is stronger and more uniform than in the R region with in-plane electrodes on one substrate. This makes it possible to compensate the OPD in a single-gap geometry. As a consequence, the identical transmitted and reflected intensities with analog gray-scale capability can be obtained as shown in Fig. 5(c). The dynamic EO response of our transflective FLC cell showed $\tau_{\text{on}} \approx 135 \mu\text{sec}$ and $\tau_{\text{off}} \approx 50 \mu\text{sec}$ in both the T and R regions.

4 Conclusion

We presented a novel defect-free DHFLC mode in a VA configuration which provides analog gray-scale capability with good linearity and a fast response time suitable for dynamic image applications. Especially, the extremely uniform alignment over large area was achieved without additional processes such as rubbing or electric-field treatment. A new type of transflective LCD having fast response was demonstrated using the VA-DHFLC configuration in a single-gap geometry. In-plane electrodes on two substrates in the T regions and on one substrate in the R regions were used for the compensation of the OPD between the T and the R regions in a single-gap geometry. The response times were found to be on the order of hundreds of microseconds. Our transflective VA-DHFLC configuration is expected to have significant impact on developing next-generation LCDs and various optical devices.

Acknowledgments

This work was supported in part by Samsung Electronics, AMLCD, and the Ministry of Knowledge Economy of Korea through the 21st Century Frontier Research.

References

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