Jpn. J. Appl. Phys. Vol. 42 (2003) pp. 2752–2755
Part 1, No. 5A, May 2003

Dynamic Stability of the Fringe-Field Switching Liquid Crystal Cell Depending on Dielectric Anisotropy of a Liquid Crystal

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(Received October 8, 2002; accepted for publication December 27, 2002)

A voltage-dependent transmittance curve of the fringe-field switching (FFS) mode was studied with varying dielectric anisotropy of a liquid crystal (LC). The results show that for the LC with positive dielectric anisotropy the disclination lines existing between domains extend into the active region with increasing voltage over the operating voltage, whereas their width becomes smaller with increasing voltage for the LC with negative dielectric anisotropy. This indicates that the LC with negative dielectric anisotropy shows strong dynamic stability in the FFS mode, which can be a great advantage when fabricating microdisplays. [DOI: 10.1143/JJAP.42.2752]

KEYWORDS: fringe-field switching, liquid crystal, dielectric anisotropy, dynamic stability

1. Introduction

Image qualities of liquid crystal displays (LCDs) have been improved greatly by development of new conceptual LC modes such as in-plane switching (IPS) mode[1,2] and fringe-field switching (FFS) mode,[3,4] where the LC director rotates almost in plane. The IPS mode was the first one that exhibited high image quality among LCDs although they showed intrinsically low transmittance. The FFS mode was the first one that showed high transmittance and a wide viewing angle at the same time. At the initial state of both devices, the LCs are homogeneously aligned, and then the in-plane or the fringe electric field drives the LCs to rotate in each device. However, the different shapes of the driving fields cause the electro-optic characteristics of both devices to be different from each other.[5,6] Furthermore, in the FFS mode, the stability of the voltage-dependent LC dynamics is dependent on dielectric anisotropy of the LC. This difference also causes different behavior when the display experiences external pressure.[7,8] In the LC modes, including the FFS one, the voltage-dependent dynamic stability is very important to obtain excellent electro-optic characteristics such as high transmittance, fast response time, and low driving voltage. It is also important for pressure-resistant characteristics. In this paper, voltage-dependent LC dynamics for two types of LCs, that is, LCs with positive (+LC) and negative (−LC) dielectric anisotropy is presented in a 2-domain FFS structure.

2. Experiment

Figure 1 shows a top view of the electrode structure of the FFS mode with the LCs in the off and on state, and electric field directions. Indium-tin-oxide (ITO) with a thickness of 400 Å was deposited on a bottom glass substrate and then the passivation layer, SiN_x with 5000 Å thickness was coated by chemical vapor deposition. Finally, a second ITO layer of 400 Å thickness was deposited and patterned as wedge shaped interdigital electrodes. The wedge angle (ϕ) is 7°. The width of the second ITO electrodes was 4.3 μm with a distance of 4.3 μm between electrodes. There is no electrode on the top glass substrate. In this cell, the first and second ITO layers perform the role of a common electrode and a pixel electrode, respectively. An alignment layer from Japan Synthetic Rubber Co. (JALS-146-R39) was coated on both substrates with a thickness of 1000 Å and the rubbing was performed in antiparallel directions. The rubbing on the bottom substrate for the +LC and the −LC is given in the y and x direction in order to have an arbitrary angle over 45° with respect to the electric field direction, respectively. The pretilt angle generated by the rubbing was 2°. The two glass substrates were then assembled to give a cell gap of 4.0 μm. Super fluorinated liquid crystals with negative dielectric anisotropy ($\Delta n = 0.077$ at $\lambda = 589$ nm, $\Delta\varepsilon = -4$) and with positive dielectric anisotropy (birefringence $\Delta n = 0.099$ at $\lambda = 589$ nm, dielectric anisotropy $\Delta\varepsilon = 8.2$) from Merck Co., were used for the experiments and simulations.

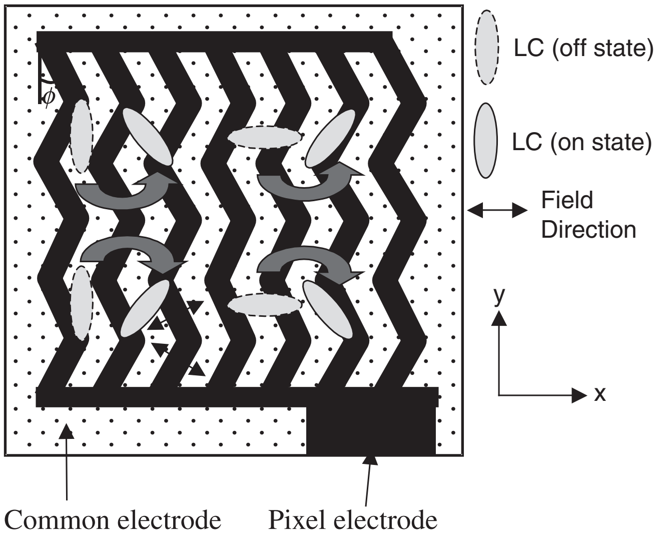

Fig. 1. Top view of the FFS electrode structure with electric field direction. Here, the initial LC alignment direction is different depending on the dielectric anisotropy of the LCs.

For the electro-optic measurements, a Halogen lamp was used as a light source and a square wave, 60 Hz voltage source from function generator was applied to the sample cell. The light passing through the cell was detected by a

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photomultiplier tube.

The voltage-dependent LC texture was observed using optical polarizing microscopy to understand how the LC director reacts to an applied voltage.

3. Results and Discussions

The normalized light transmission of a device with a birefringent LC medium under a crossed polarizer is given by:

$$T/T_0 = \sin^2(2\psi(V))\sin^2(\pi d\Delta n/\lambda)$$

where ψ is an angle between one of the transmission axes of the crossed polarizers and the LC director, Δn is the birefringence of LC medium, and λ is the wavelength of the incident light. From the equation, one can understand that ψ is a voltage dependent value, that is, with no bias voltage (off state), ψ is zero and the cell shows a dark state. With bias voltage (on state), the ψ starts to deviate from the polarizer axis, showing light transmittance.

Figure 2(a) and 2(b) shows calculated and experimental voltage dependent transmittance (V–T) curves of the FFS cells, respectively. For the simulation, we have used the commercially available software ''LCD Master'' (Shintech, Japan), where the motion of the LC director is calculated based on the Eriksen–Leslie theory and 2×2 Jones Matrix is applied for optical transmittance calculation. According to the V–T shape of the calculated results, the transmittance becomes maximal at certain voltages and then decreases with further increasing voltage. This simply indicates that the ψ value becomes 45°, giving rise to the maximal transmittance at operating voltage V_{op} and with further increasing applied voltage, the light transmittance decreases since the ψ value becomes over 45°. However, the rate of decrease in transmittance is not as steep, since the applied voltage cannot twist the LC near the surface due to the strong coupling between the LC and alignment layer. Nevertheless, the measured V–T curves show a different result for the +LC, that is, the transmittance drops rapidly with increasing voltage over the V_{op}. In order to understand what is occurring inside the cell, we have observed the LC texture using the optical polarizing microscope while changing the applied voltage, as shown in Fig. 3. The cell that showed a dark state exhibits a light transmittance with applied voltage above threshold. However, in this cell, there are two different field directions inside the cell such that in each domain the LC director rotates clockwise and anticlockwise (see Fig. 1). Therefore, the LC molecules existing between domains cannot rotate in either direction and thus the LC molecules do remain at original state, giving rise to dark disclination lines. Here, the number of dark spots indicates the existence of a ball-type spacer. When the applied voltage is 4.7 V, about V_{op}, the width of the disclination lines becomes narrower than before, indicating that more LCs at the domain boundary try to rotate to the field direction than at lower voltage. With further increasing of the voltage up to 6 V (over the V_{op}), the straight-line shape of the disclination lines starts to bulge out, in some part upward and downward. This indicates that competition between forces to rotate the LC clockwise (F_c) and anticlockwise (F_a) exists, that is, the bulge of upward direction indicates that the F_a is stronger than the F_c such that the disclination lines are pushed upward. When an applied voltage is further increased to 8 V, surprisingly, the disclination lines, which existed at the domain boundary, permeate into the domain area, resulting in low transmittance in the whole area. To understand how the disclination lines progress into the domain area at high voltage, we have magnified the area near the domain boundary, as shown in the box of Fig. 3. In the FFS mode using the +LC, the light transmittance along the x-axis is oscillating like a sine curve, due to the oscillating field intensity. As appears in the

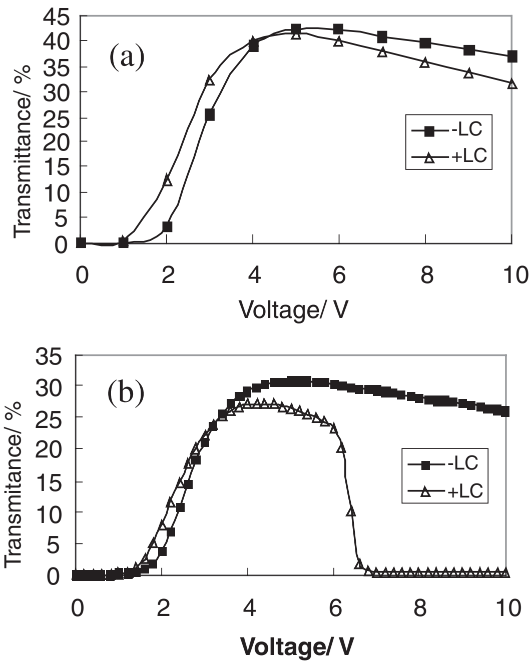

Fig. 2. (a) Calculated and (b) measured voltage-dependent transmittance curves of the FFS cells when using the LCs with positive and negative dielectric anisotropy.

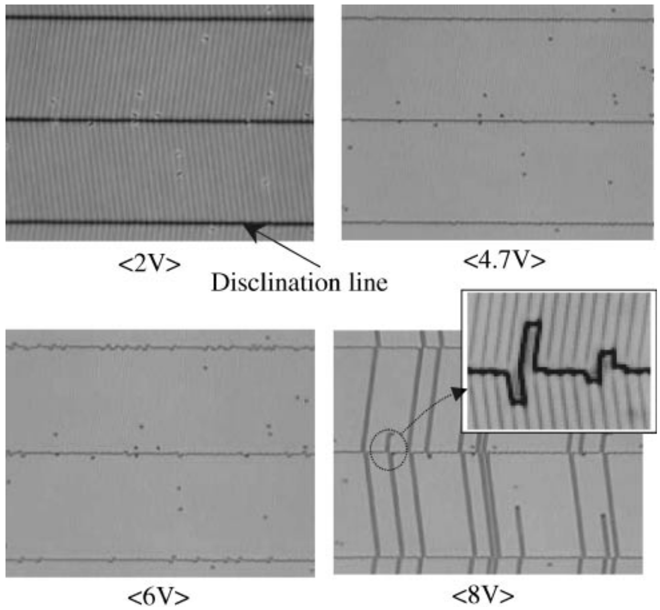

Fig. 3. Photograph of the FFS cells showing how the disclination lines progress near the domain boundary as the applied voltage increases for the +LC. The magnified photograph demonstrates how the disclination lines extend into the domain area from the domain boundary region.

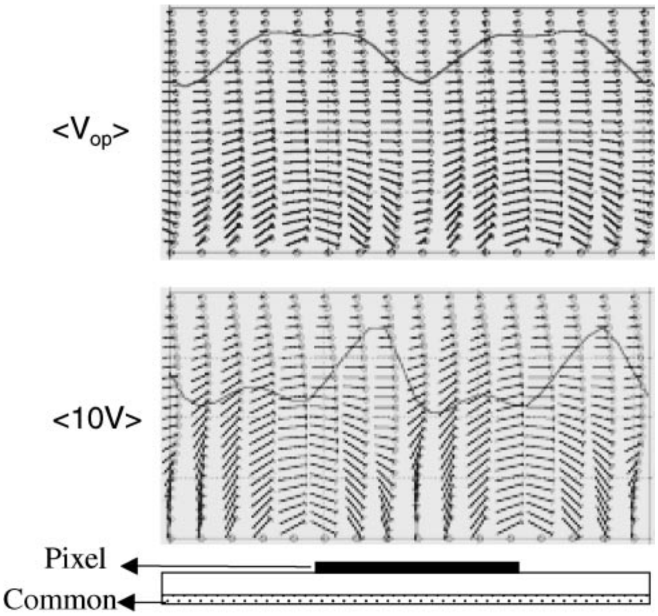

Fig. 4. Simulation results showing the LC profile and the corresponding light transmittance with two bias voltages, V_{op} and 10 V. Here the solid line indicates the light transmittance at given voltages.

photograph, the light transmittance is periodically changing along a horizontal axis and also the disclination lines are pushed either upward or downward along the lines with the lowest transmittance. We have performed a simulation to understand the profile of the light transmittance in the x direction and finally to find out in which electrode position the competition exists. Figure 4 shows a profile of the LC molecules when the applied voltage is V_{op} and 10 V with corresponding light transmittance. Here, the LCs are aligned to have 83° with respect to the x axis at the initial state. With bias voltage of V_{op} the transmittance is maximal near the edge of the pixel electrode resulting from enough rotation of the LC by a strong horizontal field, and minimal above the center of the pixel electrode resulting from insufficient rotation of the LC by a vertical field. However, when $V \gg V_{op}$, the LCs near the edge of the pixel electrode are twisted fully, about 83° parallel to the horizontal field direction due to the strong horizontal field intensity, and thus the light transmittance near the edge of the pixel electrode decreases since the light transmittance is proportional to $\sin^2(2\psi)$ and ψ is overtwisted, as indicated in Fig. 4. Further, we have calculated the twist angle of the LCs near and above the center of the pixel electrode along the vertical axis as a function of the applied voltage, as shown in Fig. 5. Above the center of the electrode, the maximum twist angle is about 40°, which means that the competition force to rotate in either one direction does not exist along that line. However, near both edges of the electrode, it increases with increasing voltage and a maximum twist angle of 83° exists below $d/z = 0.2$. Therefore, in that region the competition between two forces, F_a and F_c, exists such that the disclination lines can be pushed upward or downward depending on minute conditions. Once one force overcomes the other, the disclination line permeates into the domain area along the center position of the pixel and the common electrodes and covers the whole area. As a result, the transmittance becomes very low. We also found that the disclination lines

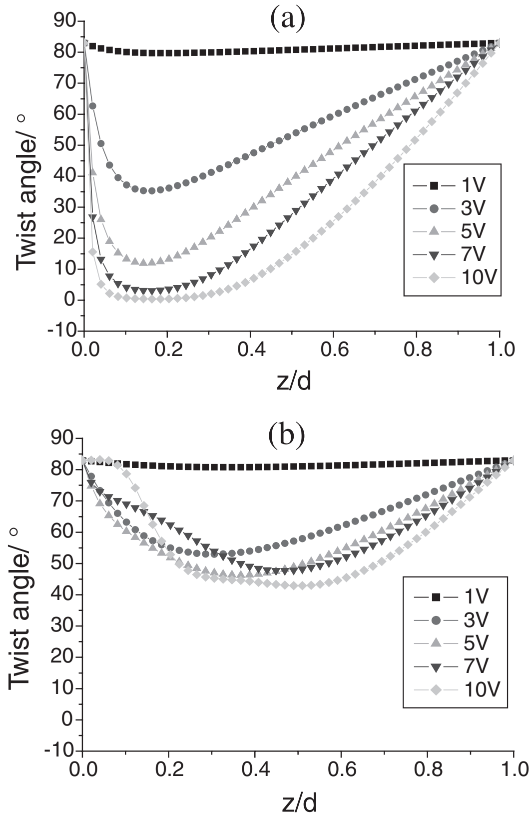

Fig. 5. Profile of voltage-dependent twist angle of the LC at two different positions, (a) near the edge and (b) above the center of the electrodes in a vertical direction.

stay at the domain boundary when the applied voltage is very high only if the wedge angle is 45°, since in this case the maximal twist angle of the LC near the edge of the electrode is 45° and thus there is no strong competition between F_a and F_c. Therefore, we can understand that a large wedge angle is advantageous to obtain stable LC dynamics against the applied voltage.

Now the question arises why such behavior occurs only when using the +LC. Figure 6 shows the voltage-dependent light transmittance of the FFS cell with the −LC. While increasing the applied voltage, the disclination lines existing at the domain boundary are not destroyed and their width becomes small, unlike that of the +LC. The major difference between the +LC and −LC is the electric field response, that is, the +LC and the −LC try to orient parallel and perpendicular to the field direction. As already mentioned, in the FFS mode, a fringe electric field that has both horizontal and vertical components is generated with a bias voltage. In the case of the +LC, the degree of freedom is just one, that is, it tries to orient along an effective electric field direction. However, for the −LC, it reacts to two different electric field. In other words, the horizontal field drives the LC to rotate while the vertical field has the role of holding down the LC in plane. Therefore, when using the −LC, both horizontal and vertical field intensity increase equally, as the applied voltage is increased and as a result, the two forces to rotate and hold down the LC are the same, keeping the disclination lines at domain boundary. Therefore, the −LC has an advantage in terms of the voltage-dependent dynamic stability in the FFS mode.

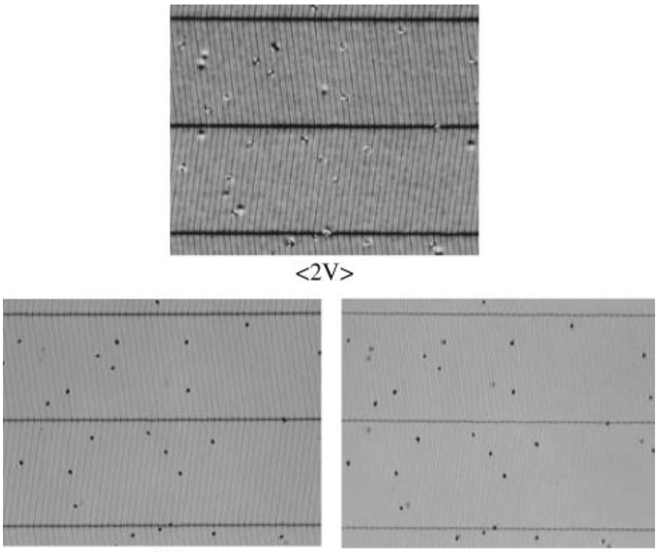

Fig. 6. Photograph of the FFS cells showing how the disclination lines progress near the domain boundary as the applied voltage increases for the −LC.

4. Conclusion

We have studied voltage-dependent LC dynamics dependent on the dielectric anisotropy of the LC in the FFS mode. When using the LC with positive dielectric anisotropy, the disclination lines existing at the domain boundary were not stable at a high voltage above the operating one due to competition forces to rotate the LC clockwise and anticlockwise, whereas they remain stable when using the LC with negative dielectric anisotropy although the competition exists. The results are very useful in the design of high image quality FFS-LCDs, especially with high resolution.

Acknowledgements

This work was supported by grant No. R05-2002-000-00736-0 from the Korea Science & Engineering Foundation.

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