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Analysis of the generation of multi-domain in vertical alignment (VA) mode caused by the fringe field on the side of the lower substrate

HyungKi Hong [a]

[a] Department of Visual Optics, Seoul National University of Science and Technology, Nowon-gu, Seoul, Republic of Korea

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Analysis of the generation of multi-domain in vertical alignment (VA) mode caused by the fringe field on the side of the lower substrate

HyungKi Hong*

Department of Visual Optics, Seoul National University of Science and Technology, Nowon-gu, Seoul, Republic of Korea

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The generation of multi-domain vertical alignment (VA) is important in order to reduce the dependence of electro-optical characteristics on viewing angle characteristics. Fringe fields of different intensities are generated by the control electrode and slit pattern of the pixel electrode on the side of the lower substrate. These fringe fields are used to generate the multi-domain inside the liquid crystal cell. As the voltage of the control electrode is fixed and AC voltage is applied to the pixel electrode, domains of different configurations are induced depending on the (+) or (-) sign of the first frame. Once domains are generated, these remain unchanged for much longer than the duration time of one frame, even at the pixel voltage of the opposite sign.

Keywords: fringe field; liquid crystal display (LCD); multi-domain; vertical alignment (VA)

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1. Introduction

Nowadays many types of liquid crystal (LC) display modes are used for various applications [1–5]. Multi-domain vertical alignment (VA) is one of these modes, where multi-domains of different tilted directions are made inside the LC cell to reduce the dependence of electro-optical performance on viewing angles. Various methods of generating multi-domains have been reported. Some of these methods are illustrated in Figure 1, such as using the horizontal electric fringe field, the rib pattern of the geometric shape or ultraviolet (UV) [6–9]. These methods are known to be effective for the stable generation of multi-domains. However, the first and second of these methods are known to require additional processes to make the ITO slit or the rib pattern on the side of the upper substrate. The UV alignment method requires multiple UV radiation procedures to induce the different pretilt angles on the alignment layers. When the upper and lower substrates are attached, these structures may result in different ratios of domain area if some misalignment between the substrates occurs.

In this paper, a method for the generation of multi-domains is investigated using only the fringe field on the side of the lower substrate. Factors determining the rotating direction at different positions inside the LC cell are investigated. As it is necessary to apply alternating current (AC) voltage to the LC cell to prevent performance degradation, the behaviour of LC directors under AC driving is analysed using 2-dimensional simulation of LC directors.

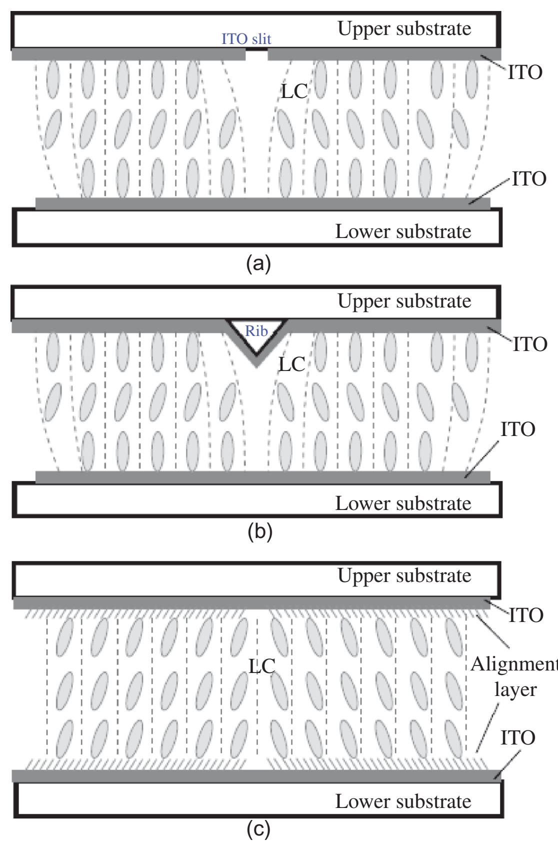

Figure 1. Examples of various methods for the generation of multi-domains in VA mode: (a) using the fringe field; (b) using the rib structure; (c) using UV alignment. Ellipses and dotted lines represent LC directors and the direction of the electric field (colour version online).

*Email: hyungki.hong@snut.ac.kr

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2. Theory

LC directors of VA mode with negative dielectric anisotropy $\Delta\varepsilon$ align perpendicular to the direction of the electric field. If multi-domains are induced only by the fringe electric field on the side of the lower substrate, an electric field of strong and weak intensity should be located alternately . In this case, the rotating direction of LC directors between the weak and the strong fringe field would be the same, and the positions of the weak and strong fringe field would become the boundaries of the domains [10] This schematic is illustrated in Figure 2.

The weak fringe field is induced by making a slit pattern on the pixel indium tin oxide (ITO) electrode. The strong fringe field is induced by placing the control electrode below the slit pattern on the pixel ITO electrode. The difference between the voltage of the control electrode and the ground ITO electrode should be larger than the difference between the voltages of the pixel ITO electrode and the ground ITO electrode. This relationship is written as Equation (1),

$$|V_c - V_g| > |V_p - V_g|. \quad (1)$$

V_c and V_p represent the voltage applied to the control electrode and the pixel electrode on the side of the lower substrate. V_g represents the voltage applied to the ground electrode on the side of the upper substrate.

In driving the LC display, AC driving should be applied to the LC cell to prevent the degradation of the LC cell. Voltages larger than V_g and smaller than V_g should be applied successively to the pixel electrode with the same duration of time, as illustrated in Figure 3. The difference between these voltages and the ground voltage is the same. These voltages are represented as $(+)V_p$ and $(-)V_p$. The duration time of one frame is represented as T. The frame where the pixel voltage is higher or lower than the ground voltage is represented as the frame of (+) polarity or (−) polarity.

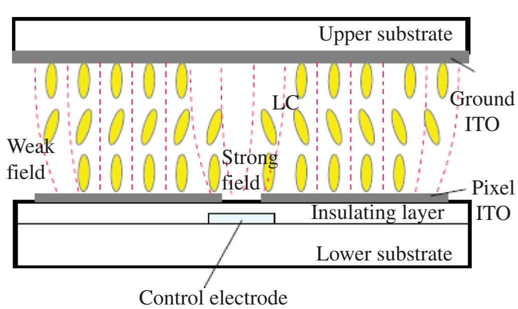

Figure 2. Schematic of VA LC cell where multi-domains are generated by the fringe field due to the control electrode and ITO slit. Ellipses and dotted lines represent LC directors and the direction of the electric field (colour version online).

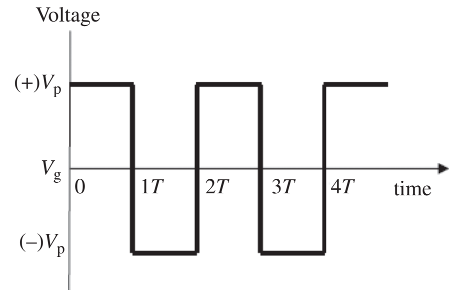

Figure 3. AC driving scheme where $(+)V_p$ and $(–)V_p$ are alternatively applied to the pixel electrode while the ground voltage V_g remains constant. Horizontal axis represents the time. T represents the duration time where voltage of (+) or (–) polarity is applied.

If V_c remains a fixed value, Equation (1) will be satisfied for one polarity of AC driving, but not for the other. Hence, stable domain generation cannot be guaranteed. One solution would be to switch the polarity of the control voltage also in each frame, in accordance with the polarity of the pixel voltage. However, switching of the control voltage would require additional bus lines, additional capacitance inside the pixel structure and additional circuitry in the driving systems [10]. Therefore, the behaviour of LC directors, and how the domains are generated in each frame of the different polarities under the control electrode of constant voltage, are investigated here.

3. Simulation

A commercial 2D LC simulation program (Techwiz 2D™) was used to investigate the behaviour of LC directors and domains under electric fields [11]. The side view of the layout of the LC cell for the simulation is illustrated in Figure 4(a). The horizontal size and LC cell gap are 120 μm and 4 μm, respectively. Pixel electrodes are placed on the side of the lower substrate.

Slit patterns on the pixel electrodes are placed at positions of 0, 30, 60, 90, and 120 μm. Hence, pixel electrodes are divided into four regions, separated by the slit of 6 μm width. The same voltage V_p is applied to these divided pixel electrodes. A control electrode of 10 μm width is placed below the pixel electrode and overlaps each side of the pixel electrode by 2 μm. An insulating layer 0.2 μm thick is placed between the control electrode and the pixel electrode. The material parameters of the LC used for the simulation are: dielectric constant $\varepsilon_e = 3.6$ and $\varepsilon_o = 7.8$, refractive index $n_e = 1.5587$ and $n_o = 1.4765$, $\Delta n = 0.0822$, elastic constant $K_{11} = 16.7$ pN, $K_{22} = 7.3$ pN, $K_{33} = 18.1$ pN. The vertical alignment (VA) where the polar angle of the pretilt is 90° is selected as the alignment condition of LC cell. The periodic boundary condition is used for the horizontal direction. The fringe field will appear where the pixel electrodes are divided.

Figure 4(b) illustrates the relationship between the voltage and normalised transmittance, which is calculated from a1D cell with the same LC parameters and cell gap of 4 μm. From this relationship, pixel voltages V_p of 2.95, 3.25, 3.9 V are selected. These voltage levels approximately correspond to LC states whose normalised transmittances are 25%, 50%, 75%, respectively.

Pixel voltage profile schemes are illustrated in Figure 5. In TFT (thin film transistor) LCDs, the gate bus line and data bus line exist inside each pixel, and the voltage level of the gate bus line remains for most of the time at a fixed value called Gate-Low-Voltage. If the control voltage is connected to the gate bus line, no additional bus line is necessary to apply the voltage to the control electrode. So, it is assumed that V_c is the same as the Gate-Low-Voltage. Voltage V_c is selected as −10 V, which is approximately the same voltage as the Gate-Low-Voltage.

To investigate the effect of (+) and (−) polarity on the generation of the domains, various pixel voltage profiles were devised as illustrated in Figure 5. Figures 5(a) and 5(b) represent the conditions where constant pixel voltage without polarity change is applied. Figures 5(c) and 5(d) represent the conditions where pixel voltages of (−) and (+) polarity are applied successively in alternate frames. The duration time of each frame is 16 ms, which is slightly shorter than the duration time of 60 Hz. These profiles are used to investigate the importance of the initial polarity in domain generation, and the stability of domains. Figures 5(e) and 5(f) represent the conditions where pixel voltages of (−) and (+) polarity are applied for a much longer duration than the

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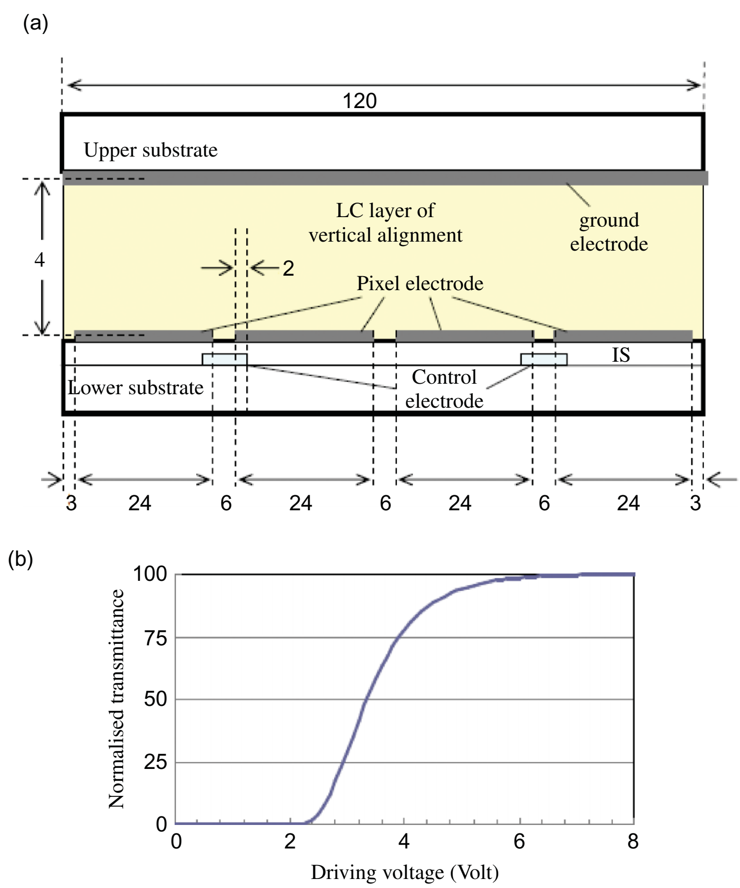

Figure 4. (a) Side view of LC cell layout for 2D LC simulation. Pixel electrodes are divided into four regions, separated by 6 μm. A control electrode of 10 μm width overlaps each side of the pixel electrode by 2 μm. Horizontal direction is defined as the x-direction. IS represents the insulation layer between the pixel electrode and the control electrode. (b) Voltage–transmittance curve of LC cell of mono domain VA (colour version online).

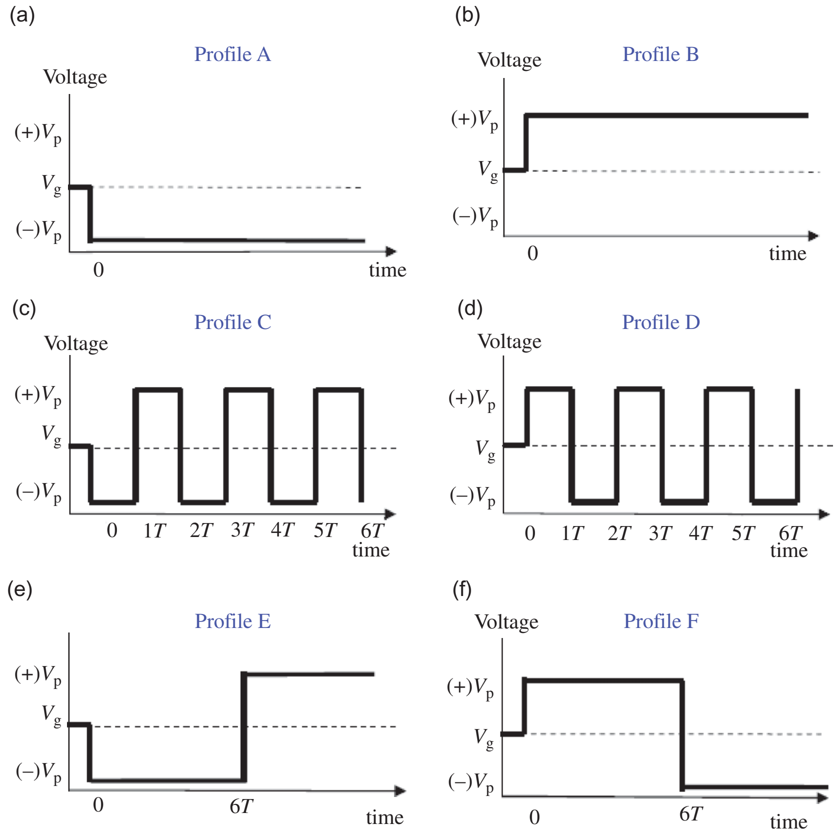

Figure 5. Scheme of pixel voltage profiles applied to the pixel electrode. LC directors are initially aligned vertically at zero voltage. Horizontal and vertical axes represent time and the pixel voltage, respectively. T is 16 ms. V_g represents the ground voltage. (a) (–)V_p is applied. (b) (+)V_p is applied. (c) (–)V_p is applied at the first frame. Then (+)V_p and (–)V_p are applied successively in the following frames. (d) (+)V_p is applied at the first frame. Then (–)V_p and (+)V_p are applied successively. (e) (–)V_p is applied for $6T = 96$ ms and then (+)V_p is applied. (f) (+)V_p is applied for 6T and then (–)V_p is applied.

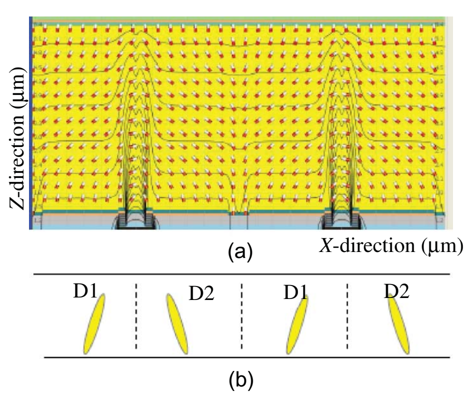

Figure 6. (a) Calculated results of LC director distributions at the time of 96 ms when the driving voltage profile A of Figure 5 with $(-)V_p = -3.25$ V is applied. (b) The schematic domain configuration of the result. Vertical direction represents the direction of the cell gap. Horizontal direction represents the plane where the electrodes are placed. D1 and D2 represent the LC domain where LC directors are rotated right and left. Ellipses and curved lines represent LC directors and the equi-potential lines. Dotted lines represent the domain boundaries (colour version online).

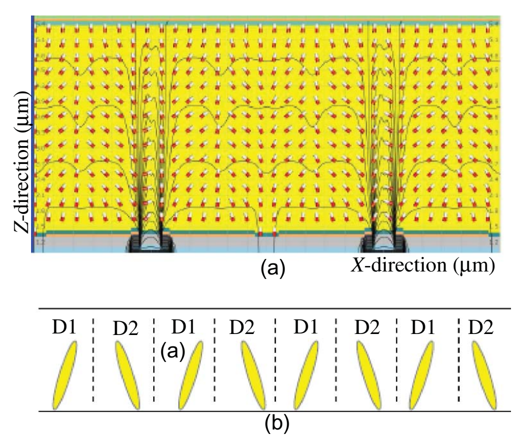

Figure 7. (a) Calculated results of LC director distributions at the time of 96 ms when the driving voltage profile B of Figure 5 with $(+)V_p = 3.25$ V is applied. (b) The schematic domain configuration of the result. Vertical direction represents the direction of the cell gap. Horizontal direction represents the plane where the electrodes are placed. D1 and D2 represent the LC domain where LC directors are rotated right and left. Ellipses and curved lines represent LC directors and the equipotential lines. Dotted lines represent the domain boundaries (colour version online).

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time period of one frame. These profiles are used to investigate the stability of domains.

4. Results and analysis

Figures 6, 7 and 8 illustrate the calculated results when the voltage profiles A and B of Figure 5(a) and 5(b) are applied. Figure 6 illustrates the result at the time of 96 ms where pixel voltage of $(-)V_p = -3.25$ V is applied. Under this driving condition, four domains of right, left, right, left rotating directions, and of about the same width of 30 μm, are formed. Domain boundaries are located at the points of the pixel slits where the fringe field exists. As the polarity of the pixel voltage and the control voltage are the same, a strong fringe field is induced near the control electrode. When the slit on the pixel electrode is located further away from the control electrode, this induces a weak fringe field.

Figure 7 illustrates the result at 96 ms where a pixel voltage $(+)V_p = 3.25$ V is applied. Eight

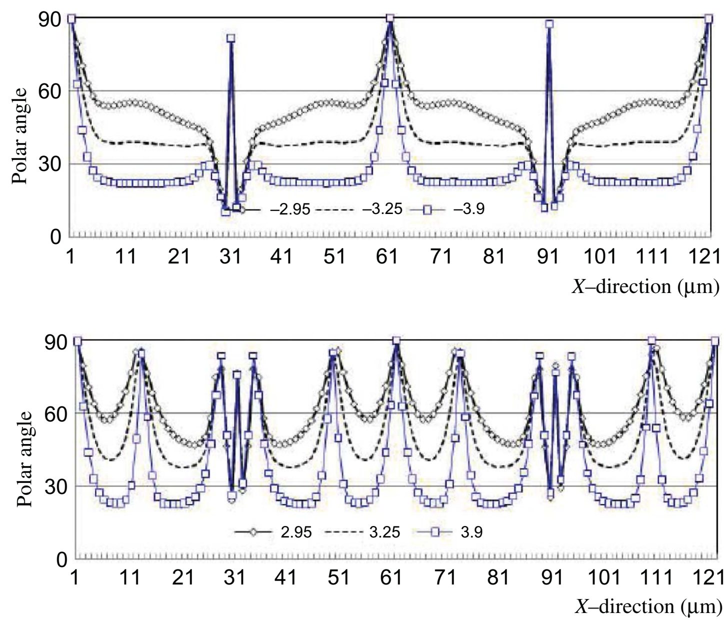

Figure 8. Calculated polar angles of LC director distributions at the centre of the LC cell under different pixel voltages at the time of 96 ms. (a) Calculated result when the driving voltage profile A of Figure 5 with $(–)V_p = –2.95$, –3.25, –3.9 V is applied. (b) Calculated result when the driving voltage profile B of Figure 5 with $(+)V_p = 2.95$, 3.25, 3.9 V is applied. Vertical direction represents the polar angle of LC directors at the centre of the LC cell. Horizontal direction represents the plane where the electrodes are placed. Numbers on the lower side of each graph represent the values of the pixel voltages (colour version online).

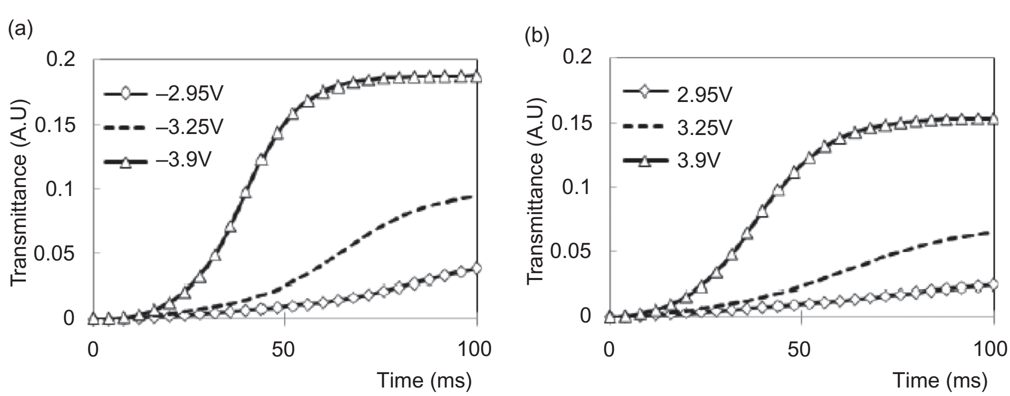

Figure 9. Calculated transmittance versus time when (a) the driving voltage profile A of Figure 5 with $(–)V_p = –2.95$, –3.25, –3.9 V is applied; (b) the driving voltage profile B of Figure 5 with $(+)V_p = 2.95$, 3.25, 3.9 V is applied. Vertical direction represents the transmittance in arbitrary units. Horizontal direction represents the time in ms. Numbers on the upper left side of each graph represent pixel voltage values.

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domains of around 15 μm width are observed. Domain boundaries are formed on the slits of the pixel electrodes as well as between the slits of the pixel electrodes. The rotating directions at the adjacent slits of the pixel electrodes are opposite. This can be attributed to the fact that the polarity of the pixel voltage and the control voltage are opposite, and a strong electric field is not formed. Figures 6(b) and 7(b) illustrate the simplified domain configurations of Figures 6(a) and 7(b). These domain configurations are represented as type A and type B throughout the paper.

Figure 8 illustrates the calculated result of LC directors at the centre of cell gap at the same voltage profiles as Figures 6 and 7. In Figure 8, the slit patterns of the pixel electrode without the control electrodes are placed at the position of 0, 60, 120 μm. The positions of 0 and 120 are connected by the periodic boundary conditions. The slit patterns of the pixel electrode above the control electrodes

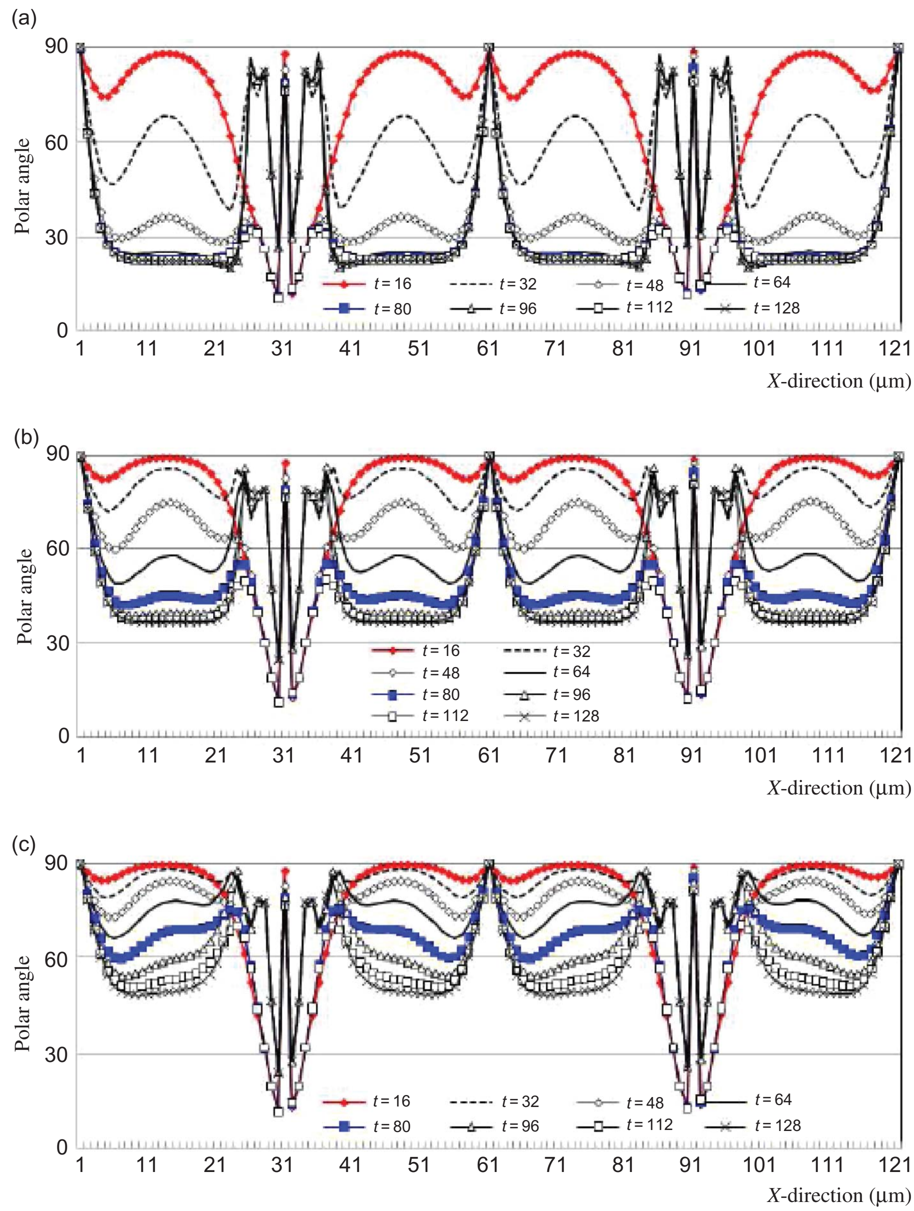

Figure 10. Calculated polar angles of LC directors at the centre of the cell gap when pixel voltages of (+) and (–) polarities are applied successively, starting from the (–) polarity as described in the voltage profile C of Figure 5. Absolute values of pixel voltages of each graph are (a) 3.9 V, (b) 3.25 V and (c) 2.95 V. Vertical direction represents the polar angle of LC directors at the centre of LC cell. Horizontal direction represents the plane where the electrodes are placed. Numbers on the lower side of each graph represent time (ms).

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are placed at 30 μm and 90 μm. The polar angle approaches 90° near the horizontal position where the slit patterns are located. A comparison of Figures 6, 7 and 8 shows that polar angle approaches 90° around the horizontal positions where domain boundaries are formed. Hence the polar angle of LC directors at the centre of the cell gap can be used to represent the positions of the domain boundaries.

Figures 9(a) and 9(b) illustrate the calculated result of transmittance after the pixel voltage is applied. For the pixel voltage of smaller value, transmittance shows increasing trends for the time of 100 ms. For the pixel voltages of −3.9 V and 3.9 V, the graph shows that the transmittance reaches saturated value. However, the time required to reach saturated value is still longer than 16 ms. Therefore, Figures 9(a) and 9(b) show that LC states do not reach the stable state at T = 16 ms.

Figure 10 illustrates the calculated polar angle of LC directors at the centre of the cell when pixel voltages of (+) and (−) polarity are applied successively, starting from the (−) polarity as described in the voltage profile C of Figure 5(c). After the first few frames, LC directors between the slits of the pixel electrodes stabilise. LC directors near the slits above the control electrode fluctuate at each frame as the polarity of

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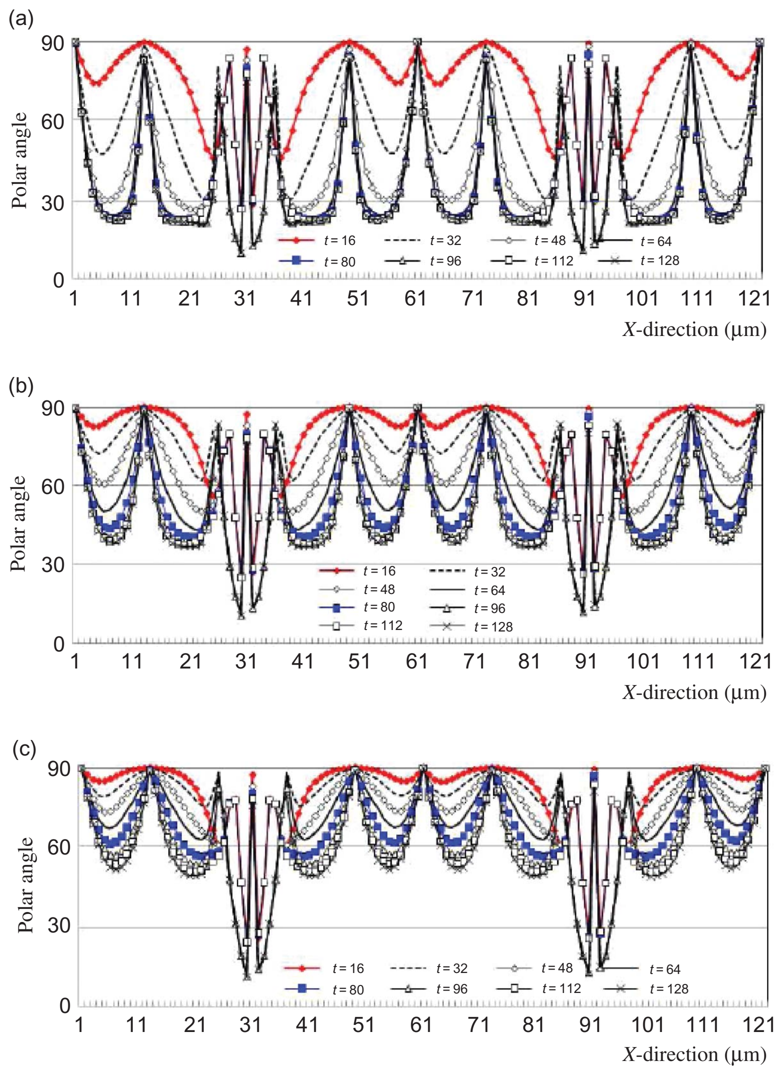

Figure 11. Calculated polar angles of LC directors at the centre of the cell gap when pixel voltages of (–) and (+) polarities are applied successively starting from the (+) polarity as described in the voltage profile D of Figure 5. Absolute values of pixel voltages of each graph are (a) 3.9 V, (b) 3.25 V and (c) 2.95 V. Vertical direction represents the polar angle of LC directors at the centre of the LC cell. Horizontal direction represents the plane where the electrodes are placed. Numbers on the lower side of each graph represent time (ms) (colour version online).

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the applied voltage changes. Overall domain configuration is similar to that of type A, which is formed when V_p of (−) polarity is applied for times much longer than one frame, as in Figure 6.

Figure 11 illustrates the calculated polar angle of LC director at the centre of cell when pixel voltages of (−) and (+) polarity are applied successively, starting from the (+) polarity as described in the voltage profile D of Figure 5(d). LC directors near the slits above the control electrode fluctuate at each frame as the polarity of the applied voltage changes. Overall domain configuration is similar to that of type B, which is formed when V_p of (+) polarity is applied for times much longer than one frame, as in Figure 7.

The calculated results in Figures 10 and 11 show different domain configurations. The only difference in the voltage profiles between Figures 10 and 11 is the polarity of the starting frame. A control voltage of fixed value makes the whole driving scheme unsymmetrical with respect to the ground voltage V_g. It can be assumed that the initial polarity plays the crucial role in determining the domain configuration of type A and B when a control voltage of fixed value is used to induce the fringe field.

In order to investigate the time that the domain configuration of type A changes to type B, type A was generated first by applying the driving voltage of (−) polarity for the duration of 6 T. Then the driving voltage of (+) polarity was applied, and the change of LC directors observed. The results for the pixel voltage of 3.25 V are illustrated in Figure 12(a). The change of LC directors starts near the control electrode, and progresses to other positions as time passes. Yet, LC directors far from the control electrodes are not affected, even when 5 T had passed following the polarity change of the pixel voltage. The same calculation was done to investigate the change from type B to type A. The results are illustrated in Figure 12(b). This shows that the changes of LC directors progress from the positions of the control electrode, similar to Figure 12(a).

These results show that the initial polarity of the first frame determines the type of domain configuration, and that the transition time between domain

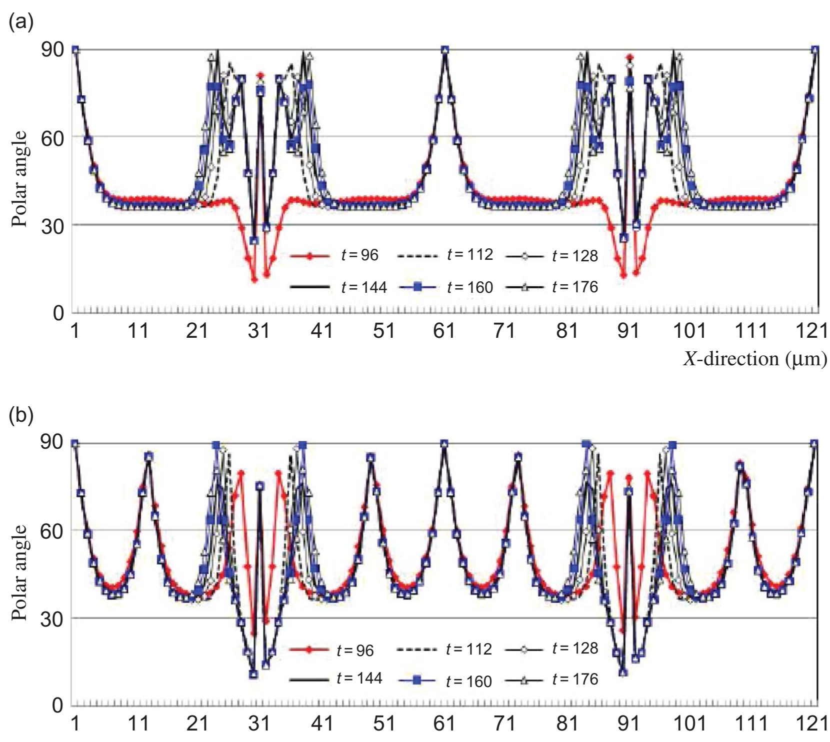

Figure 12. Calculated polar angles of LC directors at the centre of the cell gap when a pixel voltage of 3.25 V is applied. (a) (–) polarity is applied for 96 ms and then (+) polarity is applied as describe in the voltage profile E of Figure 5. (b) (+) polarity is applied for 96 ms and (–) polarity is applied as described in the voltage profile F of Figure 5. Vertical direction represents the polar angle of LC directors at the centre of the LC cell. Horizontal direction represents the plane where the electrodes are placed. Numbers on the lower side of each graph represent time (ms) (colour version online).

configuration of type A and B by the fringe field is much longer than the duration of one frame.

5. Conclusion

Domain generation by the fringe field induced by the slit pattern on the pixel electrode and the control electrodes on the side of the lower substrates are investigated under AC driving, where pixel voltages of (+) and (−) polarity are alternately applied.

When a control electrode of fixed voltage value is placed inside LC cell, the electric field distribution is no longer symmetrical for the frame of (+) and (−) polarity. In addition, the polarity of the pixel voltage of the first frame determines the two different domain configurations, even though the pixel voltages of (−) and (+) polarity are repeatedly applied after the first frame.

In display applications, the generation of the correct multi-domain configuration is important where domain boundaries are not located between the slits of the pixel electrodes. The correct configuration can be generated by applying a pixel voltage of (−) polarity to LC directors which are vertically aligned. Once LC directors are aligned into the correct multi-domain, this configuration is expected be subsequently preserved, as the transition time from one type of domain configuration to the other is much longer than the duration of one frame.

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