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Improvement of voltage-dependent dynamics through an oblique electric field in vertically aligned liquid crystal director surrounded by patterned polymer walls

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Abstract

Voltage-dependent liquid crystal textures in a homeotropically aligned nematic liquid crystal (LC) device, where the chiral-doped liquid crystal with negative dielectric anisotropy is locked by polymer walls with crossed polarizers, have been investigated. The device shows wide viewing angle characteristics with advantages that it is free from rubbing process and spacer. The time-resolved LC textures show that they are not stable enough during an instantaneous reorientation of LC when a voltage is applied. To improve dynamic characteristics, we propose advanced cell structure where the bend and twist deformation is controlled by polymer wall plus an oblique electric field through patterned electrode. Consequently, dynamic characteristics of the device are greatly improved.

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Keywords: Liquid crystal display; Vertical alignment; Polymer wall; Oblique electric field

1. Introduction

Recently, the replacement of cathode ray tube by LC displays (LCDs) has become a general trend because of excellent performance and high image quality of different LC modes. One of the well-known LCD driving modes was twisted nematic (TN) mode [1,2], because of low operating voltage, high light efficiency and high image quality only at normal direction. To achieve high image quality in all the directions, various liquid crystal modes such as in-plane switching (IPS) mode [3], fringe-field switching (FFS) mode [4–6], multi-domain vertical alignment (MVA) mode [7], and patterned vertical alignment (PVA) [8–10] had been proposed and commercialized. Nevertheless, when these LC modes are applied to large-size LCD panels, they are very sensitive to show gravity mura because LCs could flow to the bottom of the panel by gravity. Furthermore, for small sized LCDs with higher resolution, the pixel size of few tenths of micrometer is required.

As one of the solutions to solve these problems have been proposed by Lee et al. [11], in which LCs are vertically aligned and locked by polymer wall and named as locked super homeotropic (LSH) mode. In such device, the light modulation does occur using polarization rotation and multi-domain is formed by boundary condition of surrounding polymer wall. There are two different approaches to make the LSH cell depending upon order of polymer wall and vertical alignment layer in cell fabrication, which

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results in different behavior in voltage-dependent LC reorientation. However, irrespective of manufacturing process, both cells exhibited instantaneous unstable LC textures on applied voltage, which resulted in slow response time. In this paper, voltage-dependent LC dynamics for two (LSH) cells having different boundary conditions have been investigated and compared. Voltage-dependent LC dynamics have also been proposed to improve the cell structure.

2. Experimental condition

Fig. 1 shows schematic LSH cell structures depending on cell fabrication process. Both substrates have transparent indium-tin-oxide (ITO) electrodes. The polymer wall made of photoresist (PR) can be formed before and after coating vertical alignment layer. In the first case (named C-1 cell), the negative photoresist (AZ CTP-100 from AZ-Korea) was coated with a thickness of 4 μm and then UV was exposed to PR. The PR was etched by developer (AZ 300 MIF from AZ-Korea) to form a patterned structure with square shape of holes. The vertical alignment layer was then spin-coated on the surface of a wall and also ITO coated glass on top substrate. In the second case (named C-2 cell), the vertical alignment layer was already coated on the substrate and then the polymer wall was formed. In the device, the thickness of LC layer (d) was about the same as height of PR. The LC has birefringence (Δn) of 0.11 at 550 nm and dielectric anisotropy $\Delta\varepsilon = -4.7$. The LC was filled using one-drop-filling technology to bottom substrate and then the top and bottom substrates were assembled together using a sealant. The LC has a pitch (p) of 16 μm so that a d/p ratio is about 0.25. Fig. 2 shows image of scanning electron microscope (SEM) of patterned polymer walls using fine chrome mask. One side of patterned area in a square shape is 80 μm and width of polymer wall is 5 μm.

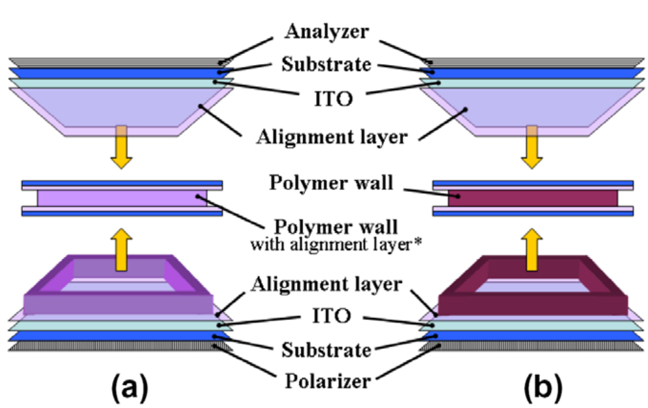

Fig. 1. Structures of (a) C-1 cell and (b) C-2 cell.

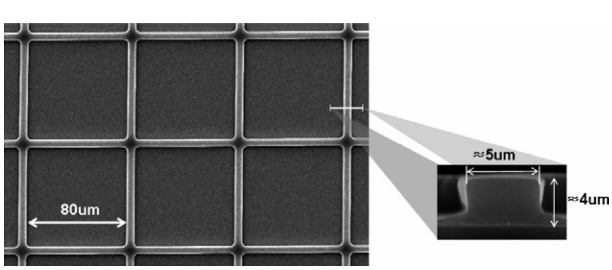

Fig. 2. Top-view and cross section of polymer wall on the bottom substrate.

3. Observation and discussion

The textures of fabricated cells were observed under polarizing optical microscope by applying a square wave voltage of 60 Hz. Fig. 3 shows optical microphotographs of the LSH cells in a dark (0 V), gray-scale (2.6 V), and white (5 V) state according to fabrication process in which the transmission axes of crossed polarizers are positioned along horizontal and vertical direction. Interestingly in on-state, four-brush schlieren textures in different directions are observed in both the cells which appears along diagonal direction in C-1 cell and horizontal and vertical direction in C-2 cell. This indicates that the voltage-dependent liquid crystal reorientation is strongly dependent on boundary condition of polymer wall.

Because the vertical alignment layer is covered over the polymer wall in the C-1 cell, the chiral-doped LC on the surface of polymer (if exists with a cell gap less than 1 μm) could be aligned vertically, and thus the texture above polymer wall at 0 V shows a perfect dark state. However, the vertical alignment layer is also coated on sides of polymer wall and thus the LC could be deformed with tilt and twist from vertical alignment condition. As a result, some liquid crystals along the tangent surface of a wall are deformed and their optic axes are deviated from the polarizer axis, causing a light leakage. If the cell is rotated by 45°, the light leakage becomes stronger, as shown in Fig. 4a. This indicates that the LC near sides of polymer

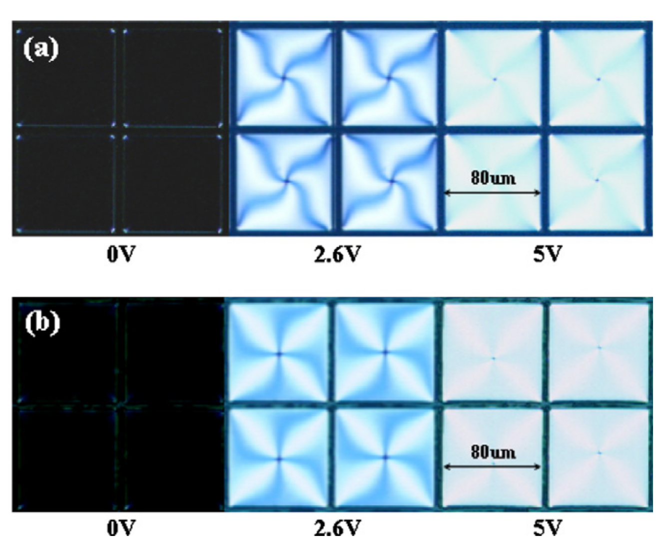

Fig. 3. Optical microphotographs of the LC textures at 0 V, 2.6 V, and 5 V in (a) C-1 and (b) C-2 cells.

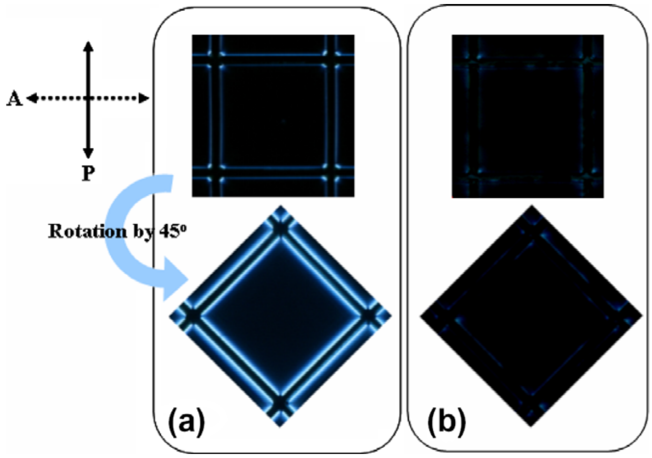

Fig. 4. The light leakage of a dark state in (a) C-1 and (b) C-2 near the polymer wall according to transmittance axis of crossed polarizer.

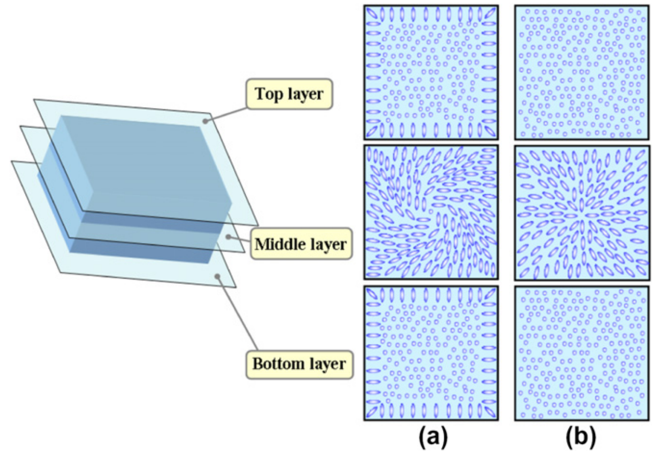

Fig. 5. Schematic two-dimensional orientation of LC in on state at three different vertical distances for (a) C-1 and (b) C-2 cells.

wall is twisted from top to bottom substrate and β defined as an angle between the polarizer axes and initial biased azimuthal directions is 45°.

In contrast to the light leakage in the C-1 cell, the C-2 cell just shows a little light leakage near the polymer wall, but not along the tangent surface of the polymer wall because the vertical alignment layer is not coated on polymer wall in the C-2 cell, as shown in Fig. 4b. Although the cell is rotated by 45°, the light leakage is still little and this much amount of light leakage can be blocked by an optimal design of black matrix (BM) on color filter, when this structure is applied to real LCDs. In addition, minute amount of light leakage in C-2 cell shows that the gap between the top substrate and polymer wall is almost negligible for orientation of LC molecules.

Let us now consider an origin of schlieren textures observed in the C-1 and C-2 cells. The existence of the four-brush texture along diagonal in C-1 cell, and horizontal and vertical direction in C-2 cell indicates that the mid-LC director makes an angle of 0° and 45° with the transmittance axis of polarizers, respectively, although both cells show axially symmetric aligned LC orientation with singularity $S = +1$. We also understand that in the presence of an electric field, the LCs near polymer wall is strongly deformed in the C-1 cell such that the mid-LC director orients perpendicular to the wall, whereas in the C-2 cell, it is almost vertically aligned, but the textures of C-2 is changed similar that of C-1 with time during applying the high voltage for stabilizing order of LCs. From these dark and white state textures, we could assume that the LC orientation in the white cell at three different vertical distances: top, middle and bottom can be existed, as shown in Fig. 5. The orientation of mid-LC director has more degree of curl than that in the C-1 cell.

Additionally, the generation of textures as a function of time by applying an operating voltage is investigated to understand how the textures are formed, since it is strongly related to a response time of the LC mode. In the C-1 cell, the Freedericksz transition voltages near polymer wall and center of wall are different each from other, that is, the voltage near the wall is smaller than that in the center since the LC near polymer wall has some tilted angle from vertical alignment. Therefore, in the C-1 cell, the LCs start reorientation from the sides of polymer wall to the center of the cell. However, in the C-2 cell, the LC reorientation responding to applied voltage is purely depends on shape and size of wall [12] so that more collisions between LC than that in the C-1 cell is expected. However, the C-2 cell is advantageous to achieve a high contrast ratio because it exhibits less light leakage in the dark state than that in the C-1 cell.

For the C-2 cell to exhibit an improved response time, a nucleation of starting point of the LC texture other than just wall is required. Hence, a part of the top electrode for playing role of starting point for reorientation of LCs is patterned at the center of a pixel, as shown in Fig. 6 [13]. In this way, a fringe electric field instead of pure vertical electric field is formed and this field will tilt down the LC in radial direction around this point.

Finally, time-resolved textures of three structures are compared, as shown in Fig. 7. The C-1 cell takes 66 ms for the LC texture to be stabilized while the C-2 cell takes 75 ms due to more collisions than that in the C-1 cell. In

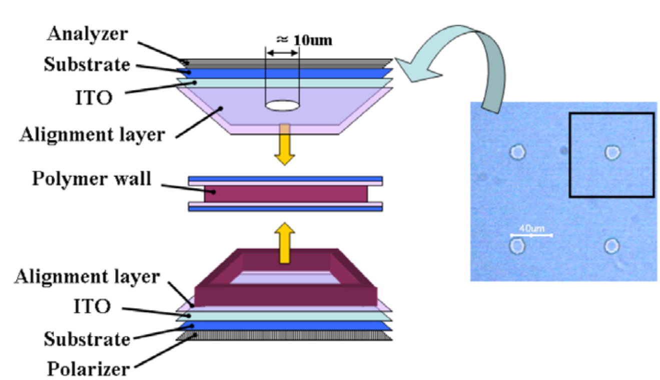

Fig. 6. Structures of C-2 cell with removed part of upper electrode.

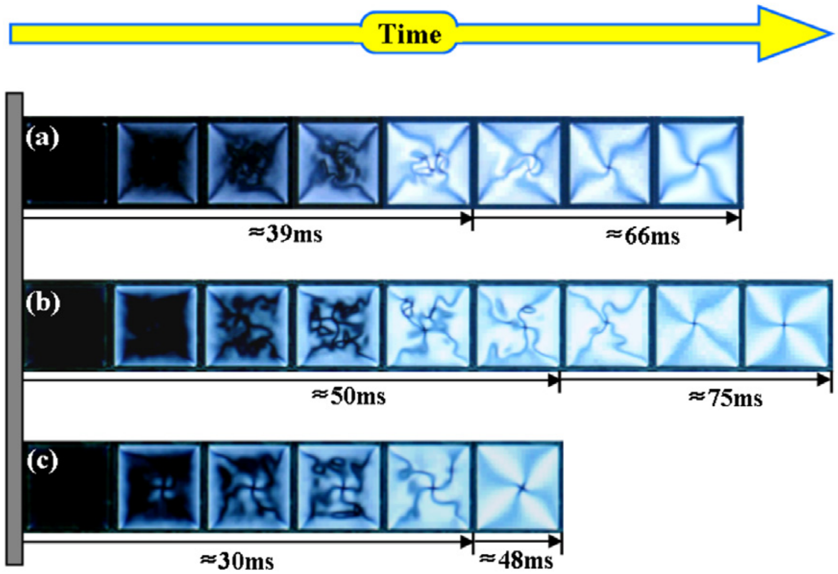

Fig. 7. Comparison of time-resolved textures when an operation voltage is applied to (a) C-1, (b) C-2, and (c) C-2 cell with removed part of upper electrode.

both cases, the light transmittance starts to appear from walls. However, in the C-2 cell with patterned electrode, the transmittance starts at the center of a pixel as well as near polymer walls and thus the appearance of four-brush texture is quicker than other two cells. Consequently, the texture in the proposed cell is stabilized in a shorter time than others, giving rise to fastest response time. In addition, the proposed device could exhibit wide viewing angle, too due to formation of multi-domain with four-brush texture.

4. Conclusion

The LC dynamics in the LSH cell is investigated depending on cell structures. The proposed LSH cell (C-2) with patterned electrode on top side and polymer wall without alignment layer, it exhibits a fast response time and high contrast ratio as compared to C-1 and C-2 cells. We believe that this device has a potential to use in large-size LCDs with high resolution and fast response time.

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