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Dynamic Characteristics of Vertically Aligned Liquid Crystal Device Using a Polymer Wall Associated with the Boundary Condition of Alignment Layer

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Voltage-dependent liquid crystal (LC) reorientation was analyzed in a vertically aligned nematic liquid crystal display with a polymer wall (called a locked-super homeotropic (LSH) device) through the LC textures. The LC textures generated have a singularity of $S = +1$, however, they were strongly dependent on the order of fabrication between the polymer wall and the vertical alignment layer, generating either pure radial or twisted radial orientation of the mid-director. In this article, we investigate how the boundary condition of the alignment layer on a wall surface affects the dynamics of LCs in the LSH mode.

Keywords: liquid crystal display; polymer wall; texture; vertical alignment

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INTRODUCTION

Recently, liquid crystal display (LCD) techniques using both types of an LC with positive and negative dielectric anisotropy are being greatly improved every year in terms of performance in image quality with new LC modes and materials development, and cost with innovative manufacturing techniques such as less mask [1] and new LC filling processes as one-drop filling [2]. Among several LC modes, the most representative are those with homogenous alignment, such as in-plane switching [3,4] and fringe-field switching [5–7], and those with vertical alignment (VA), such as multi-domain VA and patterned VA [8]. These LC modes are being applied to large-size LC-television (LC-TV) and all use one-drop filling manufacturing processes for the filling of LC, and are very sensitive to the gravity-mura [9].

The VA mode, in which the LCs are surrounded by a polymer wall called "locked-super homeotropic" (LSH) mode [10–12] was proposed as an alternative to conventional LC modes, which, although they exhibit high image quality, are sensitive to the gravity mura. The device exhibits a wide viewing angle since the vertically aligned LC molecules tilt down symmetrically around the center of the polymer wall with twist. To accomplish this, the device needs a vertical alignment layer as well as a polymer wall made of photo-resist, and we found that the LC orientation responding to an electric field is strongly dependent on the manufacturing order of the two. Further, time-resolution study of the texture shows that the LC reorientation responding to a vertical electric field is not stable enough, that is, the collisions between LCs occur instantaneously, thus generating undefined LC textures.

In this article, we investigate in detail the LC orientation in the initial state and the LC reorientation reacting to an applied field depending on the manufacturing order of those two layers. From this, one can find an optimal condition which shows fast response time and high contrast ratio, as well as a wide viewing angle.

CELL STRUCTURE AND EXPERIMENTAL CONDITIONS

The testing LSH cells were manufactured in two followings ways. Figure 1 shows a cross-sectional view of the LSH cells depending on manufacturing process. One has a VA layer covering the polymer wall as well as the electrode surface (LSH-1), while in the other the VA layer does not cover the polymer wall, that is, it exists only on the electrode surface of top and bottom substrate (LSH-2).

To manufacture LSH-1 test cells, the negative photo-resist, AZ CTP-100 from AZ Electronic Materials Ltd., was spin-coated on the

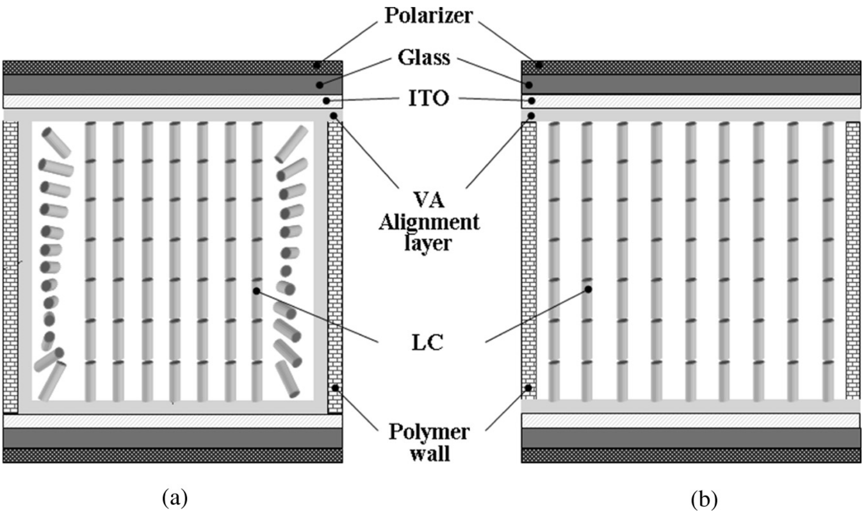
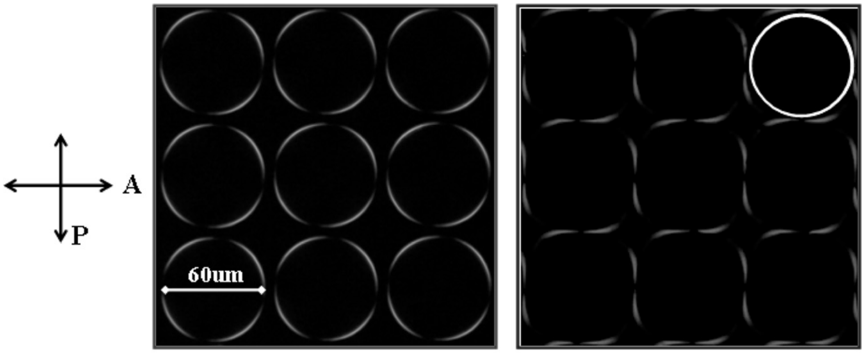


FIGURE 1 Schematic cross-sectional views of (a) LSH-1 cell and (b) LSH-2 cell and the corresponding LC orientation in a dark state.

indium-tin-oxide (ITO)-glass substrate with a thickness of 3.1 μm (this thickness becomes a cell gap (d) of the cells) and then the cylindrical holes with a diameter of 60 μm and a polymer wall with a width of 5 μm were patterned using a photo mask. Second, a homeotropic alignment layer, AL 60101 from Japan Synthetic Rubber, was spin-coated on a bottom substrate with a polymer wall. Third, the LC with negative dielectric anisotropy from Merck Co. (MJ 001911, $\Delta\varepsilon = -4.7$, $\Delta n = 0.11$ at $\lambda = 589$ nm, chiral pitch (p) = 16 μm) was filled at room temperature by the one dropping method. Finally, an ITO-coated glass substrate with a homeotropic alignment layer was attached to the bottom substrate. The two polarizers were attached to the top and bottom substrates of which the axes of both are orthogonal to each other. The LSH-2 cell was also fabricated in the same way, except that the alignment layer was applied before the photo-resist. The LC textures were observed using polarizing optical microscopy.

OBSERVED LC TEXTURES AND DISCUSSION

Figure 2 shows a dark state of both LSH-1 and LSH-2 cells. As is clearly seen, the light leakage in a dark state looks different from one another, that is, it is strongly dependent on the manufacturing process of the two layers. In the LSH-1 cell, the VA layer exists on not only the top of the polymer wall but also on the side of the wall.



(a) (b)

FIGURE 2 Optical microphotographs of (a) LSH-1 cell and (b) LSH-2 cell showing light leakage in a dark state. The circles with white line indicates a hole size of patterned PR.

Since the VA layer is coated on the sides of the polymer wall, the LCs orient themselves perpendicularly to them so that the optic axis of the LC deviates from the crossed polarizer axes, giving rise to leakage. In addition, the detailed observation of the dark state indicates that the light leakage along the circular walls shows asymmetric, that is, cross-shaped dark lines, present with axes not coincident with the polarizer axes. This is related to twist deformation of the LCs from the top to bottom substrate since the LC has a chiral dopant, i.e., without a chiral dopant, the cross-shaped dark lines should exist along vertical and horizontal directions and this was observed in the other test cell. In the LSH-2 cell, the LC texture observed is quite different from that in the LSH-1 cell. In the cell, the LC textures appear above the polymer wall. In a real cell situation, there was a small gap between the two substrates, even though the top substrate was attached to the bottom substrate using a sealant. In addition, there is no VA layer on the top of the polymer wall, so the LCs could not have single domain of the VA alignment and thus generate a light leakage. However, there is no light leakage around sides of the polymer wall like in the LSH-1 cell, because the LCs are vertically aligned in those regions.

For LC-TV applications, achieving a complete dark state is a key factor for realizing a high contrast ratio (CR). Therefore, a little light leakage might deteriorate the CR seriously since the intensity of incident light is close to 10,000 nit. The dark state of both cells under strong illumination conditions are investigated, as shown in Figure 3. The LSH-1 cell shows a slight light leakage inside, as well as near the

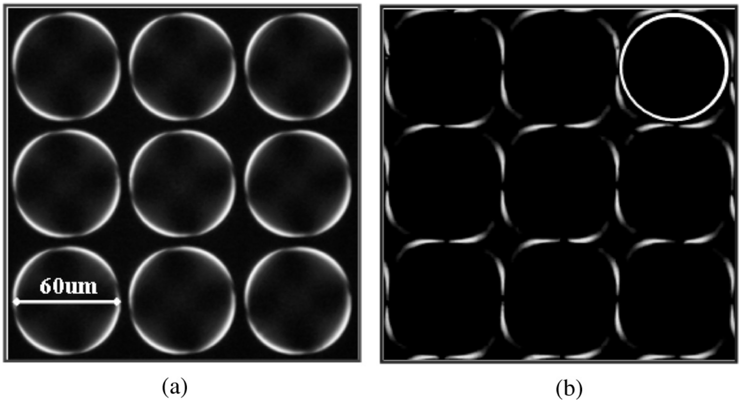
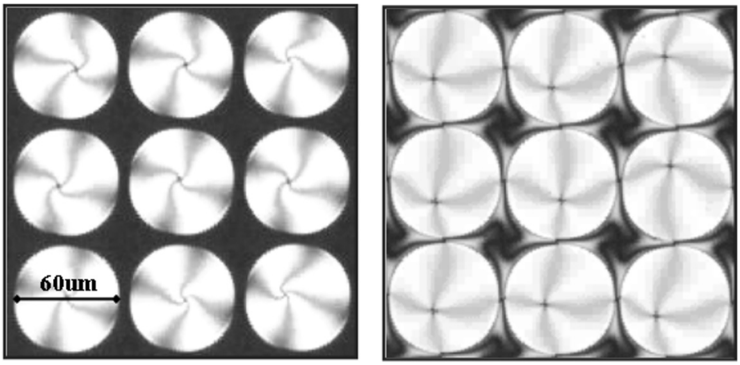


FIGURE 3 The light-leakage on the surface of a wall with switching the light source strength in LSH-1.

sides of the polymer walls. This indicates that the deformed LCs near the sides of the polymer wall affect the LC orientation even inside the polymer walls, which results from continuous LC deformation from the sides of the wall to insides. In contrast to this cell, the LSH-2 cell shows a complete dark state even in strong illumination, except for the increased light leakage above the wall. In real LCDs, each room plays the role of a pixel and thus, the polymer wall is located above signal lines such as data and gate lines, which block incidental light. In addition, the black matrix is generally located on the top substrate blocking any unwanted light. In this view point, the LSH-2 cell is advantageous to realize a high CR.

Next, the LC orientation and LC dynamics in the two cells when a voltage is applied is investigated and compared. Figure 4 shows LC textures of two cells when a voltage of 5.5 V is applied. Interestingly, both cells show crossed schlieren textures, however, the cross-shaped schlieren textures in the LSH-1 cell position themselves along diagonal directions while they position themselves along horizontal and vertical directions in the LSH-2 cell. Since the LC has a chiral dopant, the LCs tilt down with a twist of about 90° from the top to bottom substrate when the voltage is applied. With this assumption, the transmittance was calculated while rotating the 90° twisted VA cell, as shown in Figure 5. For this calculation, the transmittance for parallel polarizers was assumed to be 38%. Here, the angle β is defined as an angle between the polarizer axis and the tilting direction of the first LC layer on the top substrate. The transmittance oscillates as a function of angle β, such that it is minimal and maximal when β is



(a) (b)

FIGURE 4 Optical microphotographs of (a) LSH-1 cell and (b) LSH-2 cell showing dark brush in a white state at the 5.5 V.

45° and 0°, respectively. In other words, the transmittance is lower when a mid-director makes an angle of 0° with the polarizer axes than when it makes an angle of 45° with the polarizer axes. From this result, one can estimate an LC orientation in a white state in the LSH-1 and the LSH-2 cells, as shown in Figure 6. In the LSH-1 cell, the mid-director has a twisted radial configuration (the mid-director has a slant angle with respect to the sides of the polymer wall and a twist along the sides of the polymer wall) whereas in the LSH-2 cell,

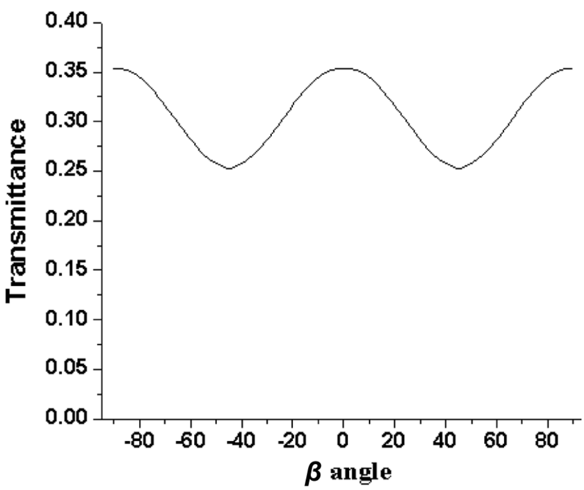


FIGURE 5 Transmittance variation according to angle β in the VA-TN.

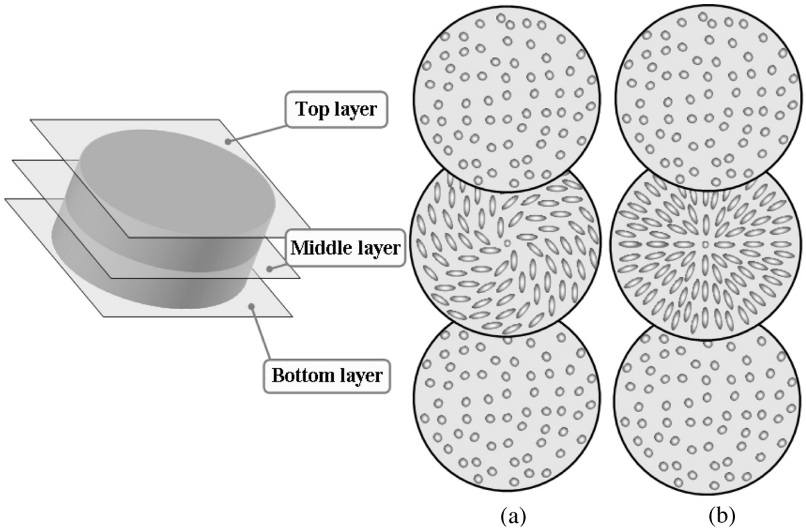
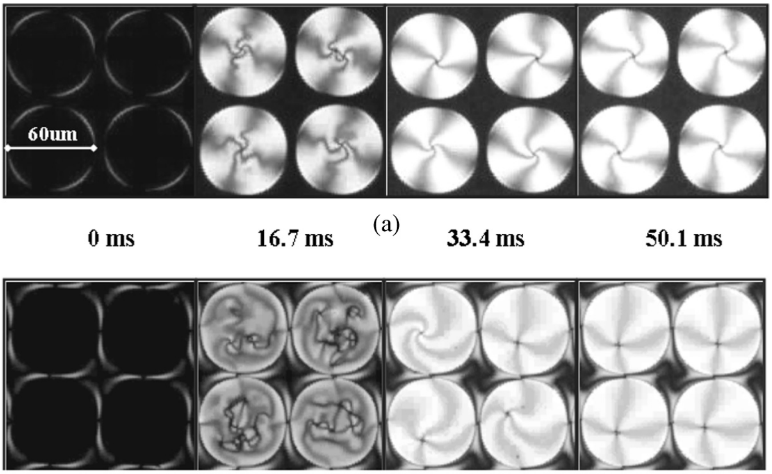


FIGURE 6 The time-resolved textures of LSH-1 cell and LSH-2 cell in crossed polarizers.

it has a radial configuration (the mid-director is perpendicular to the sides of the polymer wall). Nevertheless, both cells have a defect with a singularity of $S = +1$ at the center of each room.

Now, the LC textures have been studied more in detail as a function of time resolution, because time-resolved texture is strongly related to the response time of the device. Although the LC textures remain very stable after enough relaxation time, instantaneous reorientation to the applied voltage shows dynamic instability, as shown in Figure 7. As indicated, in the LSH-1 cell, the deformed LC near the sides of the polymer wall plays the role of a starting point for field-response deformation. Nevertheless, the LC dynamics show instability at an instantaneous time of 16.7 ms. Unlike in the LSH-1 cell, the LSH-2 cell exhibits more instability at an instantaneous time when voltage is applied. The vertically aligned LC molecules far away from the sides of the polymer wall do not know where to go and collide each other, generating undefined LC texture. Over time, the polymer wall plays role of boundary conditions which define for the LCs to be deformed in a minimizing free energy. This makes reorientation time very slow, though, this unstable texture could be removed by patterning the center of ITO with a circle shape on the top substrate because this also plays the role of nucleating seeds for the LCs to be deformed in a defined way [13].



(b)

FIGURE 7 Schematic LCs orientation in (a) LSH-1 cell and (b) LSH-2 cell in a circular hole at on state.

SUMMARY

Manufacturing process-dependent LC dynamics in the LSH cell have been investigated. Considering a dark state, the LSH-1 cell shows a stronger light leakage than that of the LSH-2 cell. However, the LSH-1cell is more stable than the LSH-2 cell in terms of time-dependent LC textures when voltage is applied because the deformed LC from the initial state near the sides of the polymer wall plays a role in deforming them. Both cells show a defect point with a singularity of $S = +1$, though the on-state LC configuration is slightly different between the two. Time-resolved LC textures inform us that neither cell is enough to give rise to a fast response time, which is very important in LC-TV applications. Further efforts to improve response time are in progress [13].

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