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Surface Polymer-Stabilized Vertically Aligned Liquid Crystal Cells with Various Polymer Wall Structures

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Vertically aligned liquid crystal (LC) surrounded by polymer wall, which is also known as locked-super homeotropic (LSH) mode has several advantages such as rubbing- and spacer-free, wide-viewing angle and stable LC dynamics against external pressure. However, the LSH mode shows slow response time due to the instantaneous collision between the LC molecules when a vertical electric field is applied, because the reorientation of chiral doped vertically aligned LC is only determined by the polymer wall. We found that the slow response time can be improved by surface polymer-stabilized technique where surface pretilt angle is defined on alignment layers. This technology can be used in any shape of polymer wall. (PACS 42.79.Kr, 85.60.-q).

Keywords: liquid crystal; polymer stabilization; polymer wall; vertical alignment

1. INTRODUCTION

The market of liquid crystal display televisions (LCD TVs) is growing rapidly with the development of different LCs modes such as

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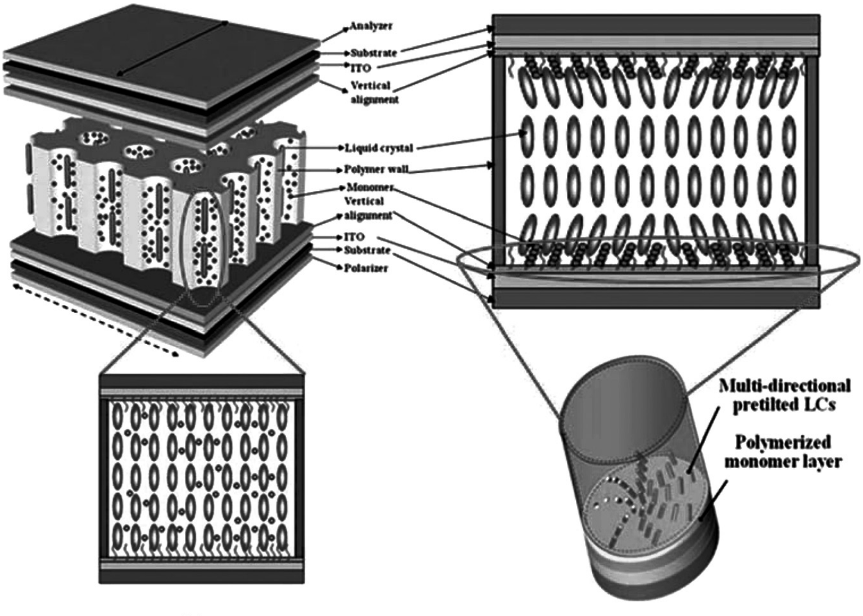
multi-domain vertical alignment (MVA) [1–3] fringe-field switching (FFS) [4–6] and in-plane switching (IPS) [7]. These modes show both the high image quality and wide viewing angle. At present, there are two main approaches to form multi-domain without a rubbing process. One is to form a protrusion which is called MVA, and the other is to pattern pixel and counter electrodes called patterned VA (PVA) [8–11]. In the commercialized MVA and PVA modes, the LCs with negative dielectric anisotropy are almost perfectly vertically aligned corresponding to the substrates. For the LCs nearby the protrusion or patterned electrode, they are triggered by the oblique electric field generated by either the protrusion or patterned electrode to tilt down the LC molecules in multiple directions. In the regions away from the protrusion or patterned electrode, LCs will be bent down in any azimuthal direction under the applied electric field, which generates the collisions between LCs and therefore decreases the transmittance of the LCD. In addition, both MVA and PVA LCDs are very sensitive to the external pressure. The LC orientation will be disturbed instantaneously with strong ripple marks when the pressure is applied. This phenomenon is especially undesirable for touch panel LCDs. To suppress ripples, another type of MVA, called locked-super homeotropic (LSH) cell where the LC is surrounded by polymer walls was suggested [12–15]. In the LSH mode, the polymer wall is formed at the border of each pixel acts as a spacer and also limits the LC in each pixel.

In the previous reports about the LSH cells, the polymer wall with a cylindrical shape was mainly investigated because the LCs can reorient with axially symmetric alignment with defect strength $S = +1$. However, in a real pixel structure, the pixel shape is not cylindrical. Instead, it is rectangular with horizontal to vertical length ratio of 1:3. Therefore, the LC reorientation responding to an electric field in different structures of polymer walls such as square, hexagon, and rectangular shape should be investigated. Furthermore, since the reorientation of the LC is determined only by polymer wall structure in the LSH cell, the rising response time is rather slow [15]. Previous reports showed that the rising time of the LSH cell can be improved by adopting surface polymer-stabilized technique in which surface tilt angle on vertical alignment layer is defined without rubbing process [16]. We have also investigated different kinds of polymer wall structures if this technology is still valid, which structure shows better electro-optic performances, and how the LC orientation is especially in the rectangular structure which is similar to conventional pixel structure.

2. CELL STRUCTURE AND SURFACE POLYMER-STABILIZED TECHNOLOGY

Figure 1(a) shows the cell structure of the LSH mode. In this device, two indium-tin-oxide coated glass substrates are used. At first, vertical alignment layers are coated on both substrates and then the polymer wall is formed on one of the substrates using photoresist [12]. The chiral-doped nematic LC with reactive mesogen monomer is dropped into the polymer wall on bottom substrate and finally, the top substrate is attached to the bottom one. The cell appears to be black in the absence of the electric field under crossed polarizer since the LCs are vertically aligned. When an electric field larger than the threshold voltage is applied, the LCs near polymer wall are first reoriented and then form axially symmetric alignment showing four-brush schlieren texture due to cylindrical shape of polymer wall, which gives rise to the transmittance of the LSH cell. However, since the nucleation point starts from the wall in this structure and the LC is perfectly vertically aligned inside each polymer wall, it takes quite



(a) (b)

FIGURE 1 (a) Schematic cell structure of the LSH cell with reactive mesogen doped LC and (b) Cross-sectional view of one pixel showing polymerization of reactive mesogen on vertical alignment surfaces.

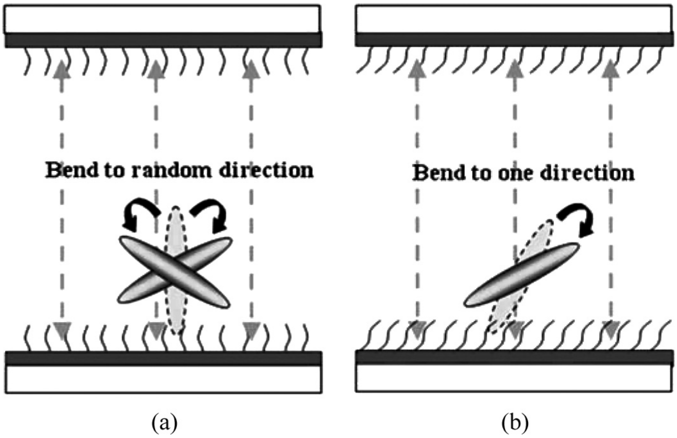


FIGURE 2 Effect of (a) nonexistence and (b) existence of defined pretilt angle layer in the LSH cell. The LC can tilt down in any direction without the defined tilt angle, while it can tilt in one direction with the defined tilt angle in the presence of a vertical electric field.

long time for the LC texture to get stabilized, showing slow rising response time.

In order to overcome such slow response time, surface polymer-stabilized technology is applied. In this technology, less than 1 wt.% of reactive mesogen monomer is typically doped into the LC media and the orientation of LC molecules follows nematic ordering. At first, a voltage larger than threshold voltage is applied to the cell so that the LC molecules can transform into the axially symmetric orientation due to chiral dopant and polymer wall [12], and then the cell is exposed to the UV radiation. At optimal exposure conditions the monomer can be polymerized on vertical alignment surface forming multi-directional defined surface pretilt angle, as shown in Figure 1(b). The LC with pure vertical alignment can be bent in any azimuthal direction, causing collisions between LCs while the LC with defined tilt angle can be bent only in one direction in the presence of vertical electric field, as shown in Figure 2. Hereafter, the LSH cell with surface polymer-stabilized technique will be assigned as Q-LSH cell.

3. RESULTS AND DISCUSSION

During the cell fabrication, a LC material (dielectric anisotropy $\Delta\varepsilon = -4.9$, birefringence $\Delta n = 0.14$ at $\lambda = 589\,\text{nm}$, chiral pitch $=$ 16 μm) from Merck-Korea is used. The LC material was mixed with

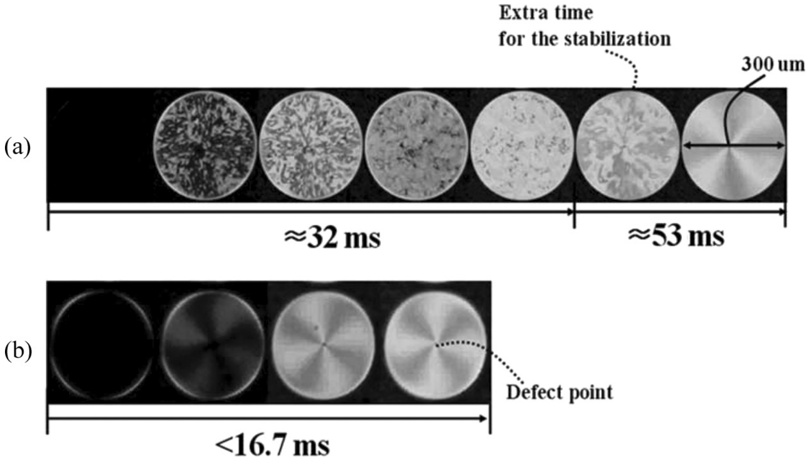
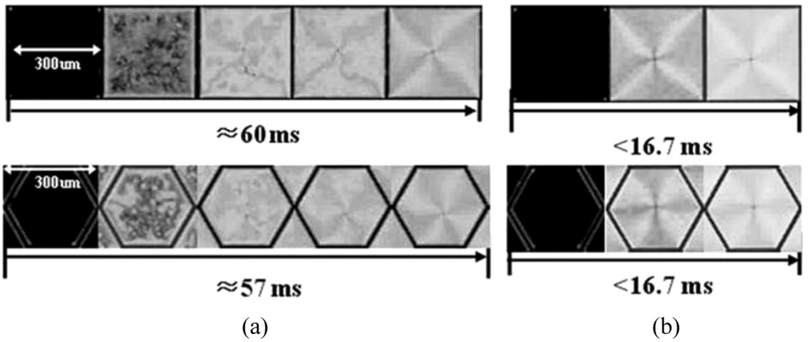


FIGURE 3 Comparison of series of the time-resolved LC textures to reach 90% of maximum transmittance according to the size of polymer wall between conventional LSH (a) and Q-LSH (b) cells.

a reactive mesogen monomer RM 257 from Merck and a photo initiator Igracure 651 from Ciba. The weight percents of the monomer and the photo initiator with respect to the LC were 0.1% and 0.001%, respectively. The spacer height was 4 μm, which is equal to a cell gap. Four different polymer wall structures such as circular, square, hexagonal, and rectangular shape in terms of top view have been investigated.

Figure 3 shows the effect of the defined pretilt angle in Q-LSH cell when a voltage V_{90} at which 90% of maximum transmittance reaches is applied. We compare a series of time-resolved textures and measured the response times of Q-LSH and conventional LSH, which have defined and random pretilt angles, respectively. The diameter of observed circle was 300 μm. In the conventional LSH cells, the LC texture is undefined at an instant time when the voltage is applied and reaches final stabilized texture with four brushes, as shown in Figure 3(a). It takes about 32 ms to change into a four-brush texture and another 53 ms to get stabilized. However, in the Q-LSH cell, the whole process takes less than 17 ms, as shown in Figure 3(b). In addition, in the conventional LSH cell, the location of defect point with defect strength $S = +1$ is not fixed at the center of the polymer wall. Therefore the location of the defect point could be varied depending on the applied voltages. However, in the Q-LSH cell, it is fixed at one position, which induces fast response.



(a) (b)

FIGURE 4 Comparison of series of the time-resolved LC texture to reach 90% of maximum transmittance in the square and hexagonal shape of polymer walls between conventional LSH (a) and Q-LSH (b) cells.

Figure 4 compares a series of time-resolved textures with various shapes of polymer walls in order to observe the shape effect. In the LSH cell with both square and hexagonal walls, the LC textures are undefined at an instant time when a voltage V_{90} is applied but reaches stable four brushes schlieren texture after total relaxation time of about 60 ms for both cases. Whereas in the case of Q-LSH cell, both cells exhibit total relaxation time less than 17 ms.

In real LC-televisions, the pixel structure is in a rectangular shape due to color filter arrangement. We also investigated performance of LSH cell for a large pixel size with 200 μm (horizontal) $\times$ 600 μm (vertical). As indicated in Figure 5(a), the LC texture is random instantaneously when a voltage is applied and reaches final stable texture with three consecutive defect points. The full relaxation process takes about 71 ms in conventional LSH cell while Q-LSH cell only needs less than 17 ms. The location of defect points in LSH cell are time- and voltage-dependent and hence it might be the reason for the slow response time. Furthermore, according to the analysis of mid-director distribution along disclination line at the center of rectangular wall, the LC is still forming multi-domain, which means Q-LSH cell even with rectangular shape could exhibit wide viewing angle.

From the above results, it can be seen that that relatively free design is possible in the Q-LSH cell regardless of the shape and size. In this way, it is possible to improve the response time of the LSH cell while keeping wide viewing angle characteristics.

The aperture ratio and light leakage effects also need to be taken in account in LSH cell. When patterning photoresist using

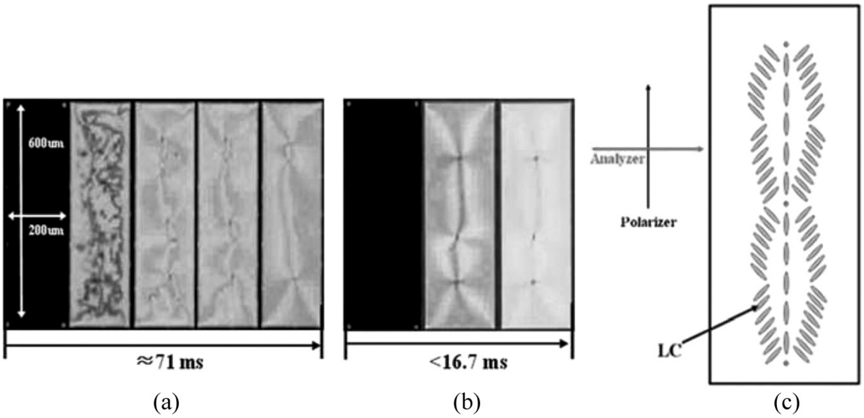


FIGURE 5 Comparison of series of the time-resolved LC texture to reach 90% of maximum transmittance in the rectangular shape of polymer walls between conventional LSH (a) and Q-LSH (b) cells, and (c) analysis of mid-director distribution in the Q-LSH cell.

photolithography process, the scanning electron microscopy image of wall shape shows that it is not perfectly patterned as much as expected, as indicated in Figure 6(a), that is, the wall has some taper angle and also the width of polymer wall on the bottom side is wider

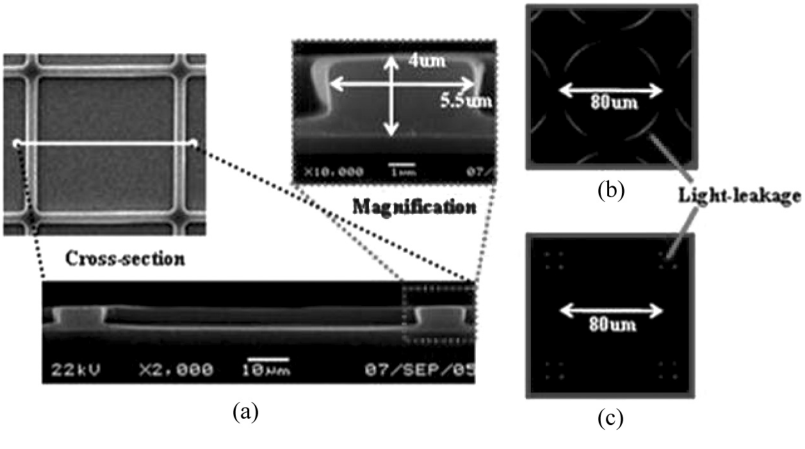
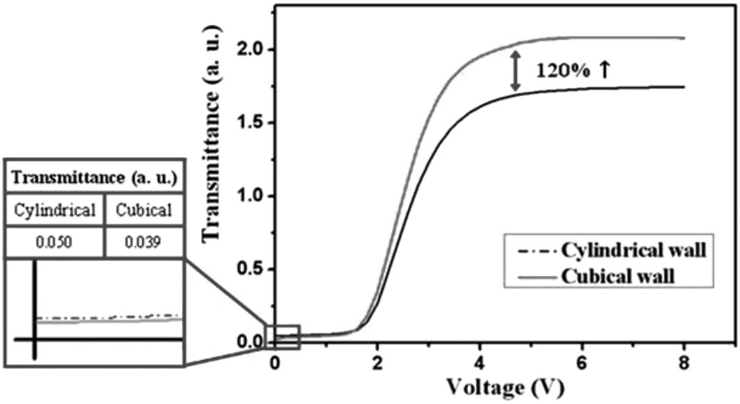


FIGURE 6 Scanning electron microscopic image of polymer wall in the LSH mode with top and cross-sectional view (a), and light-leakage of cylindrical polymer wall (b) and cubical polymer wall (c) at the dark state.



Transmittance (a. u.)	
Cylindrical	Cubical
0.050	0.039

FIGURE 7 Comparison of voltage-dependent curves of cylindrical and cubical polymer walls. The inset indicates light leakage level of a dark state.

than that of top side. This causes deformation of vertically aligned LC and hence generating some light leakage under crossed polarizer, as shown in Figures 6(b) and 6(c). The Q-LSH cell with cylindrical wall has some light leakage along the tangent of the wall; however, no light leakage exists in the horizontal and vertical direction because the optic axis of the LC is coincident with the polarizer axis. In the cell with cubical structure, light leakage occurs only at four corners of the wall because the bend direction of LCs caused by tapered polymer wall is coincident with the polarizer axis. As a result, although there is LC deformation, it does not cause light leakage.

Figure 7 shows the comparison of voltage-dependent transmittance curves between the cubical and cylindrical polymer walls. Both devices shows exactly same threshold voltage, however, the cell with cubical wall shows less light leakage and higher transmittance than those of the cell with cylindrical wall. The higher transmittance in the cubical wall than that in the cylindrical wall simply comes from high aperture ratio, which is defined as the ratio of transmittance area to total area, since the polymer wall under crossed polarizer cannot transmit light.

4. SUMMARY

In this study, we investigated the shape effect of polymer walls on electro-optic characteristics of the LSH mode cell and the influence of surface polymer-stabilized technique on response time as well as LC texture of the LSH cell. The results show the LSH cell with the defined pretilt angle can greatly improve the response time as compared to normal LSH cell due to stabilized texture without causing molecular collisions. In addition, surface polymer-stabilized technique is valid in any shape and size of polymer wall, which makes this technology easier to utilize in the practical LCDs.

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