Homeotropically aligned nematic liquid crystal device locked by a polymer wall with wide viewing angle

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We fabricated a homeotropically aligned nematic liquid crystal display (LCD), where the chiral-doped LC with negative dielectric anisotropy is locked by a polymer wall under crossed polarizers and whose on and off states are controlled by a vertical electric field. In the absence of an electric field, the rubbing-free device appears to be dark. In the presence of the field, the homeotropically aligned LCs tilt down, giving rise to brightness but four brush schlieren textures appear with point singularity $S=+1$. This indicates that the mid-directors have radial alignment inside the polymer wall in the voltage-on state. Consequently, the device shows excellent viewing angle characteristics. The electro-optic characteristics of one prototype with excellent viewing angles are reported herein. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1849842]

Liquid crystal displays (LCDs) that play an important role in human to machine interfaces are being widely used in various applications such as mobile displays, notebook computers, personal computer (PC) monitors, and televisions (TV). In particular, the PC monitor and TV applications have been made possible with the help of several new LC devices exhibiting high image quality such as film-compensated TN using discotic liquid crystals,[1] in-plane switching (IPS),[2,3] multidomain vertical alignment (MVA),[4,5] and fringe-field switching.[6–8] Recently, various kinds of the large-size LCDs using the IPS device (52 in.),[9] and MVA devices like patterned vertical alignment (PVA)[10] with 57 in. and advanced super-view[11] with 37 in.

In matters of fabricating the large-size LCDs, the IPS device requires a rubbing process, which may cause dust and electrostatic problems but all MVA devices do not require the rubbing process but need an extra process such as formation of protrusion and fine patterning of a transparent electrode. In those LCDs, the column spacer using a photoresist is used to keep a cell gap between top and bottom substrate instead of using plastic balls in the conventional process. As a result, all devices have one common problem. The LC drops down to the bottom of the cell by gravity, causing nonuniformity in the displayed area (called gravity mura).[12] Besides, another type of LC device called axially symmetric aligned microcell[13] was reported, which utilizes a phase separation between the polymer monomer and the LC, but it has not been used commercially so far. Therefore, the fabrication of the LCDs with a rubbing-free process, wide viewing angle, and without the gravity mura is most desirable if possible.

In this letter, we suggest rubbing-free superhomeotropic LCD where the LCs are locked in each domain by a polymer wall, named locked-super homeotropic (LSH) device. In the LSH device, the polymer wall plays the role of both the spacer and the locking of the LCs in a confined area. The device shows a dark state since the vertical LCs exist under crossed polarizers at an initial state and with applied vertical electric field, the LC mid-directors tilt down symmetrically around a center in each domain, exhibiting a wide viewing angle.

The cell fabrication was as follows. First, a homeotropic alignment layer JALS-204 from Japan Synthetic Rubber Co. was spin-coated on an indium-tin-oxide (ITO) coated glass substrate with 800 Å thickness. Second, the negative photoresist AZ CTP-100 from Clariant Korea Co. was spin-coated on the glass substrate with 3.1 μm thickness [same as the cell gap (d)] and then the cylindrical holes with their diameter of 60 μm and width of polymer wall 20 μm were patterned using a photo mask, as shown in Fig. 1. Third, the LC with negative dielectric anisotropy from Merck Co. [$\Delta\varepsilon=-4.7$, $\Delta n=0.11$ at $\lambda=589$ nm, chiral pitch $(p)=16$ μm] was filled at room temperature by the one dropping method.[14] Finally, an ITO-coated top substrate with a homeotropic alignment layer was attached to the bottom substrate and then the polarizers were attached to the top and bottom substrates which crossed each other. Figure 2 shows a schematic cell structure of the LSH device, assuming that the LCs are vertically aligned to the substrates and parallel to the polymer walls. Since the LCs are filled inside the polymer walls and locked by boundary conditions, the LCs in one hole do

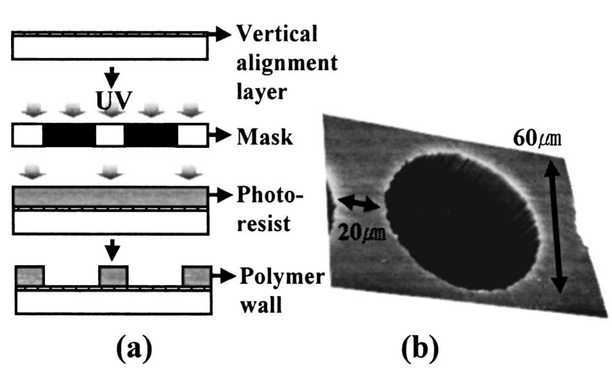

FIG. 1. Cell fabrication process of the LSH cell (a) and noncontact 3D measurement of a hole which exhibits the hole size and depth (b).

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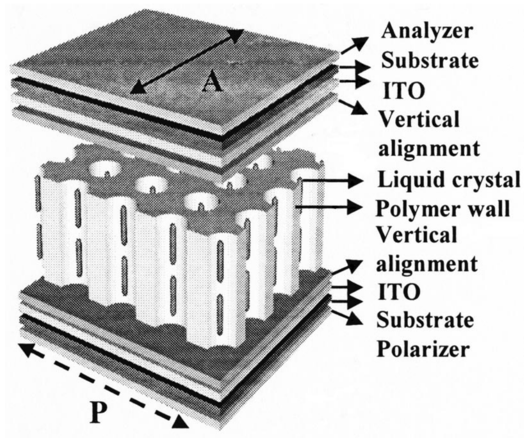

FIG. 2. Schematic cell structures of the LSH cell, where P and A indicate the polarizer and analyzer, respectively.

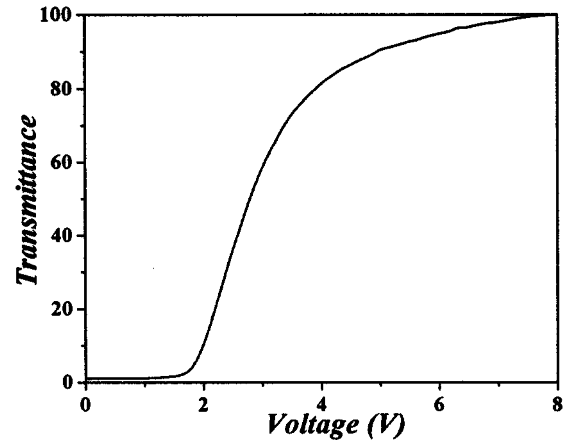

FIG. 4. Voltage-dependent optical transmission curve.

not flow into the other holes by gravity and external pressure applied to the cell.

The test cell made was observed under optical polarizing microscopy by applying a square wave voltage of 60 Hz, as shown in Fig. 3. At a voltage below Freedericksz transition threshold, V_{th}, the LC molecules are anchored homeotropically on both alignment layers so that the polarization state of an incident light through the polarizer remains unchanged. Consequently, the light is blocked by the analyzer, giving rise to a completely dark state although a little light leakage is observed near polymer walls.[15] With increasing voltage larger than V_{th}, the transmittance starts to occur since the LC tries to orient perpendicular to the vertical field direction but four dark brushed textures whose axes make 45° with crossed polarizer axes appear. Here, we have rotated crossed polarizers by 360° and the textures rotate in the same direction, implying that the LC orientation has radial configuration with point singularity $S=+1$. Similar texture has been observed in droplets of the LC with negative dielectric anisotropy.[16] With further increasing voltage, the transmittance increases while the darkness of the four dark brushed textures weakens although such textures still remain. Irrespective of applying voltage, the dark points which are disclination lines exist at the center of the holes, indicating that the LCs are vertically aligned at those points. Next, the transmitted light intensity as a function of applied voltage for the cell is measured, as shown in Fig. 4. A slight light leakage is observed at 0 V, and the transmittance begins to occur at 1.5 V. At 5 V, the transmittance reaches 90% of maximal transmittance but it keeps increasing until 8 V since the cell retardation value is not high enough to maximize the light efficiency. Since the LSH device is chiral-homeotropic cell, the optimal effective $d\Delta n$ of the cell should be much higher than $\lambda/2$, i.e., 0.562 μm to maximize the transmittance.[17]

In order to understand more clearly the LC configuration inside a cylindrical cavity, we have performed a computer simulation using the commercially available software "LCD Master" (Shintech, Japan), where the motion of the LC director is calculated based on the Eriksen–Leslie theory[18] and 2×2 Jones matrix is applied for optical transmittance calculation. Here, we assumed the $d\Delta n$ of the cell and the d/p ratio to be 0.34 μm and 0.19 with LC's elastic coefficients ($K_1=13.5$ pN, $K_2=6.5$ pN, $K_3=15.1$ pN), respectively, like in the experiment and both surfaces have biased azimuthal directions perpendicular to each other with surface tilt angles of 88° such that the LC with negative dielectric anisotropy tilts down by a vertical electric field, while twisting by 90° from the top to bottom substrates. At several different gray levels, the transmittance was calculated while rotating the cell from 0° to 90° under crossed polarizers to explain the transmittance change along the azimuthal directions inside circular holes, where β indicates an angle between the polarizer axes and initial biased azimuthal directions. As indicated in Fig. 5, the transmittance oscillates along the azimuthal angles such that it is highest when the biased directions coincide with the polarizer axes while the mid-director makes about 45° with the polarizer axis, and is lowest when β is 45° while the mid-director makes about 0° with one of the polarizer axis. This implies that the LCs are twisted and the

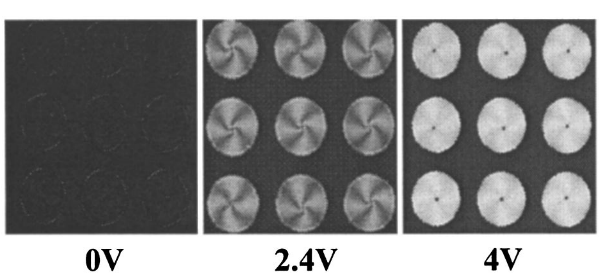

FIG. 3. LC cell textures in cylindrical holes observed under polarizing microscopy with increasing voltage.

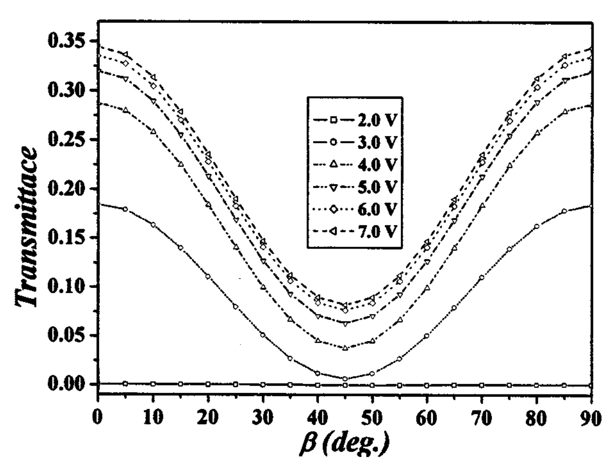

FIG. 5. Calculated transmittance at several grey levels while rotating the cell under crossed polarizers explaining the transmission change in a circular hole.

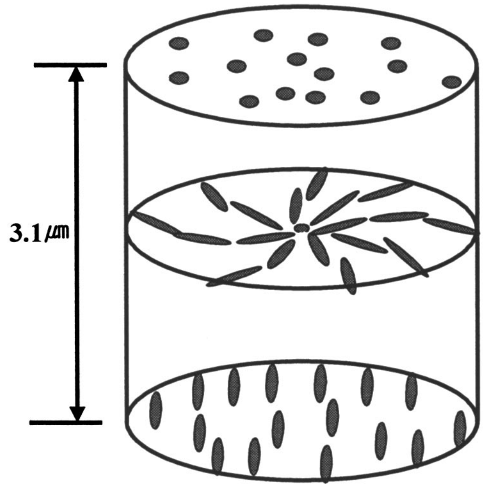

FIG. 6. Schematic LC orientation in a circular hole.

mid-directors have radial configuration around the center axis of the hole in the on state, resulting in a continuous change in angles between the mid-directors and crossed polarizer (Fig. 6). Consequently, such a director configuration generates the four brushed dark textures inside a circular hole. Since the mid-directors are axially and symmetrically aligned, the effective phase retardation $d\Delta n$ at given a polar angle is almost constant along all azimuthal directions at given polar angles, which will exhibit an excellent luminance uniformity in the on state. Figure 7 shows iso-luminance curves when the transmittance is at 2.8 and 7 V, which represents mid and white greys, respectively. Here, T_{90}, T_{80}, T_{70}, T_{60}, and T_{50} indicate relative transmittance of 90%, 80%, 70%, 60%, and 50% to the maximum intensity with 7 V at normal direction, respectively. Iso-luminance curve at both greys exhibits excellent symmetry and in addition, the luminance uniformity in white state is excellent such that the relative transmittance of 60% exists over 60° of polar angle at all directions due to symmetric configuration.

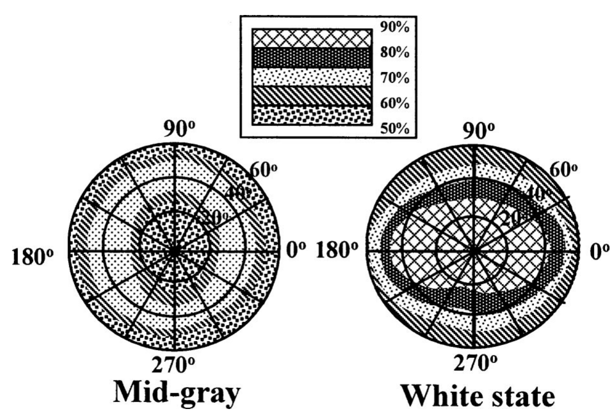

FIG. 7. Measured iso-luminance curves when the transmittance at normal direction is in mid-gray and white state.

We have also investigated the LC orientation when the polymer wall has a square shape instead of a circle but the result was similar.[19] This indicates that the shape of the polymer wall to generate the radial confinguration in the white state could be designed according to the requirements in LCDs.

In summary, we have reported a vertically aligned cell, where the LCs are locked by polymer walls such that the device is free from the gravity mura and has strong resistance against external pressure. In the device, the LCs are vertically aligned at an initial state, and they tilt down symmetrically around the center axis of the circular hole with bias voltage. This radial orientation of the LCs with point singularity $S=+1$ gives rise to excellent luminance uniformity, thereby exhibiting a wide viewing angle. We expect that this concept of the LSH device has strong potential applications to wide viewing angle active-matrix LCDs.

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