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Vertical alignment liquid crystal cell with optically compensated splay configuration of the liquid crystal

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We have observed a phenomenon associated with a transition from vertical alignment to an optically compensated splay structure. With rubbed homeotropic alignment in parallel directions, the device shows vertical alignment but the liquid crystals (LCs) are twisted 180° in the absence of an electric field. Depending on the voltage applied, two different configurations of LCs are possible. After applying a critical voltage, the LC configuration becomes splayed such that the middirector lies parallel to the substrate and around it, and a hybrid structure forms symmetrically. A method for obtaining the transition and the electro-optic characteristics of the device is discussed. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1652230]

Liquid crystal displays (LCDs) play an important role in human to machine interfaces. At present, twisted nematic (TN) LCDs are mainly used for portable notebook computers. However, they show limited viewing angles due to asymmetric director alignment in the gray scale, which limits their application as a replacement of the cathode-ray-tube (CRT) monitor. To be competitive in image quality with the CRT in monitor and television markets, the viewing angle range should be increased and response time of less than 16 ms is required. Recently several new nematic LCD modes to overcome the narrow viewing angle have been introduced. Among them are film-compensated TN using discotic liquid crystals,[1] in-plane switching (IPS),[2,3] multidomain vertical alignment (MVA),[4,5] optically compensated bending (OCB),[6–8] and fringe-field switching (FFS).[9,10] Among them, the OCB mode exhibits the fastest response time, less than 10 ms, due to flow acceleration effects; thus this device is one of the strongest candidates for LC television application. In the OCB mode, the LC has splay alignment at the initial state and when a voltage is applied to the cell, it transits to a bending state, but time is required for the transition from the splay to bending state. By applying an initial voltage setting, the transition time can be controlled.[11] Optical switching of a white and a dark state in the OCB cell is obtained in the bending state by controlling voltages and the device with the help of a self-compensation structure. Optical compensation films shows wide viewing angles.[12]

In this letter, we propose a LCD mode with an optically compensated splay (OCS) structure achieved from vertical alignment at the initial state. We describe how a vertically aligned cell can be transited depending on the voltage applied so the OCS structure is obtained, and also discuss its electro-optic characteristics evaluated by simulations.

For cell fabrication, a vertical alignment layer from Japan Synthetic Rubber (JALS-696) with thickness of 700 Å was coated on indium–tin-oxide (ITO) deposited glass substrates where the electrode area was 1 cm^2. The rubbing was done on top and bottom substrates in parallel directions to give a pretilt angle of 89°. Both substrates were assembled to provide a cell gap (d) of 5.3 μm. Then the LC had negative dielectric anisotropy of -4 and birefringence of 0.077 at 589 nm was filled into the cell at room temperature.

The test cell made was observed under optical polarizing microscopy by applying a sine wave voltage of 60 Hz. First, the rubbing direction (RD) of the cell is coincident with one of the transmission axes of the crossed polarizer. Before voltage is applied, the cell shows a good dark state, indicating the LCs are almost vertically aligned as shown in Fig. 1(a). When voltage V is applied above threshold voltage V_{th} of 2.7 V_{rms}, the transmittance starts to increase, but disclination lines occur, indicating some collisions between the LC molecules as shown in Fig. 1(b). Here, the picture was taken 1 s after applying V_{th} and then as the voltage was increased gradually to high voltage V_H of 20 V_{rms}, the disclination lines disappear, giving rise to uniform transmittance bluish white in color as shown in Fig. 1(c). Then the voltage was released to zero and initial vertical alignment of the LC was

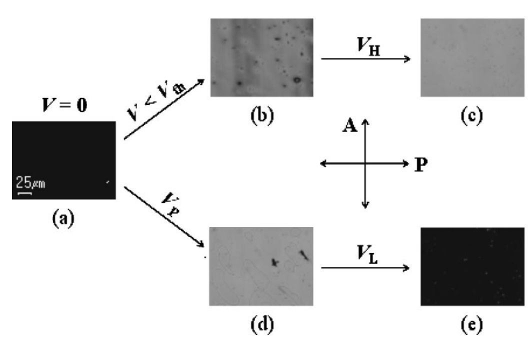

FIG. 1. Optical microscopic image of the texture depending on the voltage applied. When the voltage applied starts to increase from zero to larger than V_{th} and high voltage the transmittance starts to increase. However, when high pulse voltage V_P is applied, a new domain starts to form and extends to the whole area if the voltage decreases from V_P to V_L.

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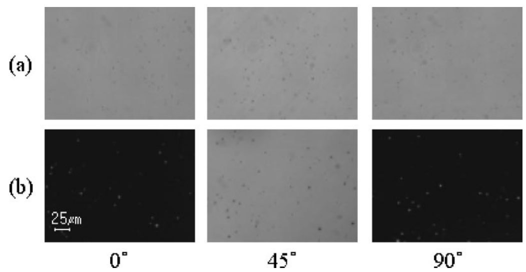

FIG. 2. Optical microscopic image of the texture when the rubbing direction makes angles of 0°, 45°, and 90° with transmission axes of a crossed polarizer for the twist (a) and splay (b) states.

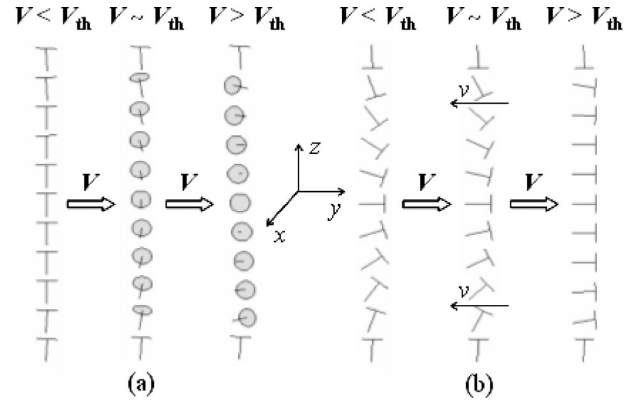

FIG. 3. Possible configuration and deformation of LC molecules as a function of the voltage applied for a parallel rubbed vertically aligned cell: (a) LC with 180° twist from top to bottom and (b) LC without twist. Here, ν indicates a flow direction by deformation of the LCs during the transition.

obtained. Interestingly, when pulse voltage V_P as high as 50 V_{rms} is applied to the cell instantaneously, an abnormal phenomenon occurs: Under observations of the cell with the rubbing direction coincident with the polarizer's axis, closed loops appear[13] first and near the line of loops some dark domains start to occur, as shown in Fig. 1(d). The size of the dark domains becomes larger and they can be accelerated if the voltage pulse is applied continually or a higher voltage pulse is applied, or the voltage decreases to a low value of V_L. Finally, the domain covers the whole area and the cell becomes completely dark if the voltage decreases to 3 V_{rms} after 3 min, as shown in Fig. 1(e). The texture in Fig. 1(e) was stable and remained that way as long as voltage larger than 3 V_{rms} was applied.

From the observations, we think of two possible states: First, in normal operation, the LCs tilt down in three dimensions and twist, and thus transmittance occurs. Second, in the domain generated, the LCs tilt down in two dimensions and thus the black state is obtained under crossed polarizers. To confirm the LC configuration, the cell with the white state achieved by applying voltage of 20 V_{rms} was rotated 0°, 45°, and 90° under a crossed polarizer and in all directions; transmittance occurs but changes periodically as shown in Fig. 2(a). This indicates that the linearly polarized light that passed through the polarizer becomes elliptically polarized, due to the fact that the LC molecules deform in three dimensions when voltage is applied. However, when voltage of 20 V_{rms} was applied to the cell with the dark state in Fig. 1(e) the dark state remained the same and now when the cell is rotated 45° (that is, the rubbing axis of the cell makes a 45° angle with the transmission axes of the crossed polarizer), the cell appears to be white, and again becomes dark when it is rotated 90°, as shown in Fig. 2(b). This clearly indicates that in the domain generated the LCs are deformed in two dimensions so that linearly polarized light passes through the cell without a change of polarization state when the rubbing axis is coincident with the polarizer axis, thus giving rise to a dark state. Further, the transmittance for the cell that makes an angle of 45° with the crossed polarizer [see Fig. 2(b)] was observed in each diagonal direction, and it shows a change in symmetry when the polar angle changes upward and downward, indicating that the LC has a symmetric configuration around the middirector.

In order to understand what kind of LC configuration shows such transmittance characteristics in two different cases, we performed computer simulation. The simulation conditions are the same as those in experiments. Deformation of the LC with a bias electric field is determined based on the well-known Freederickz transition using elastic continuum theory.[14] The first configuration can be considered to be vertical alignment but with slightly bent deformation and a twist angle of 180° from top to bottom, as shown in Fig. 3. In this structure, when voltage larger than V_{th} is applied, the LC tilts downward and twists. The second configuration can be considered a splay structure with no twisting of the LC, where the middirector lies parallel to the substrate and around it the LC has a hybrid structure with mirror symmetry. Here, the tilt angle Θ along the LC layer can be given by $\Theta(z) \fallingdotseq \pi/d\ (z-d/2)$, so that Θ is zero at midlayer ($z=d/2$) and is almost 90° vertically aligned at both surfaces. With a further increase in voltage, the LCs try to align parallel to the substrate except for the surface since the LCs with negative dielectric anisotropy become oriented perpendicular to the field and, in general, the LCs are anchored strongly on the polymer surface. In switching the transmittance using this deformation, the cell may show a fast response time because the flow directions (ν) in the top and bottom halves of the cell are the same, like those in the OCB cell. Next, we calculated the transmittance of the cell with twist and splay configuration by rotating the cell under crossed polarizers. As shown in Fig. 4, the transmittance alternates without extinction of the cell with twist but with extinction of the cell with splay depending on the angle between the rubbing direction and the crossed polarizer axis.

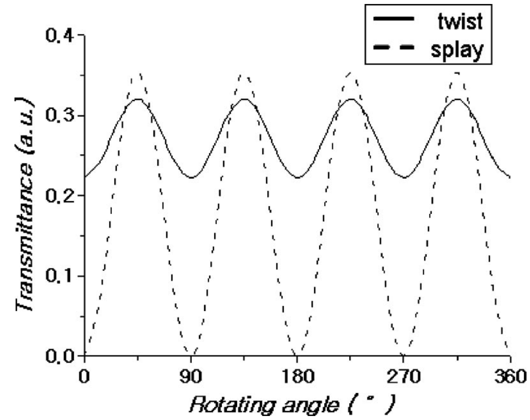

FIG. 4. Transmittance as a function of the angle between the rubbing axis and the crossed polarizers for the twist and splay states.

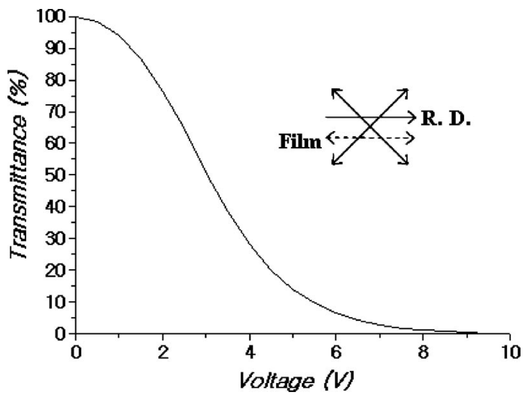

FIG. 5. Calculated voltage-dependent transmittance curve of the film compensated OCS cell.

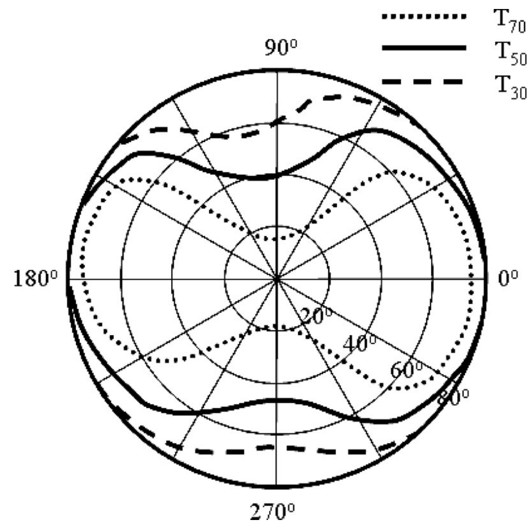

FIG. 6. Calculated isoluminance curves when the transmittance at normal direction is 50%.

This matches the experimental results exactly, proving that for the cell with splay configuration the LCs deform only in the $y-z$ plane; thus when the transmission of the crossed polarizer makes angles of 0° and 45°, the cell appears to be black and white, respectively.

Using the cell with splay configuration, an electro-optic LC device can be made. In order for the cell to modulate light effectively, the difference in phase (δ) of the cell should be modulated from 0 to π or π to 2π under a crossed polarizer since the transmittance is proportional to $\sin^2(\delta/2)$. Several cell configurations with optical compensation film are possible. For instance, with the help of uniaxial film compensation with retardation value of 220 nm, a good shaped voltage-dependent transmittance curve is obtained as shown in Fig. 5. Here, the transmittance can be changed by controlling the configuration of the LC in the splay state. Further, due to mirror symmetry around the middirector optical self-compensation effects exist and thus the cell could exhibit a wide viewing angle intrinsically. Figure 6 shows isoluminance curves when the transmittance is 50%. Here, T_{70}, T_{50}, and T_{30} indicate relative transmittance of 70%, 50%, and 30% of the maximum intensity at normal direction, respectively. The luminance uniformity is excellent even in the midgray state, that is, relative transmittance of 30% exists over 60° of the polar angle for all directions without showing the excessive bright and dark regions that existed in the TN mode, and it is due to the symmetric configuration.

In summary, we have found a vertically aligned cell associated with a transition from a vertically aligned to a self-compensated splay structure by applying a high pulse voltage. The device has good potential for application in displays which require a wide viewing angle, cell fabrication is relatively easy and it has a fast response time.

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