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Wide viewing angle, homeotropic nematic liquid-crystal display controlled by effective field

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The electro-optic properties of a liquid-crystal display associated with a homeotropic to multidomainlike transition for a liquid crystal with a positive dielectric anisotropy have been investigated. The cell plates are prepared in such a way that, in the absence of an electric field, the liquid-crystal alignment is homeotropic. an electric field created by interdigitated electrodes on both substrates causes a director deformation of a multidomain type. The display shows wide viewing angle, excellent color characteristics, and a fast response time. The molecular director configuration, together with the electro-optic characteristics of the device, are discussed in this letter. © *1998 American Institute of Physics.* [S0003-6951(98)04730-5]

Liquid-crystal displays (LCDs) represent the dominant trend in flat panel display technologies. The majority of LCDs currently on the market utilize the twisted nematic (TN) or the super-twisted nematic (STN) modes. The TN and the STN displays exhibit excellent electro-optic characteristics when the point of observation is normal to the screen but the quality of the displayed image decreases rapidly at oblique viewing angles. Various display devices have been developed to overcome the viewing angle dependence of the TN and the STN electro-optic properties. Among them, in-plane switching (IPS),[1,2] optically compensated bend (OCB),[3,4] vertical alignment (VA),[5] and homogeneous-to-twisted planar (HTP)[6,7] modes have shown superior viewing angle characteristics.

Improvement in viewing angle characteristics is related to obtaining brightness uniformity in the on-state, and minimal color shift when the viewing direction is varied. The TN and single domain VA modes have intrinsic problems with brightness uniformity because an excessively bright or excessively dark image exists when the display is viewed from upper or lower directions, respectively. The IPS mode has an excellent contrast ratio at a wider range of viewing angles than the TN mode but the brightness and the color characteristics have a viewing angle dependence. In addition, the rubbing process required to obtain the necessary homogeneous alignment can introduce dust particles and cause electrostatic charge buildup, which may damage the thin-film transistors in an active matrix display.

In this letter we present a nematic LCD associated with a homeotropic to multidomainlike (HMD) transition. This rubbing-free, vertically aligned device controlled by an effective field created by interdigitated electrodes located on both substrates, shows wide viewing angle and excellent color characteristics. The electro-optic effect of the HMD cell is investigated in this letter.

The HMD cell configuration is similar to that of the HTP cell,[6,7] and is illustrated in Fig. 1(a). Interdigitated electrodes made of MoW were patterned on the top and bottom substrates, and assembled by transposing them as shown in Fig. 1(a). The electrode width was $w = 10$ μm and the distance between the electrodes was $l = 20$ μm. A vertical alignment layer from the Japan Synthetic Rubber Co. (JALS-726) was coated on both substrates, and assembling was done to give a cell gap $d = 5$ μm. This is in contrast with the HTP cell where the liquid crystal was homogeneously aligned, and the cell gap d was larger than the electrode distance l. In addition, the HTP cell was filled with a negative dielectric anisotropy liquid crystal, while in the case of the HMD cell a

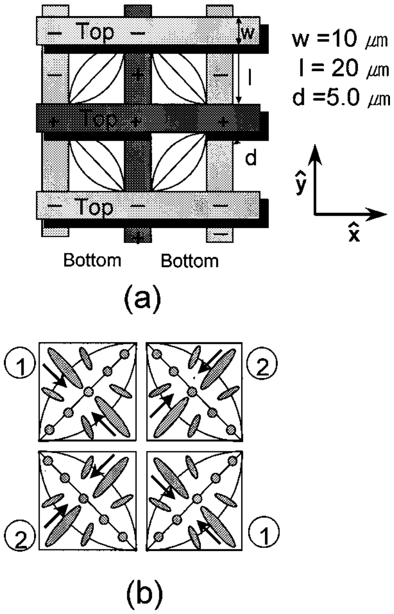

FIG. 1. (a) A schematic diagram of the LC cell structure with interdigital electrodes on the top and bottom substrates. (b) Top view of the molecular director deformation with effective equipotential lines. The arrows indicate the tilting directions of the LC molecules.

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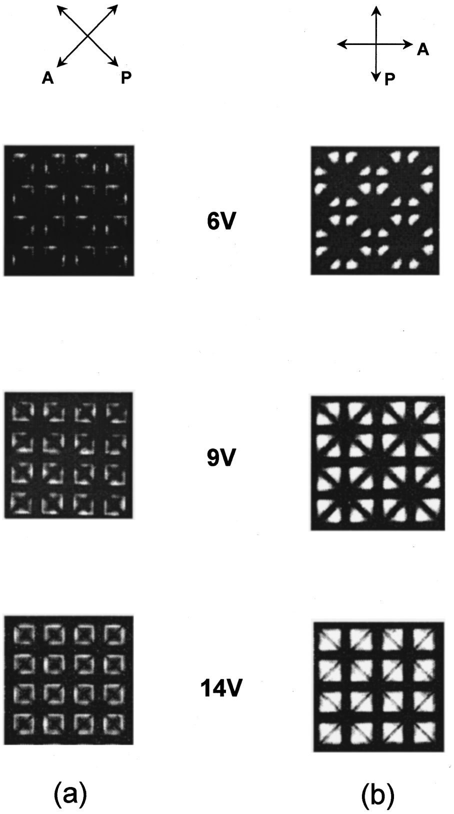

FIG. 2. Voltage-dependent transmission patterns with crossed polarizers. P and A represent the polarizer and the analyzer, respectively.

liquid-crystal material with a positive dielectric anisotropy is used. The liquid crystal (LC) was obtained from Merck-Korea, and had a birefringence $\Delta n = 0.088$ (20 °C, 589 nm) and a dielectric anistropy $\Delta\epsilon = 7.4$ (20 °C, 1 kHz). The polarizer and the analyzer were crossed, and a film with a negative birefringence $[(n_x - n_z)\delta = 400$ nm, $(n_x - n_y)\delta = 15$ nm at 589 nm, where δ is the film thickness] was inserted between the analyzer and the LC cell in order to compensate the light leakage of the homeotropically aligned state at off-normal directions.

When no voltage is applied to the HMD cell, the LC molecules are vertically aligned, and under crossed polarizers the cell appears black. When a bias voltage is applied to the electrodes, an electric field is created whose equipotential surfaces are those for a cell gap smaller than the electrode distance. These have been discussed elsewhere.[6,7] The surface in-plane equipotential lines, together with the nematic director configuration in the on-state, are schematically illustrated in Fig. 1(b). Due to the positive dielectric anisotropy of the liquid crystal, the molecules have a tendency to orient along the electric field, and thus, perpendicular to the equipotential surfaces. In the voltage-on state, the LC director with orientation along the equipotential surfaces does not undergo any deformation. In those regions the angle between the director and the electric field is 90°, and therefore, the torque on the director is zero. Deformation does occur in all regions where the angle between the LC molecules and the field takes a value intermediately between 0° and 90°. In addition, the distortions in any two adjacent subpixels [denoted by 1 and 2 in Fig. 1(b)] are mirror images of each other with respect to the shared electrodes.

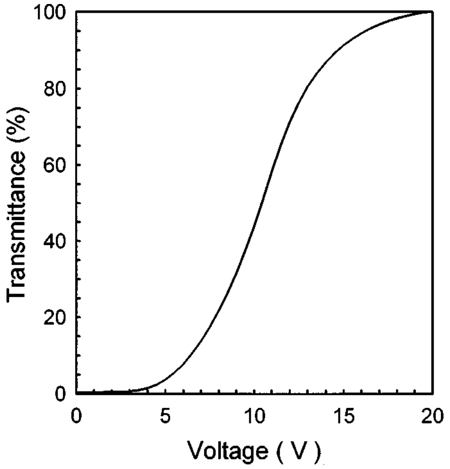

FIG. 3. Voltage-dependent transmittance curve at normal direction. The transmittance is normalized to be 100% at 20 V.

Due to the structure of the electric field, the transmission patterns are expected to be different for different orientations of the crossed polarizers. In the case when the angle between the polarizer *P* and the electrodes at the top plate is 45°, the transmission does not increase much with increasing the voltage [see Fig. 2(a)]. The observed dark diagonal lines result from no change in the LC orientation in these regions. Dark-shaded patterns perpendicular to the dark diagonal lines can also be seen in Fig. 2(a). In those areas, the LC molecules do undergo tilt deformation but the tilt direction coincides with the polarization axis of either the polarizer or the analyzer, and therefore, no light transmission occurs

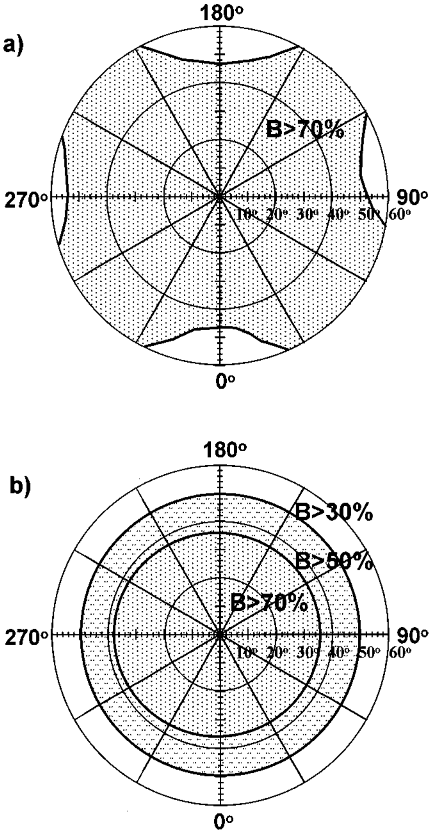

FIG. 4. Viewing angle dependence of brightness B. References are the light intensities with bias voltages of (a) 10 V and (b) 20 V at normal direction.

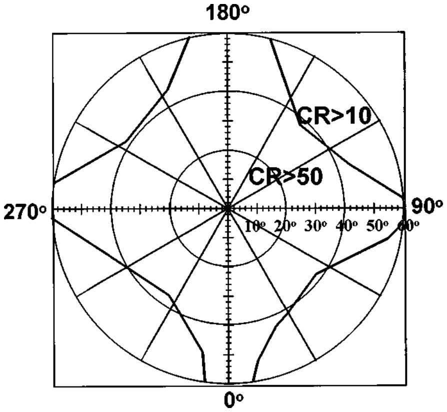

FIG. 5. Isocontrast curve of the HMD device.

through the cell. In the case when the crossed polarizers are oriented in such a way that the polarizer *P* is along the electrodes at the bottom plate, as shown in Fig. 2(b), the dark diagonal lines still exist but the regions of the dark-shaded patterns now transmit light. This is due to the fact that in this case the angle between the tilt direction and the polarization axes is 45°. As can be seen in Fig. 2(b), the dark diagonal lines become sharper, and the intensity of transmitted light increases with increasing the voltage, showing that the LC is deformed in the whole area where the electric field has vertical (out of the *x*–*y* plane) components.

To perform the electro-optical measurements, a halogen lamp was used as a light source, and a square-wave voltage with a frequency of 60 Hz from a function generator was applied to the sample cell. The light passing through the cell was detected by a photomultiplier tube. The normalized light intensity as a function of the applied voltage is shown in Fig. 3. Light transmission starts to occur at about 2 V, and the transmittance almost saturates at 20 V. The required voltage depends mainly on the cell gap, the electrode distance, and the liquid-crystal dielectric anisotropy, and therefore, optimizations of d, l, and $\Delta\epsilon$ are necessary to obtain a low driving voltage.

The viewing angle dependence of the brightness is shown in Figs. 4(a) and 4(b), where the light intensities at 10 and 20 V, respectively, at normal direction are taken as references. As can be seen, the brightness is axially symmetric at 20 V [Fig. 4(b)], which is due to the multidomainlike deformation of the vertically aligned nematic liquid crystal. When the applied voltage is 10 V [Fig. 4(a)], a brightness of more than 70% is obtained even at polar angles of 60° in most azimuthal directions. Therefore, even though the low aperture ratio causes a relatively low absolute value of the intensity in comparison with the conventional TN cell, the quality of the displayed image remains approximately the same when the viewing direction is changed, and there are no excessively dark or excessively bright regions at off-normal directions. The isocontrast plot of the HMD cell is shown in Fig. 5. The region with a contrast ratio (CR) greater than 10 extends to polar angles of more than 60° in all azimuthal directions. Especially, the viewing angle is superb in horizontal and vertical directions. The color characteristics of the HMD cell is shown in Fig. 6. For comparison, the viewing angle dependence of the IPS cell white level is also presented in Fig. 6. As can be seen, when the viewing angle is varied, the HMD mode exhibits much smaller color shift compared to that of the IPS mode. The reason for this effect is related to the fact that while in the IPS cell the LC molecules rotate in the same direction, causing a large Δn difference for different viewing angles, in the HMD cell the LC molecules in different parts of the cell tilt in opposite directions, which results in an optical self-compensation effect. In other words, the change in the $d\Delta n$ value with varying the viewing angle is very small. We also measured the response time characteristics. The rising time with an applied voltage of 20 V is 12 ms and the decaying time is 10 ms. The total response time of the HMD cell is faster than those of the IPS and the TN cells.

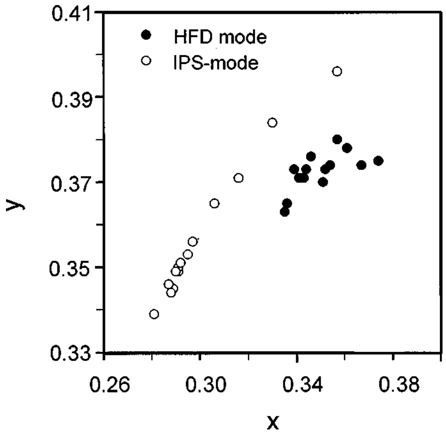

FIG. 6. Viewing angle dependence of the HMD and the IPS cells white level. The polar angle is varied from 0° to 60° at azimuthal angles of 0°, ±45°, and 90°.

In summary, we have fabricated a rubbing-free, homeotropic nematic LCD controlled by an effective electric field. This device, associated with multidomainlike deformation of a vertically aligned liquid crystal with a positive dielectric anisotropy, shows a wide viewing angle, excellent color characteristics, and a fast response time.

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