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# Electro-optic characteristics of a liquid crystal cell in a homogeneous-to-twisted planar mode

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The electro-optic properties of a novel liquid crystal device associated with a homogeneous to twisted-planar (HTP) transition have been investigated. The cell plates are prepared in such a way that in the absence of an electric field the liquid crystal orientation is uniform throughout the cell, and thus between crossed polarizers the cell appears black (off state). When an electric field of a particular configuration is applied, a 90° twist is imposed, and the cell transmits light (on state). It was found that the HTP device exhibits wide viewing angle and excellent color characteristics. The dependence of the electro-optic effect on rubbing directions and cell gap has also been investigated.
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The electro-optic effect of a twisted nematic cell has been used for both passive and active liquid crystal displays despite its narrow viewing angle characteristics.[1] In an attempt to improve the performance of the twisted nematic display, a number of new liquid crystal devices have been developed. Among them the in-plane switching (IPS),[2,3] the axially symmetric aligned microcell (ASM),[4,5] and the multidomain twisted nematic[6] modes have shown superior viewing angle characteristics.

In this letter, a novel liquid crystal optical device is reported. In the case of the conventional nematic cell, a twisted structure exists in the absence of an electric field, and this structure is destroyed when a field is applied. In contrast, in the new device reported in this letter, the liquid crystal is uniformly oriented in the absence of a field, and an applied field creates a twisted structure.

The electrode configuration used for obtaining a twisted liquid crystal structure in the presence of an electric field is well illustrated by the following idealized situation. Suppose that four line charges (two positive and two negative) of equal magnitude and of length $2L$ are positioned at two parallel surfaces a distance $2d$ apart, as shown in Fig. 1. The line charges at the $y=-d$ plane are oriented parallel to the $\hat{z}$ coordinate axis, and are at a distance $2L$ from each other. The charges at the $y=d$ plane are also a distance $2L$ apart but are oriented parallel to the $\hat{x}$ coordinate axis. It is simple to calculate the electric field created in vacuum in the region between the two planes.[7] The field is nonuniform and its structure strongly depends on the $d/L$ ratio. Cross sections of the equipotential surfaces of the field created by this charge configuration are shown in Fig. 2 at several intermediate planes between $y=-d$ and $y=d$, and for different values of $d/L$. The equipotential surfaces are drawn in such a way that the potential difference between neighboring surfaces remains the same. Therefore the regions of stronger electric field are identified by denser equipotential surfaces. As can be seen in the figure, in the case when $d \leqslant L/6$, the electric field has approximately the same strength for the entire region $-d \leqslant y \leqslant d$, and its projection in the planes parallel to the bounding surfaces makes an angle of nearly 45° with the electrodes at both surfaces. (Exceptions are the regions near the electrodes.) When the thickness to electrode distance $(d/L)$ ratio is increased, the electric field in the region between the surfaces becomes weaker and at some value of $d/L$ the projection of the field in the planes parallel to the bounding planes rotates through an angle of 90° from one surface to the other.

When a liquid crystal with negative (positive) dielectric anisotropy is present in the region $-d \leqslant y \leqslant d$, it will preferentially orient along (perpendicular to) the equipotential surfaces. Even though the presence of the liquid crystal medium will modify the electric field created by the line charges in vacuum, the diagrams presented in Fig. 2 can still be used as

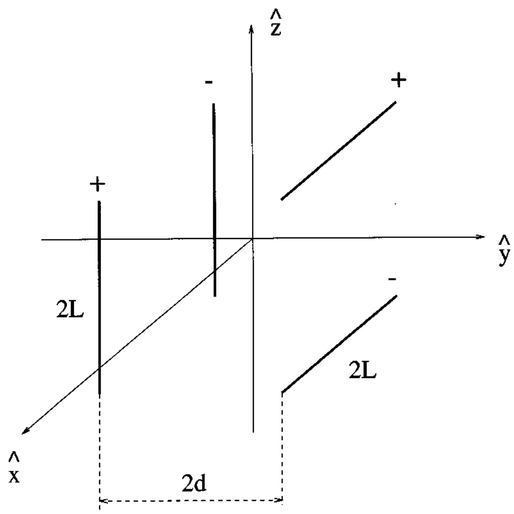


FIG. 1. Schematic diagram of the HTP mode electrode configuration.

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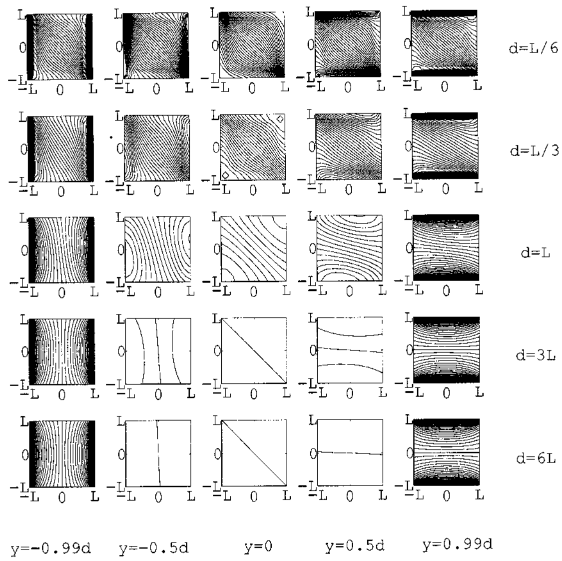


FIG. 2. Equipotential surface cross sections of the electric field created in vacuum by the electrode configuration in Fig. 1.

a guide for the choice of electrode distance and cell gap. It is clear that in order for a twisted liquid crystal structure to be obtained, it is necessary that $d$ and $L$ satisfy the condition $d>L$.

A schematic diagram of the HTP cell used in the experiment is shown in Fig. 3. Interdigital electrodes made of MoW were patterned and assembled by transposing them at the top and bottom substrates as illustrated in the figure. The electrodes were 10 $\mu$m wide and the distance between them was 20 $\mu$m. Before assembling both substrates were coated with polyimide and rubbed in antiparallel directions. The pretilt angle generated by the rubbing was 1°, and the rubbing direction, defined with respect to the electrode orientation at the top plate, was different for the different cells tested. The polarizer was always oriented along the rubbing direction at the top plate, and the analyzer was perpendicular to the polarizer. Cells with cell gaps of 4.2 and of 60 $\mu$m were filled with liquid crystal material with negative dielectric anisotropy. The liquid crystal was obtained from Merck–Korea and had birefringence $\Delta n = 0.076$ (20 °C) at 589 nm, dielectric anisotropy $\Delta\epsilon = -3.6$ (20 °C, 1 kHz), and rotational viscosity $\gamma_1 = 134$ mPas at 20 °C.

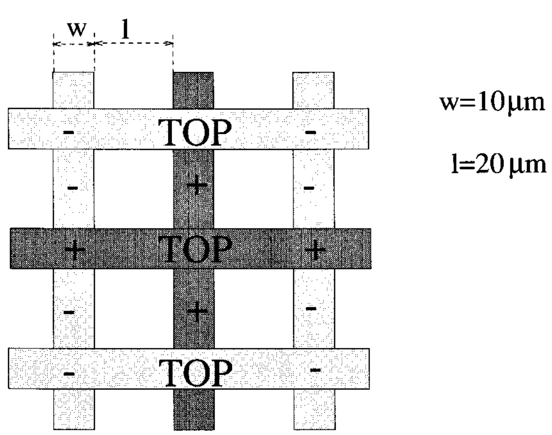


FIG. 3. Schematic diagram of an HTP cell.

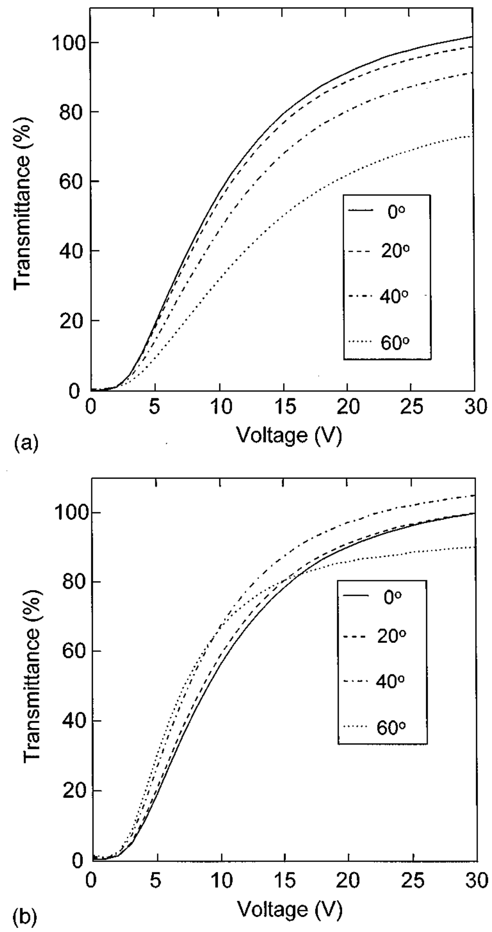


FIG. 4. Transmittance of a 60-$\mu$m-thick HTP cell vs. applied voltage: (a) left-right viewing angle characteristics, and (b) up-down viewing angle characteristics.

The experimental results for the case of a cell with a cell gap smaller than the electrode distance have been discussed elsewhere.[8] In this letter, the characteristics of a cell with a cell gap larger than the electrode distance are reported. As discussed earlier, a twisted liquid crystal structure in the presence of an electric field is expected in an HTP cell with a cell gap larger than the electrode distance. To investigate this effect, a cell with $d = 60$ $\mu$m was prepared and the substrates were rubbed at an angle of 45° with respect to the electrodes at the top plate. When no voltage is applied, the liquid crystal is uniformly oriented throughout the cell and between crossed polarizers the cell appears black. A bias voltage applied to the electrodes causes the liquid crystal to undergo a predominantly twist deformation, and the cell transmits light. The transmittance versus voltage curves for different viewing angles are shown in Figs. 4(a) and 4(b). The transmittance is normalized to be 100% at 0° viewing angle and at a voltage of 30 V. It can be seen that the homogeneous to twisted-planar transition exhibits no threshold character. This result is expected since an applied voltage results in the presence of an in-plane electric field at the surfaces making an angle of 45° with the nematic director, in which case, the dielectric torque is maximum, and in addition, the weak bulk electric field also favors liquid crystal twist deformation. No gray-scale inversion was observed along the transmission axes of the crossed polarizers. How-

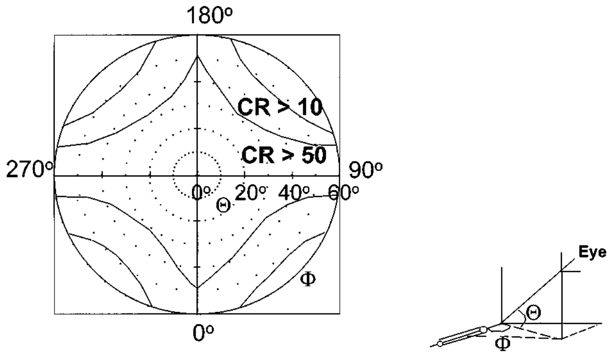


FIG. 5. Iso-contrast plot of an HTP cell. The contrast ratio **CR** is defined as the ratio of the intensity of the transmitted light in the on state to that of the off state at 30 V.

ever, gray-scale inversion was found to occur at dark gray levels in a direction making a 45° angle with the transmission axes of the crossed polarizers.

The iso-contrast plot of the HTP device is shown in Fig. 5. As can be seen, the device exhibits excellent symmetry and much wider viewing angle in comparison to that of the conventional twisted nematic cell. The viewing angle dependence of the HTP cell chromaticity[9] is shown in Fig. 6. The polar angle is varied in the range from 0° to 60° at azimuthal angles of 0°, ±45°, and 90°. For comparison, the chromaticity of an IPS cell is also included in Fig. 6. In contrast to the IPS mode, the color change of the HTP mode with viewing angle is very small. For cells in the IPS mode, the homogeneously aligned nematic liquid crystal molecules rotate in the same direction with bias voltage so that the phase retardation in a direction perpendicular to the liquid crystal director (slow axis) is strong, resulting in a yellowish color

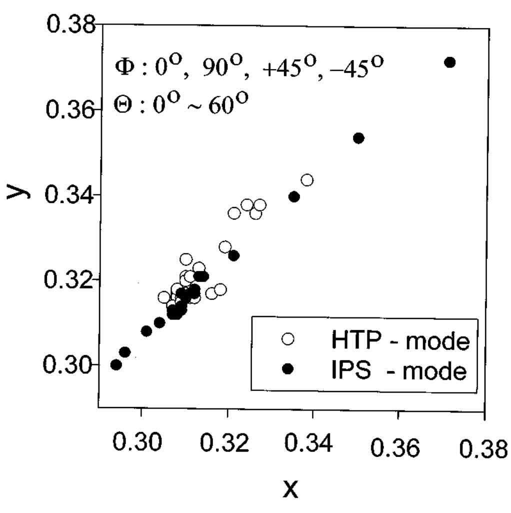


FIG. 6. Chromaticity diagram of an HTP cell.

with oblique viewing angle. Unlike in the case of the IPS mode, when an HTP cell is in its on state, lower and upper parts of the liquid crystal medium rotate in opposite directions with respect to the midlayer, which results in an optical compensation effect.

The response time characteristics of the HTP cell were also investigated. The rising and decaying times with an applied voltage of 30 V were found to be 8 and 150 ms, respectively. It must be emphasized, however, that the measured times are for a cell with a relatively large thickness (60 $\mu$m). Decreasing the cell gap is expected to significantly reduce the decaying time.

In summary, the electro-optic characteristics of an HTP cell with a cell gap larger than electrode distance and filled with negative dielectric anisotropy liquid crystal were presented in this letter. The device was found to exhibit wide viewing angle and excellent color characteristics. These properties are not associated only with a liquid crystal with negative dielectric anisotropy. A similar effect is expected to occur for a positive dielectric anisotropy liquid crystal with homogeneous or homeotropic surface alignment. The transmittance versus voltage curves and the switching times given in the letter are for a cell 60 $\mu$m thick. Decreasing the cell gap and preserving the $d/L$ ratio is expected to reduce both the driving voltage and the switching times. Optimization of the HTP cell is currently under way.

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