Electro-optic characteristics of 90° twisted nematic liquid crystal display driven by fringe-electric field

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We investigated the electro-optic characteristics of a fringe-field driven twisted nematic (TN) display. In the absence of an electric field, the liquid crystals (LCs) are initially twisted 90° from the top to the bottom substrate under parallel polarizers so that the cell appears to be black. In the presence of a fringe-electric field, the LCs with negative dielectric anisotropy are rotated toward a plane that is almost perpendicular to the horizontal component of the fringe field, above the entire electrode surface. The cell then appears to be white, and shows high transmittance. In addition, the cell displays a wide viewing angle and has excellent color characteristics over a wide viewing range due to almost in-plane switching, unlike a conventional TN device where the LC director tilts upward in only one direction and results in a narrow viewing angle. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1636253]

I. INTRODUCTION

Nowadays, the application range of liquid crystal displays (LCDs) has been greatly expanded from small size ones for use in mobile phones to large size ones for use in monitors and LC televisions. The twisted nematic (TN) mode is dominant in LCDs due to its very stable structure and wide process margin. However, it has an intrinsic problem with regard to the viewing angle and the response time. Many different display modes have been suggested to improve the image quality of displays over that of the TN mode. Some LCDs that have been commercialized are TN with optical-film compensation,[1] vertical alignment (VA) with protrusions,[2] in-plane switching (IPS),[3–5] and fringe-field switching (FFS).[6–8] Nevertheless, the challenges of creating new LC devices with high performance and low cost have continued. Recently, a device (called IT mode) associated with a twisted nematic, which is driven by an in-plane field that is generated by an interdigital electrode, has been suggested.[9,10] According to this report, the optimized device can exhibit an excellent viewing angle, little change in color and a wide cell gap margin. However, the device has a low transmittance problem (like in the IPS device) if the electrodes are opaque or has a low contrast ratio (CR) if the electrodes are transparent, since the LCs above the electrodes are not deformed from their initial state since there is no dielectric torque applied to them.

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In this article, we suggest a device that overcomes the problems of low transmittance and low CR of the IT mode by employing an electrode structure that can generate a fringe-electric field. The switching principle and electro-optic characteristics of the device where 90° twisted nematic LCs are deformed above by the entire electrode surface by a fringe field (F-TN) are discussed in detail.

II. CELL STRUCTURE AND SWITCHING PRINCIPLE OF THE F-TN MODE

Figure 1 shows the cell structure of a F-TN device with a schematic showing the local director orientation in both the off and on states. As is shown, the electrodes exist only at the bottom substrate. A ground electrode exists as a plane and a pixel electrode in slit form with a gap (l) existing between them. The width of the pixel electrode (w) and the gap is assumed to be 3 and 4.5 μm, respectively. The passivation layer, with thickness of 3000 Å, is positioned between the ground and the pixel electrodes. With this electrode structure, a fringe-electric field is generated when voltage is applied. The LCs are twisted 90° from the bottom to the top of the substrate and the surface pretilt angle is assumed to be 2°. One important condition is that the alignment of the LCs on the bottom substrate should be parallel (perpendicular) to the horizontal component of the fringe field when the dielectric anisotropy of the LC is negative (positive). Considering the configuration of the polarizer and the analyzer, two cases, where they are either are parallel or perpendicular to each

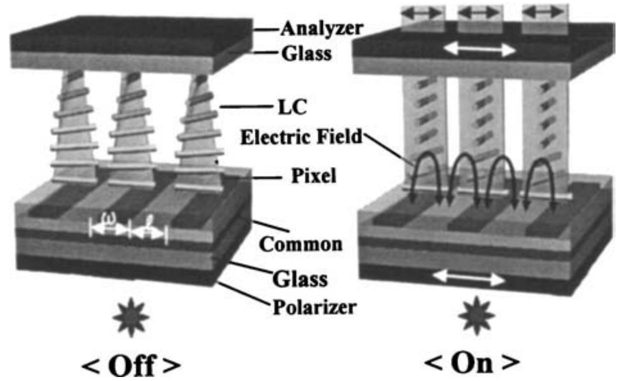

FIG. 1. Schematic of cell structure of the F-TN cell in the off and on states using a LC with negative dielectric anisotropy.

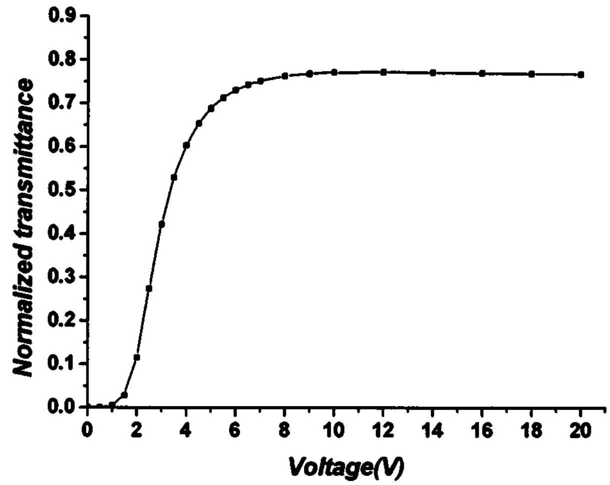

FIG. 2. Voltage-dependent transmittance curve for the F-TN cell.

other, are possible. For a device with polarizers parallel to each other and one where one of the rubbing directions is coincident to the polarizer axis, the device shows a dark state in the off state since the linearly polarized light passing through the polarizer is rotated 90° and it is blocked by the analyzer. With bias voltage applied, the LCs with negative dielectric anisotropy forming an angle with the horizontal component of the fringe-electric field are forced by the resultant dielectric torque so they try to orient themselves perpendicular to the field direction, giving rise to transmittance, as shown in Fig. 1. However, the deformation of the LCs is dependent on the electrode position since the fringe-electric field that drives the dielectric torque causing the LC to twist will change as the electrode position is altered.

From the switching principle, one can develop a transmittance equation for a normally black (NB) F-TN device, given by

$$T/T_0=\frac{1}{2}\left[\sin^2\left(\phi(V)-\frac{\pi}{2}\right)+\left(\frac{\sin^2 \pi/2\sqrt{1+[2d\Delta n(V)/\lambda]^2}}{1+[2d\Delta n(V)/\lambda]^2}\right)\right],$$

where $\phi(V)$ is the twist angle of the LC from top to bottom and is a voltage-dependent value, d is the cell gap, $\Delta n(V)$ is the birefringence of the LC and voltage-dependent value, and λ is the wavelength of incident light. In other words, in order to achieve a good dark state, the twist angle should be 90° and the cell retardation value should be 0.48 μm. When applying voltage, the transmittance becomes maximum with a twist angle of 0° and a cell retardation value of 0.

If the polarizers are crossed with respect to each other, then light is transmitted when voltage is not applied, like in conventional normally white (NW) TN mode. With bias voltage applied, the LCs try to align perpendicular to the horizontal field direction but the LC near the bottom surface will not fully rotate due to strong surface azimuthal anchoring energy (A_ϕ) of $10^{-5}\,\mathrm{J/m^2}$. Therefore, a completely dark state cannot be obtained. However, by decreasing azimuthal anchoring energy A_ϕ to a certain level the LCs can be rotated completely even over the entire electrode surface.[11]

III. ELECTRO-OPTIC CHARACTERISTICS OF THE F-TN MODE

To obtain the nematic LC director, the equation of motion for the director vector is calculated numerically based on Ericksen–Leslie theory. For the optical calculation, a 2×2 extended Jones matrix[12] at wavelength of 550 nm is used. Here, the LC (birefringence $\Delta n=0.08$ at 550 nm, dielectric anisotropy $\Delta\epsilon=-4$, elastic constants $K_1=13.5\,\mathrm{pN}$, $K_2=6.5\,\mathrm{pN}$, $K_3=15.1\,\mathrm{pN}$) and a cell gap of 6 μm are used.

Figure 2 shows the calculated voltage-dependent transmittance of the F-TN cell. As is shown, transmittance starts to occur at voltage of 1.8 V and increases to 78% at voltage of 12 V. The transmittance is slightly lower than 90.8% in the conventional TN cell. In the fringe-field driven device, the field intensity is dependent on the electrode position so the degree of rotation of the LCs is also dependent on the electrode position. Figure 3 shows a transmittance profile that is dependent on the electrode position when the transmittance is 10%, 50%, and 100% of the maximum transmittance at the normal direction. At 10% transmittance, the LCs near the

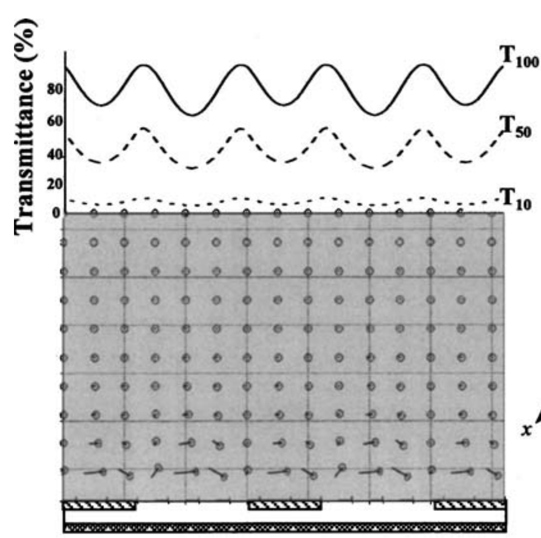

FIG. 3. Transmittance profile dependent on the electrode position at various shades of gray: low, mid- and white gray.

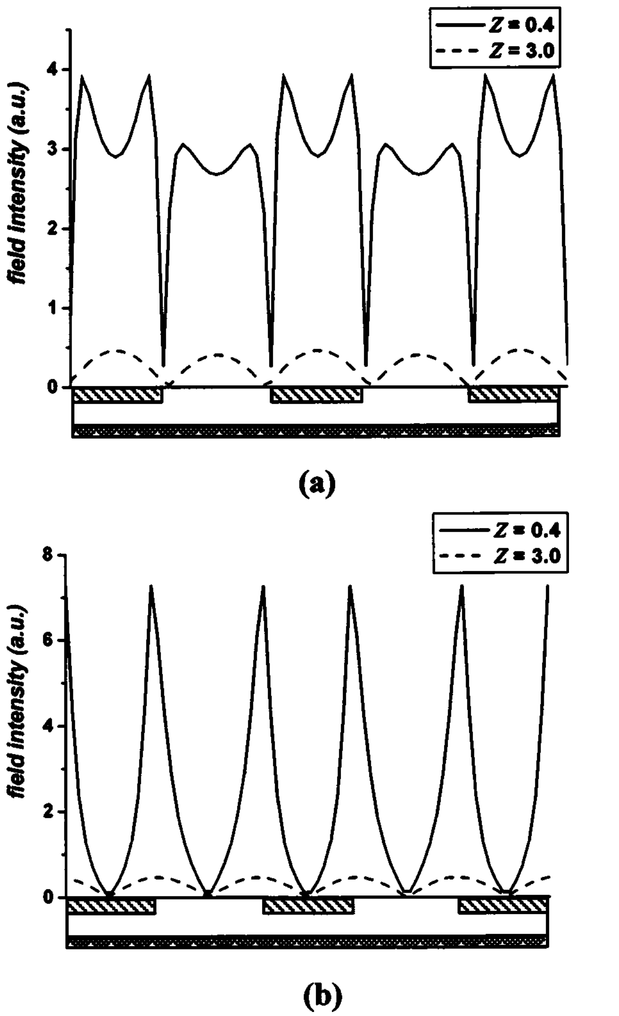

FIG. 4. Field distribution of the (a) horizontal and (b) vertical field intensity along the horizontal axis at $z=0.4$ and 3 μm.

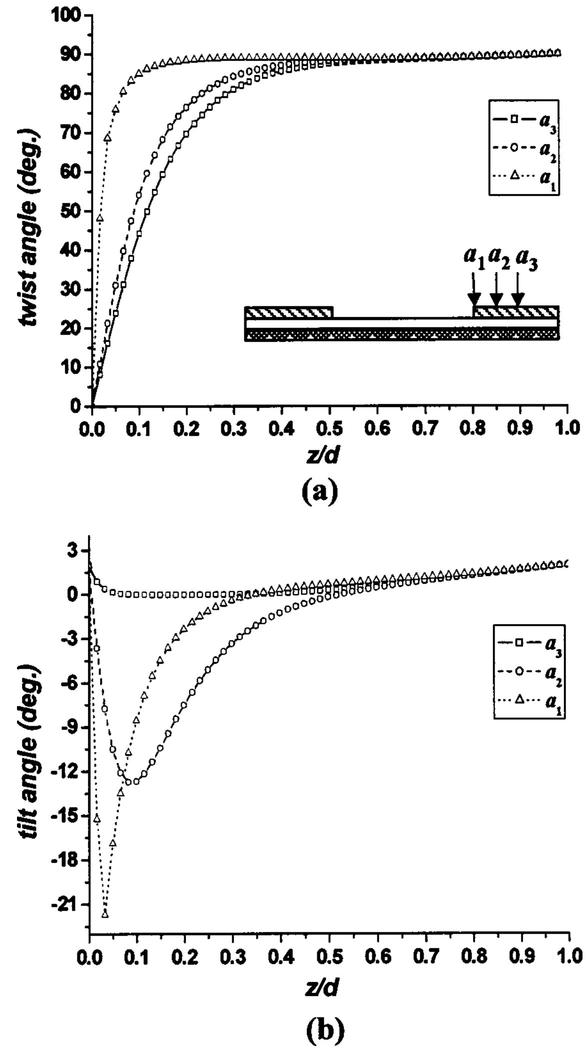

FIG. 5. Director profile of (a) twist and (b) tilt angles at three different electrode positions.

edge of the electrodes twist the most so the transmittance is higher than in the other position. By further increasing the voltage to achieve maximum transmittance, the transmittance was still found to be highest near the edge of the electrodes. Interestingly, even at the center of the electrodes, transmittance occurs although it is slightly lower than for the other positions. From the director configuration, one can notice that at the edge of the electrodes most of the LCs align perpendicular to the horizontal field direction, but not those LCs that are close to the surface. However, at the center of electrodes the LCs close to the bottom surface are not twisted enough, which results in low transmittance. This explains the lower light efficiency for this design compared to the TN mode.

In order to understand the exact local director orientation at every electrode position, first we need to calculate the field distribution inside the cell. Figure 4 shows the horizontal (E_y) and vertical (E_z) field distributions at two different vertical positions: near the surface of the bottom substrate ($z=0.4\,\mu$m), and near the middle of the cell gap ($z=3.0\,\mu$m). As indicated, the field intensity of E_y around the edge of the pixel electrodes (a_1) is at a maximum and rapidly drops to zero above the center of the electrodes (a_3), and it also decreases rapidly as the point of measurement moves away from the electrode surface to the middle of the cell. In the case of E_z, the field intensities between the center of the pixel and counterelectrodes (a_2) are at a maximum although the peak value is slightly weaker than that of E_y, and similar to the behavior of E_y, it becomes weak as it moves far away from the surface. At positions between the center and the edge of electrodes, both E_y and E_z exist. In general, E_y contributes to the dielectric torque that rotates the LC and the E_z contributes to the dielectric torque that holds down the LC when a LC with a negative dielectric anisotropy is used. It is apparent that such field distribution in a device will definitely cause a LC to deform in different ways than if a LC with a positive dielectric anisotropy is used.

Figure 5(a) shows a profile of a LC twist angle along the LC layers at three positions: a_1, a_2, and a_3. When voltage of 12 V is applied, the twist angles of the LC molecules at positions a_1, a_2, and a_3 are about 90° and are the same above $z/d=0.5$. However, when the twist angle is less than $z/d=0.5$, they are strongly dependent on the electrode positions. That is, near the electrode edges where strong E_y ex-

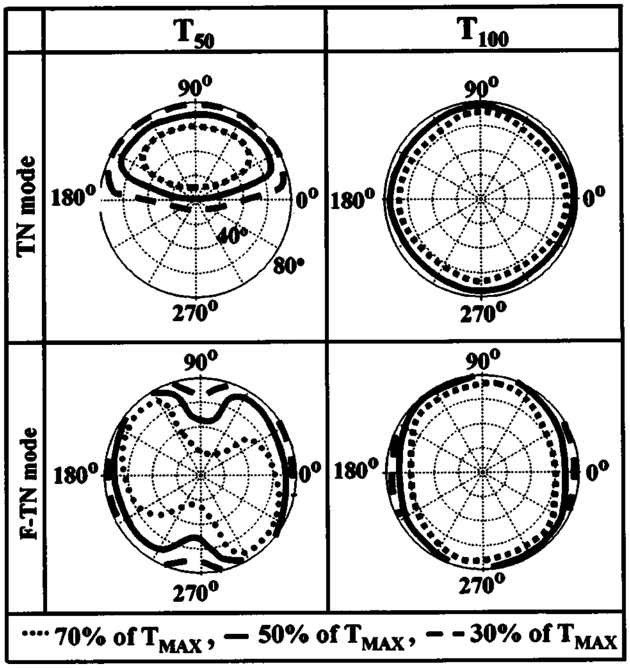

FIG. 6. Viewing angle-dependent transmittance of the TN and the F-TN cells when the transmittance at the normal direction is (a) 50% and (b) 100%.

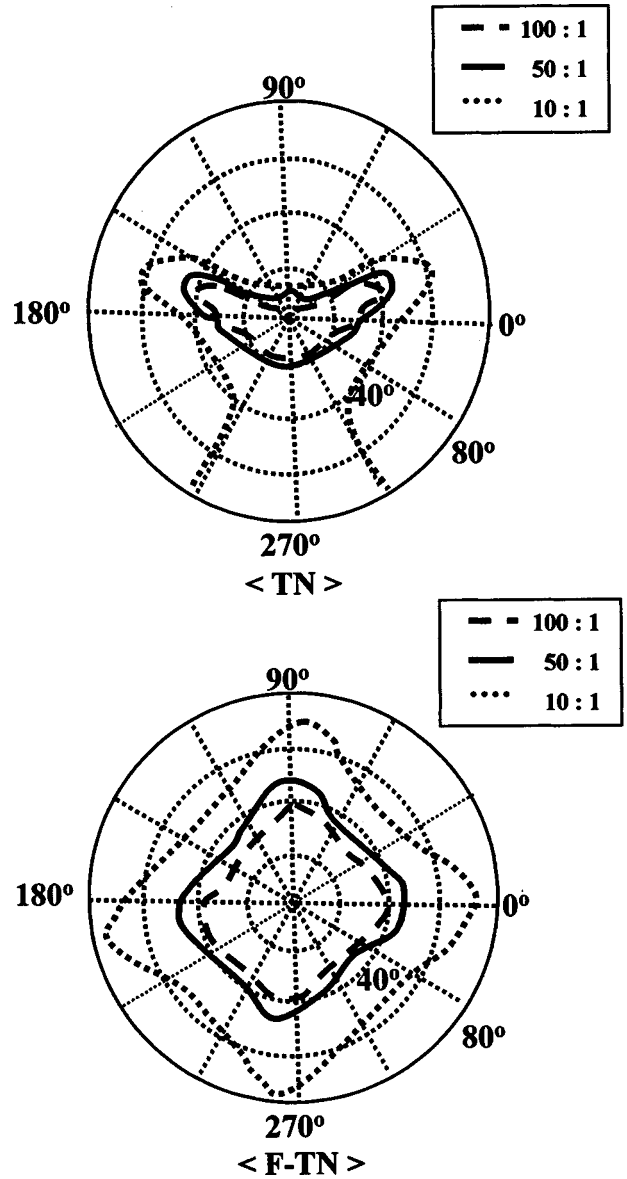

FIG. 7. Isocontrast curve for the TN and the F-TN cells at wavelength of 550 nm.

ists, the LCs are twisted the most compared with other electrode positions, giving rise to the highest transmittance amongst all the electrode positions. This indicates that for positions except those near the edge of electrodes, the field intensity of E_y is not strong enough to overcome the elastic energy of the LC that is fixed by strong surface anchoring strength. Therefore in order to increase the twist angle to improve light transmittance, a reduction of the surface anchoring energy is required as described above. In the case of the tilt angle along the LC layers measured at three different positions, it is not as high at all positions since a LC with a negative dielectric anisotropy is used. However the variation along the layer is largest at position a_2 due to the strong field intensity of both E_y and E_z at that position. The low value for the tilt angle at the operating voltage indicates that it does not have much effect on light transmittance.

Figure 6 shows isoluminance curves for TN and F-TN cells when the light transmittance is 50% and 100% of the maximum transmittance. As indicated in Fig. 6, for the TN cell the luminance uniformity is strongly dependent on the viewing angle when the transmittance is 50%, where it shows excessive brightness and darkness in the upper and lower directions, respectively. However, for the F-TN cell, the viewing angle is much improved such that relative transmittance of 50% exists over 70° and 40° polar angles in the horizontal and vertical directions, respectively, since the LC rotates almost in plane and has a very low tilt angle. When the transmittance is 100%, the amount of luminance uniformity is about the same for both devices. Figure 7 shows isocontrast curves for the TN and the F-TN cells. The F-TN cell shows a better symmetric viewing angle than the TN cell. We also investigated the viewing angle dependence for mid- gray and white chromaticity up to a polar angle of 60° in the four azimuthal directions investigated. The degree of the change in color was very small as shown in Fig. 8.

To confirm the theoretical results, we fabricated a test cell in which the electrode has an angle slightly slanted from the horizontal direction, and the electrode has a wedge shape such that the LCs rotate in opposite directions, which improves the viewing angle further.[8] Figure 9 shows the off and on states of a pixel that has a common electrode blocking light along the center of the pixel. There was good contrast between the two states and the degree of transmittance slightly oscillated depending on the electrode positions. Figure 10 shows the isoluminance of the fabricated F-TN cell. As expected, a relative intensity of 50% to the maximum at the normal direction exists over 60° of polar angle in all directions and also the luminance uniformity is symmetric horizontally and vertically.

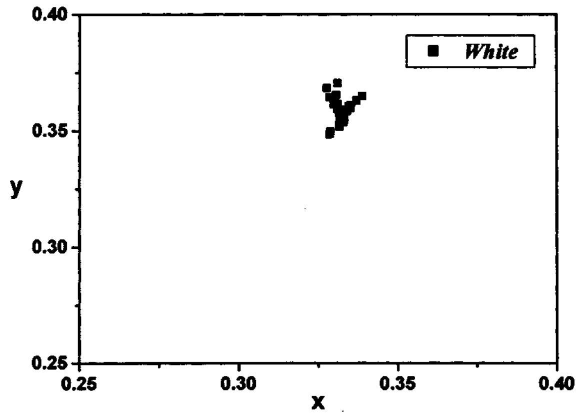

FIG. 8. Viewing angle dependence of white chromaticity up to a polar angle of ±60° in four azimuthal directions including the horizontal, vertical and two diagonal directions.

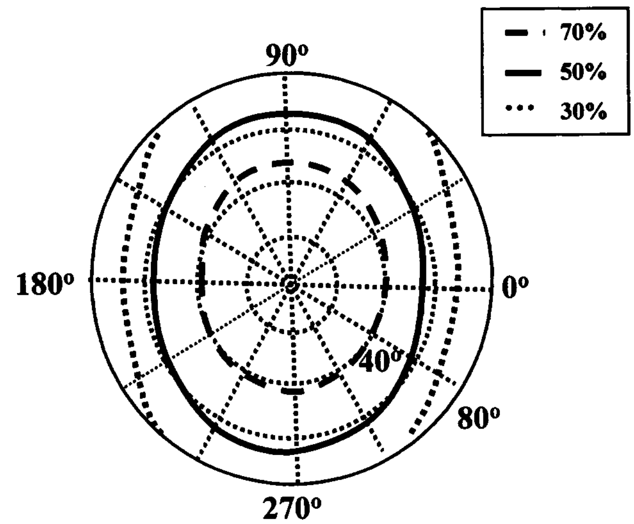

FIG. 10. Isoluminance curve for F-TN cells when the transmittance at normal direction is at a maximum.

IV. SUMMARY

We suggest the use of a fringe-field driven 90° twisted nematic cell using a LC with a negative dielectric anisotropy. For this the polarizers are parallel to each other and the alignment of the LC at the bottom substrate is parallel to the horizontal field of the fringe field. The device shows a black state before voltage is applied and appears to be white when applying a fringe-electric field. The LCs then rotate above the entire electrode surface and keep a low tilt angle, giving rise to high transmittance. Since the LCs rotate almost in plane, the device shows good viewing angle characteristics. Furthermore, the device can be used as a normally white display by controlling the surface anchoring strength of the bottom layer.

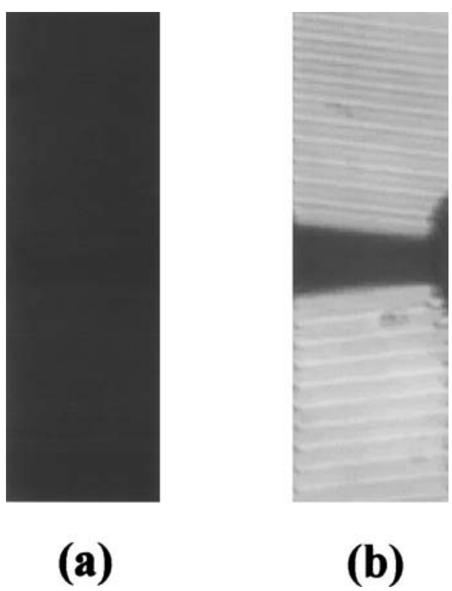

FIG. 9. Optical microphotograph of the F-TN cell in off and on states.

ACKNOWLEDGMENT

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