# Electro-optic characteristics and switching principle of a nematic liquid crystal cell controlled by fringe-field switching

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We have fabricated a nematic liquid crystal cell associated with a homogeneously aligned to twisted transition of a liquid crystal director. In the absence of an electric field, the liquid crystal molecule is homogeneously aligned under the crossed polarizers, and thus the cell appears to be black. When a fringe field induced by interdigital electrodes is applied, liquid crystal molecules rotate in plane even above electrodes and thus the cell transmits light. The device exhibits a high transmittance ratio as well as a wide viewing angle, which solves a long standing problem of low transmittance existing in the conventional in-plane switching mode. We show that the distance between electrodes smaller than the width of an electrode and cell gap is required for generating fringe field with applied voltage and rotating molecules above electrodes. We also investigate the mechanism of fringe-field switching and dependence of electro-optic effect on different cell conditions and dielectric anisotropy of liquid crystal. 
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Flat panel displays are extensively being studied for an application to personal portable computers and the replacement of Cathode-ray-tube (CRT) displays at present. Among them, twisted nematic liquid crystal displays (TNLCDs) have been mainly used for notebook computers in spite of their narrow viewing angle characteristics. Since LCDs utilize liquid crystals, organic chemicals with anisotropic structure, their electro-optic characteristics intrinsically have a viewing angle dependency. Recently, new concepts of LCDs to minimize the viewing angle dependency such as in-plane switching (IPS) mode,[1–4] the vertical alignment (VA) with negative[5] and positive dielectric anisotropy of LC[6,7] and homeotropic to multi-domainlike (HMD) VA[8,9] have been suggested. The IPS mode shows wide viewing angle characteristics comparable to the CRT displays due to in-plane rotation of liquid crystal molecules between electrodes. However, the liquid crystal above the electrodes does not twist with an applied field so that the aperture ratio, i.e., the area where the light can be transmitted, is low compared with that of the twist nematic mode. The VA modes also have demerit in transmittance with similar reasons. Such low transmittance of the liquid crystal cell needs backlight with high luminance, resulting in high power consumption.

In this letter, we suggest a nematic liquid crystal cell associated with a homogeneously aligned to twisted transition of the liquid crystal director, induced by fringe-field switching (FFS). This device shows a very wide viewing angle the same as the IPS mode but the liquid crystal molecules even above electrodes can rotate, giving rise to high transmission of the incident light.

Figure 1 shows the cell structure with equipotential lines generated by interdigital electrodes when the distance ($l$) between electrodes is smaller and larger than the cell gap ($d$). In the conventional IPS mode, the horizontal component of an electric field is dominant in the range between electrodes for $l>d$, as shown in Fig. 1. However, in the FFS mode where $l<d$, the vertical as well as horizontal components of an electric field exist above electrodes. In the IPS and FFS cells, the liquid crystal is homogeneously aligned throughout the cell gap by antiparallel rubbing of polyimides. The polarizer was oriented along the rubbing direction at the bottom plate and the analyzer perpendicular to the polarizer. In the IPS cell, the *normalized transmission of light* is

$$T/To = \sin^2(2\psi)\sin^2(\pi d\Delta n/\lambda),$$

where $\psi$ is an angle between the crossed polarizers and the liquid crystal director, $\Delta n$ is the birefringence of liquid crystal medium, and $\lambda$ is the wavelength of the incident light. Therefore, in the voltage-off state, the $\psi$ is zero and the cell appears to be black. With bias voltage larger than Freeder-

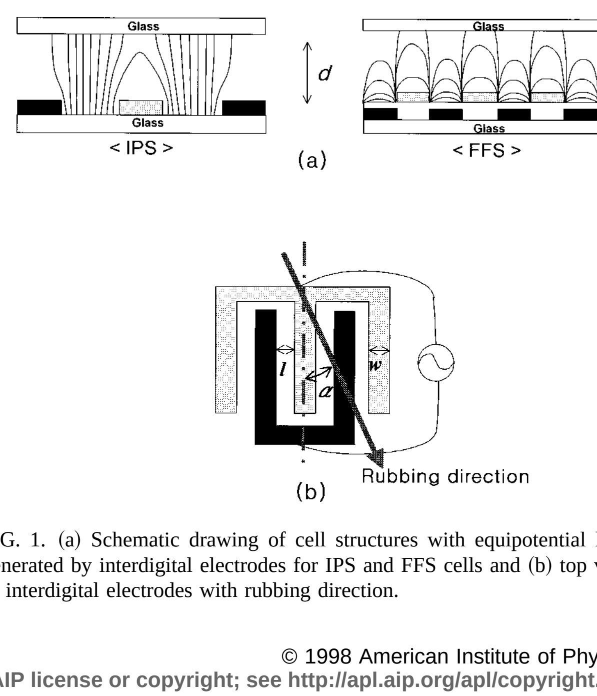


FIG. 1. (a) Schematic drawing of cell structures with equipotential lines generated by interdigital electrodes for IPS and FFS cells and (b) top view of interdigital electrodes with rubbing direction.

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icksz transition threshold, $V$th, the LC molecules are twisted along (perpendicular to) the field direction when a liquid crystal with positive (negative) dielectric anisotropy is present in the cell and thus the value of $\psi$ starts to increase, giving rise to transmission of the incident light. In the IPS cell, the electric field lines parallel to the substrate in the area between electrodes mainly exist so that only twist deformation of liquid crystal director in between them occurs, giving rise to transmission of the incident light. However, the liquid crystal molecules above electrodes do not experience twist deformation due to equipotential surface of electrodes themselves. Consequently the light can be transmitted only in the area between electrodes, resulting in low transmittance compared with that of TN mode. In the FFS cell, $l$ is smaller than $d$ and $w$ so that the electric field parallel to the substrate cannot be formed but instead the electric field lines of paraboliclike form are formed in the whole area. In other words, such field lines having vertical components as well as horizontal ones exist near bottom substrates throughout the cell and the dielectric torque exists on the liquid crystal medium in the whole area, resulting in light transmission.

We have constructed several cells to investigate the electro-optic characteristics of the IPS and FFS cells, varying the cell gap, the distance between electrodes, and the liquid crystals.

For the IPS cell, the indium tin oxide (ITO) with 400 Å was deposited on the bottom glass substrate, and the interdigital electrodes with a distance of 10 $\mu$m between electrodes and an electrode width of 6 $\mu$m were patterned through the photolithographic process. For the FFS cells, the two ITO layers with passivation layer, $SiO_2$ (1500 Å), between them exists as a counter and a pixel electrode. The top ITO layer with an electrode width of 3 $\mu$m was patterned and the bottom ITO was patterned allowing the distance between the top and bottom electrodes to be varied as 0, 1, and 4 $\mu$m. The top glass substrate has no electrode on it for all cells. The alignment layer from the Japan Synthetic Rubber Co. (AL-1051) was coated on both substrates and the rubbing was done in antiparallel directions. The rubbing directions ($\alpha$) were 12° and 78° with respect to the electrode directions, which were in optimal range for maximum transmission. For the cells with rubbing directions of 12° and 78°, the liquid crystal with positive and negative dielectric anisotropy was filled, respectively. The pretilt angle generated by the rubbing is 2°. Two glass substrates were then assembled to give a cell gap of 4.0 $\mu$m. The liquid crystals with positive dielectric anisotropy ($\Delta n = 0.074$ at $\lambda = 589$ nm, $\Delta\epsilon = 8.0$) and negative dielectric anisotropy ($\Delta n = 0.074$ at $\lambda = 589$ nm, $\Delta\epsilon = -3.8$) from Merck Co. were used and filled at room temperatures.

For electro-optic measurement, the Halogen lamp was used as a light source and a square wave, 60 Hz voltage source from the function generator was applied to the sample cell. The light passed through the cell was detected to the photomultiplier tube.

Figure 2 shows *the transmitted light intensity* as a function of the applied voltage for the IPS cell with positive LC, and several FFS cells with negative LC. For the cells with $l$ of 0 and 1 $\mu$m, the light transmission starts to occur at the applied voltage of 1.3 V, an the transmission becomes almost saturated at 7 V. Furthermore, the maximum-transmitted intensity is higher than that of the cell with $l$ of 4 $\mu$m though the transmission-saturation voltage is the same. This indicates that when $l$ is smaller than $d$ with a thin electrode width, the fringe field exists and, consequently, the interaction between the liquid crystals and the horizontal component of fringe field causes twist deformation of the liquid crystal director, giving rise to light transmittance in whole area. However, when $l$ is larger than the electrode width, the liquid crystal molecules above the electrodes experience less twist deformation than those existing in the area between the electrodes, due to the weaker potential difference above the electrodes, resulting in less light transmittance. When $l$ becomes larger than the cell gap for $w$ of 6 $\mu$m, i.e., the value of $l/d$ ratio greater than 1, which is the condition for the conventional IPS mode, the intensity of the transmitted light rapidly decreases. This indicates that the width of electrodes less than 5 $\mu$m and the distance between electrodes less than 2 $\mu$m give rise to effective results in the viewpoint of transmittance. Figure 3 shows the voltage-dependent transmission curve when different types of liquid crystals are used. When the distance between electrodes is less than 1 $\mu$m, the transmittance depends on the type of dielectric anisotropy of liquid crystals. The negative type of liquid crystal gives rise to better transmission than the positive type though the transmission-saturation voltage for the positive liquid crystal is about 2.5 V lower than that of the negative one. When a negative liquid crystal is used, the interaction between the director and the *horizontal* component of the fringe field causes twist deformation, resulting in light transmission. However, the angle between the director and the vertical component of the fringe field is 90°, and therefore the probability of interaction is zero. That is, mainly twist deformation does occur in all regions where the angle between the

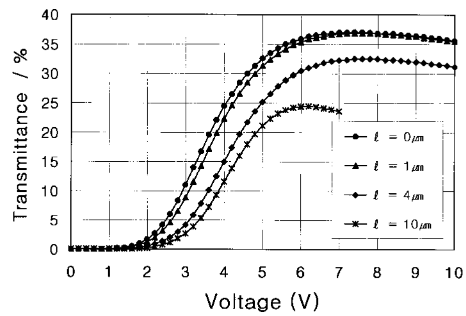


FIG. 2. Voltage-dependent transmission curves for the IPS and several FFS cells when negative LCs are used.

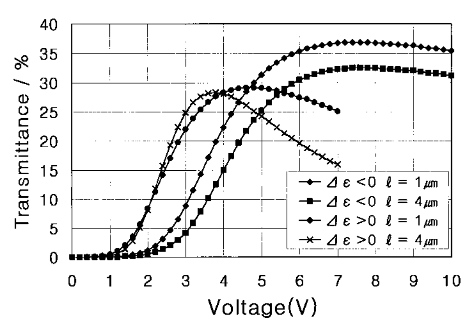


FIG. 3. Voltage-dependent transmission curve depending on different types of liquid crystals.

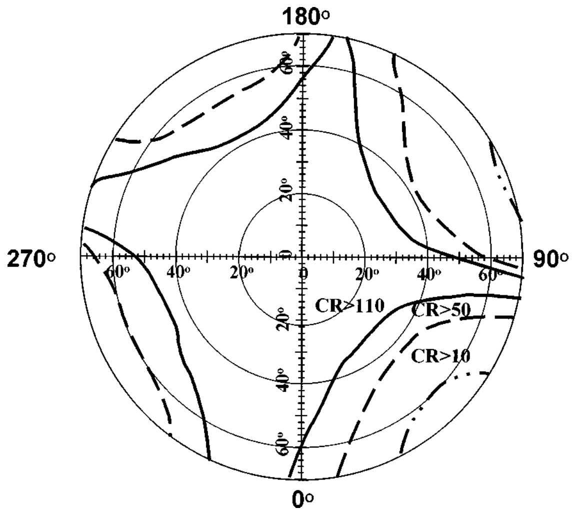


FIG. 4. Iso-contrast plot of the cell with 0 $\mu$m of $l$ for a negative liquid crystal.

LC molecules and the field takes a value intermediate between 0° and 90°. When a positive liquid crystal is used, the director has a tendency to align along the field so that it does tilt up as well as twist by the fringe field. Therefore the transmittance is less than that of cells with negative LC. However, when the value of the $l/d$ ratio greater than 1, the in-plane field mainly exists between electrodes so that the director does mainly twist deformation irrespective of the dielectric anisotropy of liquid crystal, giving rise to about the same transmission. The transmission-saturation voltage depends on the absolute value of dielectric anisotropy, i.e., inversely proportional to root of $\Delta\epsilon$.[3] This explains why it is lower for the positive type than for the negative one.

In order to verify that the director does twist deformation by fringe-field switching, we measured viewing angle characteristics. Figure 4 shows the iso-contrast plot with the applied voltage of 0 and 7 V for the off and on states, respectively, when 1 is 0 $\mu$m with the negative liquid crystal. The region where the contrast ratio greater than 10 exists over 70° of polar angle in all directions is exactly the same result as the conventional IPS cell. This result indirectly proves that the director mainly does twist deformation with the applied field.

In summary, the nematic LCD whose on and off states are controlled by fringe-field switching has been developed. In this device, the liquid crystal molecules do twist in the whole area with applied voltage when the distance between electrodes is smaller than the cell gap and electrode width. The device exhibits high transmission ratio and wide viewing angle characteristics, and overcomes the limited application of the conventional IPS cell. We expect that this concept of device is applicable to wide viewing angle active-matrix LCDs for both monitor and notebook uses.

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