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Novel Nematic Liquid Crystal Device Associated with Hybrid Alignment Controlled by Fringe Field

Seung Ho HONG, Yeon Hak JEONG, Hyang Yul KIM and Seung Hee LEE *

TFT Cell Process Development Department, LCD SBU, Hyundai Electronics Industries, San 136-1, Ami-ri, Bubal-eub, Ichon-si, Kyungki-do 467-701, Korea

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We propose a novel hybrid aligned liquid crystal (LC) cell with negative dielectric anisotropy of the nematic LC driven by fringe field, which is normally black mode. In the on-state, the dielectric torque between the LC director and horizontal component of the fringe field causes the LC director to rotate in the entire area, so that the cell appears to be white. The device, with a wedge-shaped pixel electrode and optical compensation film, also shows a wide viewing angle, high light efficiency and low driving voltage.

KEYWORDS: nematic liquid crystal display, fringe field, wide viewing angle

Liquid crystal displays (LCDs) are being widely used as an interface between human beings and machines. However, in large panels used for monitors and televisions, the speed of replacement of the cathode-ray tube (CRT) by LCDs is relatively slow due to low performance and high cost. In LCDs, the display mode mainly determines the image quality and the fabrication process related to cost issues. Recently, to achieve a display with high performance and low cost, several display modes to improve the quality of the displayed image have been introduced. The first one uses two negative birefringent discotic films in the twisted nematic (TN) mode.[1)] The second one involves in-plane rotation of the LC director, such as in-plane switching (IPS)[2)] and fringe-field switching (FFS).[3–6)] The TN, IPS and FFS modes require a process of the rubbing on the top and bottom substrates that could cause dust and electrostatic charges, resulting in a decrease in the yield. The third mode is a rubbingless vertical alignment (VA) display with multidomains.[7–9)] However, all VA modes require at least one compensation film to suppress light leakage in the off-state and also low light efficiency is inevitable due to the existence of disclination lines between domains. As a result, no single display mode dominates the market because each has both advantages and disadvantages and thus the challenge to develop a new display mode continues.

In this letter, we propose a novel nematic LCD with hybrid alignment driven by fringe-field switching (HAN-FFS). Hybrid aligned nematic (HAN) LCD driven by a vertical field for transmissive display has already been developed.[10,11)] In the previous cases, the director makes a 45° angle with crossed polarizers initially, and thus it appears white in the absence of an electric field. A dark state at an applied voltage was obtained using compensation film. And furthermore two domains in the HAN mode by mechanical double rubbing or photoalignment were necessary to improve asymmetric brightness in the tilting direction, which renders this mode difficult to apply in commercial displays. However, our HAN mode driven by fringe-field switching causes the LC director to rotate instead of tilting up as in the conventional HAN mode, and the LC director can also rotate in the opposite direction with the help of the wedge-shaped pixel electrode. With the addition of the optical compensation film to suppress the light leakage in the off-normal direction, the device has a wide viewing angle, low driving voltage and high transmittance and requires only a simple fabrication process. The simulational and experimental results exhibiting excellent electro-optic characteristics are discussed.

For a cell in uniaxial liquid crystal medium under a crossed polarizer, the normalized light transmission is

$$T/T_o = \sin^2(2\Psi)\sin^2(\pi d \triangle n/\lambda) \quad (1)$$

where Ψ is the angle between the crossed polarizer and the liquid crystal director, Δn the birefringence of the liquid crystal medium, d the cell gap and λ the wavelength of the incident light. Figure 1 shows the cell structure of the HAN-FFS device with the configuration of the LC director in the off- (dark) and on- (white) states. The condition for transparent electrodes is the same as that in our previous paper, where the horizontal distance between a pixel and common electrodes does not exist, and instead only the distance between pixel electrodes exists, resulting in fringe-field lines with bias voltage.[6)] In the off state, the LC molecules are oriented in a hybrid way and the LC director in the bottom substrate is aligned making $\Theta = 12°$ to the horizontal component of the fringe field by rubbing. One of the optic axes of the crossed polarizers is coincident with the rubbing direction, i.e., $\Psi = 0°$, and thus the cell appears to be black in the normal direction. However, in the off-normal direction, light leakage occurs, thus one discotic negative birefringent compensation film is necessary to compensate the residual birefringence in the cell. For a bright state, the applied voltage drives the LC director

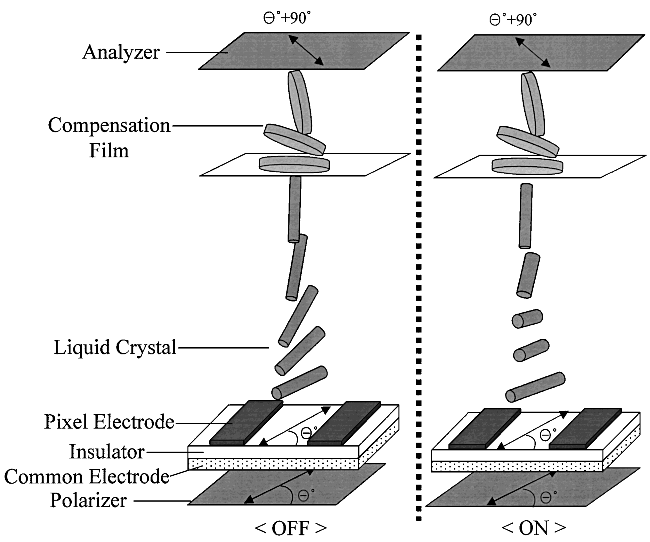

Fig. 1. Schematic drawing of cell structures of the HAN-FFS cell with the LC molecular orientation in the off- and on- states.

*E-mail address: lsh1@hei.co.kr

with negative dielectric anisotropy to deviate from the optic axis of crossed polarizer, so that the light comes through the cell. (Fig. 1)

We have performed a simulation demonstrating how the light transmission corresponding to oscillating electric field intensity occurs on the substrate surface. For the simulation, a liquid crystal ($\Delta n = 0.15$ at 589 nm, dielectric anisotropy $\Delta\varepsilon = -4.0$ at 1 kHz) is used. The pretilt angle in homogeneous alignment to the bottom substrate is 2° and in vertical alignment to the top substrate is 90°. The cell gap is 4 μm. As applied voltage increases, the light transmission oscillates along the horizontal axis and is higher near the edge of the first electrodes than in other regions at mid-gray, but the situation reverses when the voltage for the white state is applied, as can be seen in Fig. 2. Disclination lines that block light transmission do not exist in the light-modulated area but only the oscillation of light transmission with small amplitude exists and thus the light efficiency is very high and comparable to that of the TN device. However, when the LC with positive dielectric anisotropy is used, the light transmittance is significantly decreased because the LC molecules in the area between the edge and the center of the electrode tilt up along the fringe-field lines instead of twisting so that it is only slightly above the center of the electrodes. Furthermore, for this device the homogeneous alignment on the bottom substrate is essential for high light efficiency since the LC molecules near surface are driven by a strong horizontal field component of the fringe field. The light efficiency is also investigated by changing the birefringence of the LC for given the cell gap, as shown in Fig. 3. The retardation value of the cell is relatively high for maximum light transmittance compared with that of the FFS device due to hybrid alignment. (Figs. 2 and 3)

We constructed a test cell to check the feasibility and the dynamics of the device, where the d is 6.8 μm and the LC ($\Delta n = 0.084$ at 589 nm, $\Delta\varepsilon = -4.2$ at 1 kHz) is used. Using a polarizing microscope, the molecular deformation with applied voltage was observed. The light transmission oscillates but no disclination line exists in the light-modulated area as in the simulational result. The voltage-dependent transmission curves are measured and the change in light transmission starts at 1 V and saturates only at 4 V, as shown in Fig. 4. Compared with that of the FFS device with homogeneous alignment,[3] the driving voltage is relatively low owing to weak anchoring energy of the vertical alignment layer on top substrate. (Fig. 4)

In the viewing angle characteristics of the HAN-FFS cell, the compensation film of discotic LC to achieve a good dark state is optimized by the simulation. The film conditions $(nx - nz)\, d = 0.2\,\mu$m and an optic axis of 40° tilt relative to the rubbing direction on the bottom substrate are used. As indicated in Fig. 5, without the compensation film the cell

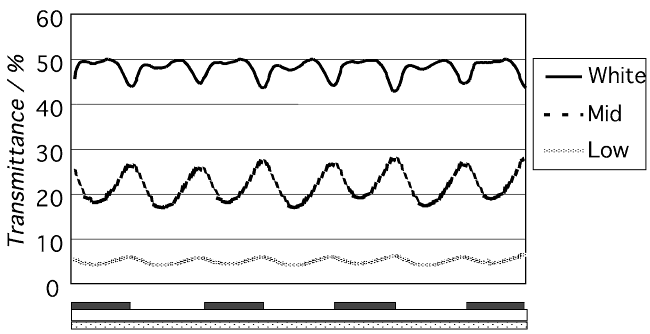

Fig. 2. Simulation result of light transmittance along horizontal direction corresponding to several voltages for low, mid and white grey levels.

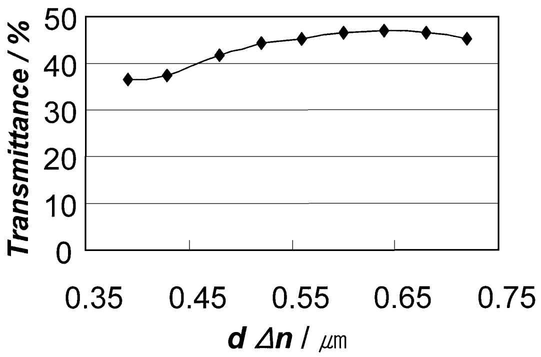

Fig. 3. Light efficiency as a function of the phase retardation of the HAN-FFS cell.

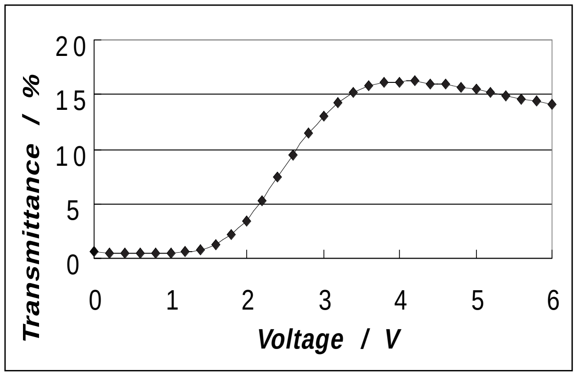

Fig. 4. Experimental result of the voltage-dependent transmittance.

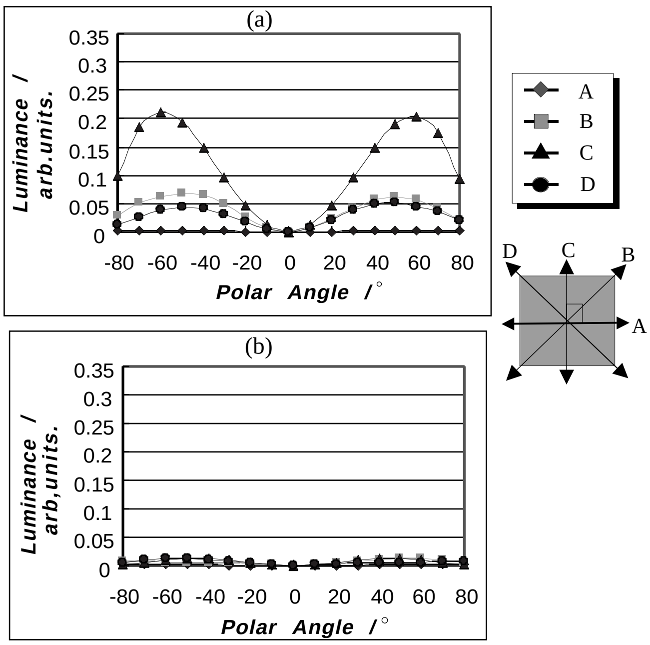

Fig. 5. Light leakage of in a dark state (a) without and (b) with compensation film.

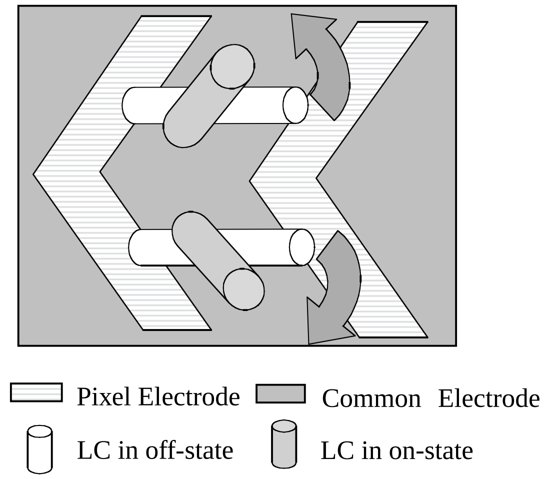

Fig. 6. Electrode structure to obtain two-domain HAN-FFS cell and the configuration of the LC director.

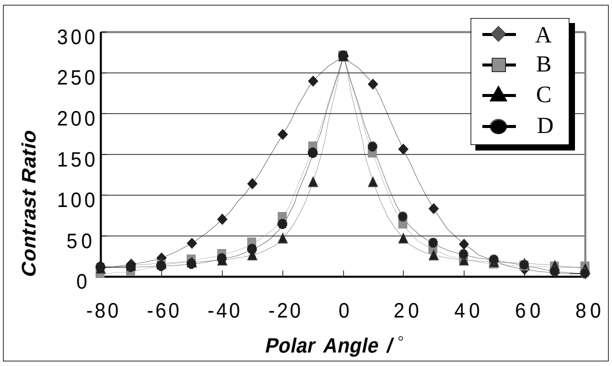

Fig. 7. Iso-contrast curves of the two-domain HAN-FFS cell with compensation film.

shows relatively strong leakage of light as the viewing directions change. However, using the compensation film, the leakage of light in all directions is well controlled. Here, A and C indicate horizontal and vertical directions, and B and D indicate the two diagonal directions. In a single domain of the HAN-FFS cell, the LC director rotates in one direction with a tilt angle of the mid-director of about 45° which causes viewing angle dependency of the phase retardation value especially along the directions parallel and perpendicular to the LC director. For the improvement of the uniformity in the white state, we propose the wedge-shaped pixel electrodes, that is, the field direction in half of one pixel is different from that of the other half. Consequently, the LC director in one pixel rotates in two directions with applied voltage, as indicated in Fig. 6, and the uniformity of the light transmittance is improved following the 2-domain concept. Figure 7 shows the simulated results of the contrast ratio (CR) for several viewing directions. A CR over 200 in the normal direction and greater than 10 in all directions exists over 60° of the polar angle. This result can be improved further with optimization of the film such that the optic axis of the discotic LC is tilted from layer to layer, and also with decrease of phase retardation of the cell by sacrificing the light transmission slightly. (Figs. 5, 6 and 7)

For the first time, we propose a 2-domain HAN-FFS device and give experimental and simulational results. The device exhibits high light efficiency more than 90% of the TN, a wide viewing angle greater than 60° in all directions, and a low driving voltage of 4 V with only one rubbing. The device needs further improvement in terms of optimization and development of the optical compensation film and cell design for an improved viewing angle. The HAN-FFS device has a potential impact on the creation of new LCDs with better image quality than that of the TN device and with high light efficiency. Furthermore, the device can be also applied to a reflective system, which is presently under study.

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