Homogeneous-aligned high-transmission and fast-response liquid crystal display with three-layer electrodes

Xiduo Hu (胡西多)[1], Yubao Sun (孙玉宝)[2*], Guoqiang Yang (杨国强)[2], Ying Xiang (项 颖)[3], and Junsheng Feng (冯俊生)[4]**

[1]*Department of Physics, Dongguan University of Technology, Dongguan 523106, China*

[2]*Department of Applied Physics, Hebei University of Technology, Tianjin 300401, China*

[3]*School of Information Engineering, Guangdong University of Technology, Guangzhou 510006, China*

[4]*Department of Physics and Electronic Engineering, Hefei Normal University, Hefei 230061, China*

[*]*Corresponding author: hmtj450@vip.sina.com; [**]corresponding author: frank_xiang68@yahoo.com.cn*

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A homogeneous-aligned, high-transmission, and fast-response liquid crystal display (LCD) with three-layer electrodes is proposed. The molecules of liquid crystals are more inclined to rotate above and between the pixel electrodes. This induces a much higher transmission than that of the cell driven by the fringe field switching method and a wide viewing angle simultaneously because of the combined fringe and in-plane electric fields. Furthermore, a trigger pulse voltage is applied between the top and common electrodes to forcibly align the liquid crystal molecules vertically to show the transient dark state, which results in a very fast turn-off time (∼1 ms). With high degree of transmission and fast response time, this kind of LCD is a potential candidate for large LCD panels.

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Liquid crystal display (LCD) has been extensively employed for computer monitors and televisions because of the continuous improvement in its image quality. In recent years, the viewing angle, contrast ratio, and color shift of LCD have been greatly improved. However, the current LCD modes can hardly meet the requirements of both high transmission and fast-response speed. For example, the homogeneous-aligned devices driven by either the in-plane switching (IPS) or fringe-field switching (FFS) method have a high transmission; however, their response speed is too slow because of the twist deformation. Although the turn-on time could be reduced by employing the overdriving method[1,2], no crucial solution exists to reduce the turn-off time limited by the slow relaxation of liquid crystal. The vertical alignment (VA) devices trade off between the transmission and the response speed. However, the multiple-domain technique is needed to tilt the liquid crystal molecules down toward different directions for the wide viewing angle. The domain walls do not contribute to light modulation; thus, the transmission is low even under high driving voltage[3].

Recently, two crossed-grating surface substrates are used in vertically aligned LCD for simple domains; however, their fabrication is very complicated[4]. A fringe-field switching, homogeneous-aligned, three-terminal LCD (FFS-3T LCD) has been used to achieve fast turn-off switching[5] based on the original three-terminal LCD with homeotropic alignment[6,7]. However, the low aperture ratio still exists because the width and gap of pixel electrodes are larger than the liquid crystal thickness. As a result, the transmittance of this liquid crystal cell is very low (27%), which means that the transmission is only 0.11 if the maximum transmission of the parallel polarizers is 0.42[5]. Therefore, the transmission needs to improve.

In this letter, a new kind of LCD with three-layer electrodes (FIS-3LE LCD) is investigated. With the combined fringe and in-plane fields, this homogeneous-aligned LCD exhibits an extremely high transmission (0.385, which is higher than that of FFS-3T LCD) and fast response (∼1-ms turn-off time).

Figure 1 shows the schematic structure of the proposed homogeneous-aligned liquid crystal cell with three-layer electrodes (FIS-3LE LCD). In the bottom substrate, the stripe electrodes work as pixel electrodes, and the plane electrode works as common electrode. These two electrodes are separated by a thin passivation layer. The pixel electrodes do not have the same potential; each alternate pixel keeps the same potential, but with an opposite polarity from the adjacent pixel electrodes. The top electrode is used to apply a trigger pulse between the top and common electrodes to forcibly align the liquid crystal vertically to show the transient dark state.

The liquid crystal cell is sandwiched between two

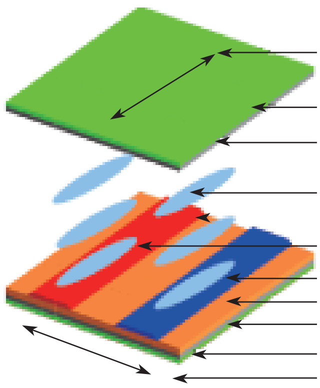

Fig. 1. Schematic structure of the proposed homogeneous-aligned liquid crystal cell with three-layer electrodes.

crossed polarizers. The employed liquid crystals posses a positive dielectric anisotropy and an initial homogeneous-alignment, resulting in a normally dark state similar to the conventional IPS- or FFS-mode LCD. When the voltage is applied on pixel electrodes for the bright state, not only is a fringe field formed between the pixel and common electrodes, an in-plane electric field is also generated between pixel electrodes. The homogenous electric field and the elastic force make all liquid crystals rotate, which leads to high transmission[8]. During the turn-off process, a trigger pulse of 10 V is applied on the top electrodes for 3 ms to forcibly align the liquid crystals vertically to show the transient dark state, which induces a very fast turn-off time (∼1 ms). As soon as the trigger pulse is removed, the liquid crystal molecules, which are unstable in the transient state, relax to the initial state. The turn-off process is optically hidden, and consequently the cell remains in the dark state because the liquid crystal director is always parallel with the transmission axis of the top or the bottom polarizer during the relaxation[4].

The electro-optic properties of the FIS-3LE LCD are simulated using a commercial three-dimensional (3D) LCD simulator (TechWiz LCD, Sanayi, Turkey), in which the liquid crystal distributions are calculated using the finite element method[9] and the optical properties are calculated using the extended 2×2 Jones matrix method[10,11].

In the simulation, the pixel electrodes have a width of W=2 μm and a gap of G=2 μm. In the proposed liquid crystal cell, the thickness of the liquid crystal layer is d=4 μm. The narrow width and gap of pixel electrodes result in a weak vertical electric field in the range above the pixel electrodes. The pre-tilt angle of liquid crystal on the top substrate and the bottom substrate are set to 1° and –1° (the parallel rubbing), respectively, and the angle between the initial liquid crystal director and the electrode's long direction is set to 2°.

The parameters of liquid crystal material in the simulation are as follows: $K_{11} = 9.7$ pN, $K_{22} = 5.2$ pN, $K_{11} =$ 13.3 pN, birefringence Δn=0.1, dielectric anisotropy $\Delta\varepsilon$=8.2, and rotational viscosity γ_1=100 mPa · s.

For comparison, a cell with two-layer electrodes (FIS-LCD) was simulated using the same parameters, except for the absence of the top electrode, and an FFS-3T LCD with the same parameters is also simulated.

The voltage-dependent transmission (V-T) curves of the FIS-LCD and the proposed FIS-3LE are shown in Fig. 2, where the transmission maxima of these two kinds of cells are nearly the same and occur at V=1.8. In other words, the top electrode of the FIS-3LE cell has little impact on the transmission of the bright state. The voltage-dependent transmission curve of the FFS-3T cell shows a low-transmission and high operating voltage. The transmission of FIS-3LE is similar to that of the FIS-LCD, which is in favor of power reduction.

Figure 3 shows the simulated distance-dependent transmission (D-T) curves of the FIS cell and the proposed FIS-3LE cell. The D-T curves of the FIS cell and the proposed FIS-3LE cell match very well, with maximum transmission occurring at an operating voltage of 1.8 V. In the FIS-3LE and FIS cell, fringing electric fields and in-plane electric fields are synchronously generated above and between pixel electrodes, and liquid crystal directors are reoriented not only near the edges of pixel electrodes, but also in the entire area of pixel electrodes having gaps, which results in a high maximum transmission in the bright state.

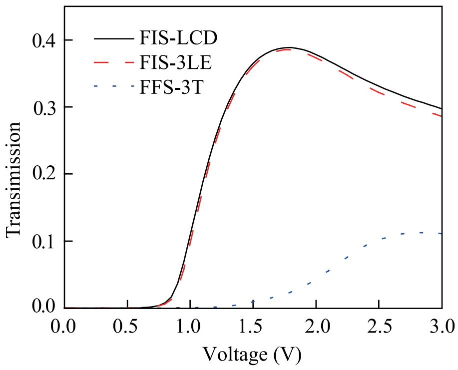

Fig. 2. Comparison of voltage-dependent transmission curves of the FIS-LCD and the proposed FIS-3T device.

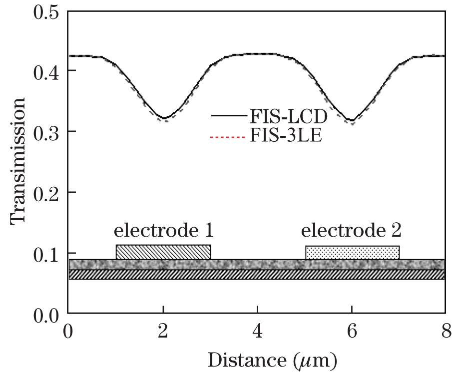

Fig. 3. Comparison of distance-dependent transmission between FIS-2T (solid line) and the proposed FIS-3T (dashed line) device.

The transmission at the area of the pixel electrodes in the FIS-3LE cell is slightly lower than that in the FIS-2LE cell, which can be attributed to the vertical electric field between the top and common electrode against the rotating liquid crystal molecules above the pixel electrodes. The transmission above the pixel electrodes and the center of the pixel electrodes in the FFS-3T cell is very low because the vertical electric field cannot facilitate transmission, which cannot be shown in Fig. 3.

Figure 4 shows the voltage waveforms applied to calculate the response behavior of the proposed FIS-3LE devices. When 1.8 and –1.8 V are applied to the pixel electrodes for 150 ms during the turn-on process, the turn-on time of the FIS-LCD and the proposed FIS-3LE cells is nearly the same, which means that the top electrode of the proposed FIS-3LE cell has no impact on the turn-on process.

The response times (10%–90% of transmission change) of the FIS-LCD and the proposed FIS-3LE cells are calculated and plotted in Fig. 5. The rise time and decay time for the FIS-LCD cell are ∼29.3 and ∼40.5 ms, respectively, whereas, for the FIS-3LE cell, the rise time and decay time are ∼30.01 and ∼1 ms, respectively.

During the turn-off process, the liquid crystal molecules freely relax to the initial homogeneous alignment when the voltage is removed; thus, the turn-off time is very slow (∼40.5 ms). For the proposed FIS-3LE cell, when the in-plane field is removed, a trigger pulse of 10 V is applied between the top electrodes for 3 ms to force the liquid crystal molecules to align vertically. As a result, the temporal dark state is shown and the turn-off time is very fast (∼1 ms).

Voltage of 10 V is used for the fast response speed from white to dark, and the 3-ms pulse eliminates the optical bounce during the turn-off process. Once the trigger pulse is removed, the liquid crystal molecules that were unstable in the temporal state relax to the initial state. During this process, the turn-off process is optically hidden because the liquid crystal director is always parallel to the transmission axis of the top or bottom polarizer; therefore, the cell remains in a dark state. The fast-response property makes this FIS-3LE device attractive for large panel LCDs because it eliminates image blurring. During the turn-on process, the response speed can be further improved using the overdrive method.

Because the initial liquid crystal molecular distribution in the FIS-3LE cell is identical to that of the FIS-LCD cell, a similar viewing angle performance is expected. Figure 6 shows the iso-contrast contour of the FIS-LCD (a) and the proposed FIS-3LE (b) with the same film compensation, where the contrast ratio is greater than 100:1 at an over 65° viewing cone in both the FIS-LCD and FIS-3LE cell.

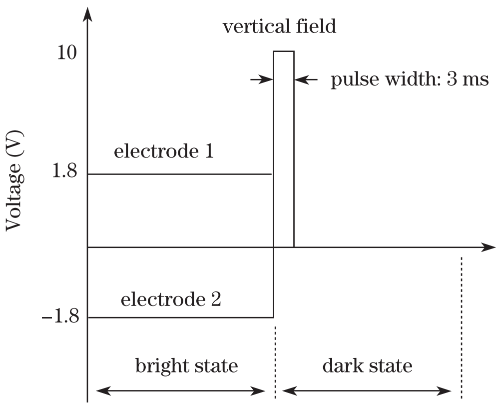

Fig. 4. Voltage waveforms applied to measure the response behavior of the proposed FIS-3T device.

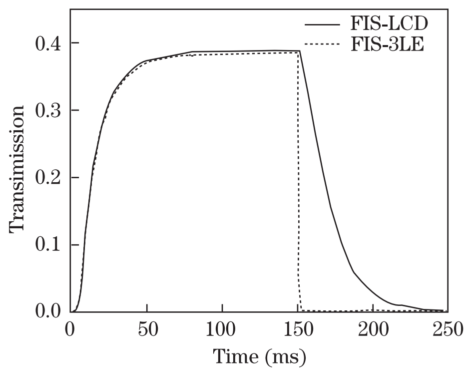

Fig. 5. Calculated response time of the FIS-LCD (solid line) and FIS-3LE (dashed line) device.

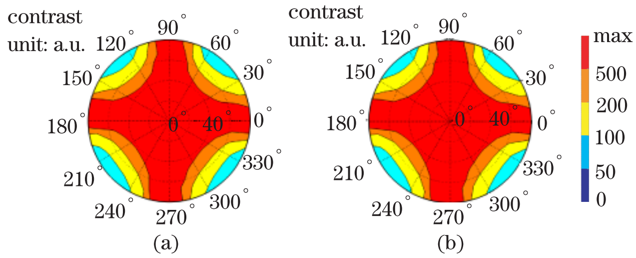

Fig. 6. Comparison of iso-contrast contour of (a) the FIS-LCD and (b) the proposed FIS-3T cells.

A homogeneous-aligned LCD with three-layer electrodes (FIS-3LE LCD) that exhibits both high transmission and fast response is proposed . The FIS-3LE LCD has high transmission because it has more homogenous electric fields compared with the FFS-3T LCD. A trigger pulse voltage is applied between the top and common electrodes to force the liquid crystal molecules to be vertically aligned to show the temporal dark state, which results in a very fast turn-off time (∼1 ms). However, three thin-film transistors are needed in this LCD, which decreases the aperture ratio and complicates the fabrication and driving . The fast turn-off time would improve the image quality (clear and no wash-off). The proposed LCD mode can be considered for application to large-panel LCD.

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