A fast-response in-plane switching liquid crystal display with a protrusion structure

Yanfeng Li (李岩锋), Yubao Sun (孙玉宝)*, and Yanli Zhao (赵彦礼)

Department of Applied Physics, Hebei University of Technology, Tianjin 300401, China

**Corresponding author: sun_yubao@163.com*

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The widespread use and application of in-plane switching liquid crystal displays (IPS-LCDs) is limited by their slow response. In this letter, a fast-response IPS-LCD with a protrusion structure is proposed. The gray-to-gray response time of the IPS-LCD is reduced by 20% to 30%. The difference in cell gap induced by the protrusion accounts for the faster response. Moreover, the viewing angle and gamma shift of the proposed IPS-LCD are simulated and found to be better than that of conventional IPS-LCDs.

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In-plane switching (IPS) liquid crystal displays (LCDs) (including in-plane switching and fringe-field switching modes) are widely used in portable devices and television displays because of their wide viewing angle, small color shift, and high point per inch[1−4]. However, the low response speed of IPS-LCDs limits their applications within text and still image displays, with restricted application in video displays[2−6]. The overdriving method has been proposed to improve response speed, but this method requires a more complex drive circuitry[7]. Polymer-stabilized liquid crystals (LCs) can reduce response time, but it also reduces the contrast ratio (CR)[8]. A double-sided fringe-field switching mode needs two thin-film transistors at the bottom and top substrates, and the cost of TFTs is too high[9]. Rise time can be improved up to three times using IPS-LCDs with an optimized rubbing angle, but these LCDs have no effect on decay time compared with conventional IPS-LCDs[10,11]. Super-twisted nematic IPS-LCDs can improve rise and decay times by more than four times, but the dark state of this type of LCDs is not good enough to obtain a high CR[12].

In this letter, we propose a fast-response in-plane switching (FR-IPS) mode with a protrusion structure. The protrusion structure in the FR-LCD mode greatly reduces the response time by lowering the part thickness of the cell gap. This protrusion structure reduces the gray-to-gray response time of the IPS-LCD by 20% to 30%. This FR-LCD mode also has a very wide viewing angle similar to the conventional IPS mode, and its gamma shift is better than that of the conventional IPS mode.

Figure 1 shows the typical structures. Figure 1(a) is a conventional IPS mode[13], Fig. 1(b) is the top view of the FR-IPS mode, and Fig. 1(c) is the cross-section of the FR-IPS mode. The cell is placed between two crossed linear polarizers, and a half wavelength biaxial film is used to obtain a wide viewing angle, as shown in Fig. 1. W_1 and W_2 are the IPS electrodes' width and gap, respectively, and W_3 and W_4 are the protrusion structure's width and gap, respectively. The width of the protrusion's top surface and the height of the protrusion are W_5 and H_1, respectively. The protrusion is made only on the top substrate, and its fabrication is similar to that of a fabricated protrusion in conventional multi-domain vertical alignment mode LCDs. In this proposed structure, the protrusion cannot affect the dark state because the LC director is along the length direction of the protrusion, as shown in Fig. 1(b); hence, the CR is not reduced.

Both the conventional IPS mode and the proposed FR-IPS mode are studied and optimized using the commercial simulation software TechWiz LCD three-dimensional (3D) (Sanayi System Co., Ltd., Korea). For comparison, the same LCD configuration of electrode width W_1=3 μm, electrode gap W_2=8 μm, and cell gap d=4 μm are used in the two modes. The LC material parameters are K_{11}=10.87 pN, K_{22}=9.5 pN, K_{33}=15.37 pN, Δn=0.0891, $\Delta\varepsilon$=10, and γ_1=60 mPa·s. The parameters of protrusion are W_3=3 μm, W_4=3 μm, W_5=2 μm, and H_1=1 μm.

Figure 2 shows the simulated voltage-dependent transmittance ($V-T$) curves of the proposed FR-IPS and the conventional IPS modes with the same rubbing angle (the angle between the initial LC direction and the sideline of electrodes equaling 12° and 18°, respectively). The

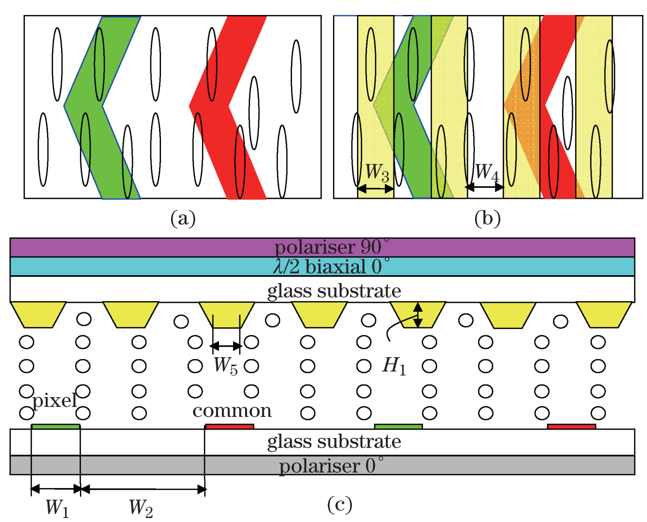

Fig. 1. (a) Structures of the conventional IPS mode. (b) Top view and (c) cross-section of the proposed IPS mode.

Table 1. Gray-to-Gray Response Time of Conventional and Proposed IPS Modes

$\tau_{\rm on}$(ms)	Conventional IPS Mode					Proposed FR-IPS Mode				
$\tau_{\rm off}$(ms)	0	1	2	3	4	0	1	2	3	4
0		70.9	45.8	31.5	12.9		52.2	35.5	23.1	8.9
1	10.1		35.6	26.3	10.7	7.1		27.2	19.2	7.2
2	10.7	43.1		24.9	11.9	7.5	31.7		18.5	8.4
3	11.4	40.4	31.7		14.7	8.0	29.1	23.1		10.1
4	12.3	38.7	30.8	25.2		8.6	26.9	21.5	18.4	

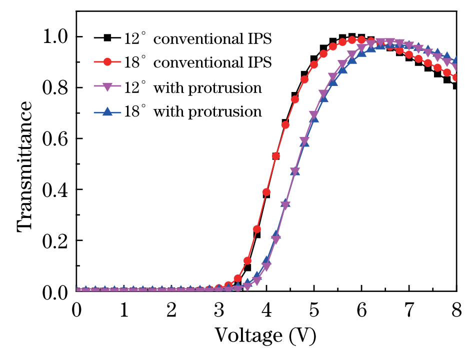

Fig. 2. Voltage-dependent transmittance of the conventional and proposed IPS-LCD.

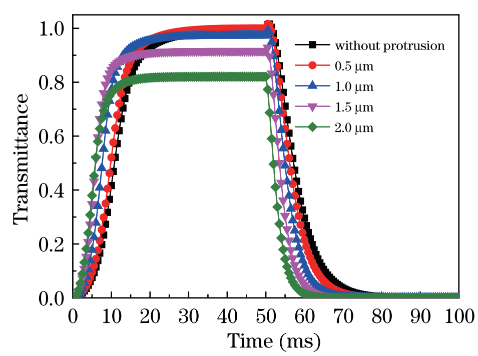

Fig. 3. Transmittance as a function of time for the cell driven between the operating and zero voltages.

maximum transmission of the conventional IPS mode is chosen as the normalized value. The maximum transmittances for 12° and 18° rubbing angles of the cell with protrusions are reduced by about 2% compared with that of the cell without protrusions. The operating voltage of the FR-IPS mode is larger than that of the conventional IPS mode. The increased operating voltages of FR-IPS compared with the conventional IPS mode are due to the low cell gap. The operating voltage is proportional to the ratio of the electrode gap and cell gap[13].

Table 1 summarizes the calculated rise and decay times among the different gray levels for the conventional IPS and the proposed FR-IPS modes. To evaluate the gray-to-gray response time, the V-T curve is divided into four gray levels. The response time is still defined as 10% to 90% transmittance change.

Compared with the conventional IPS mode, the proposed FR-IPS mode is faster. The gray-to-gray response time is reduced by 20% to 30% because of the low cell gap in the region with protrusion. The response times can be further reduced if a lower viscosity LC material is used or if the protrusion height is larger. The transmittances as a function of time for the cell driven between the operating and zero voltages for different protrusion heights are shown in Fig. 3. The response time and transmittance decrease with increased protrusion height, and the cell with a protrusion height of 1.0 μm has faster response speed and higher transmittance.

Figure 4 shows the simulated iso-contrast contour plots of the conventional IPS mode and the proposed FR-IPS mode. The CR in both modes is fairly superior. Under the same compensation film[14] (n_x=1.511, n_y=1.5095, n_z=1.51025, and film thickness=184 μm), the 1000:1 CR is over the 50° viewing cone and that of the 100:1 CR is over the 80° viewing cone. As a result, the protrusion almost has no effect on the viewing angle.

Afterwards, we calculate the gamma shift of the two modes under the different oblique viewing angle with azimuth angle ϕ=0°, 45°, 90°, and 135°. As shown in Fig. 5, the proposed FR-IPS is better than the conventional IPS mode. The conventional IPS LCD with a half-wave biaxial film has a very good viewing angle because of the two domain structures. In the proposed FR-IPS LCD, different twist distributions in the regions with and without protrusions are present. Hence, the four domain structures of FR-IPS LCD results in a better gamma shift.

In conclusion, a fast-response IPS-LCD (FR-IPS) with a protrusion structure is proposed, and its gray-to-gray response times is reduced by more than 20%. The proposed device also exhibits a good viewing angle and $V-T$ curves compared with the conventional IPS mode. Moreover, the gamma shift curves are better than

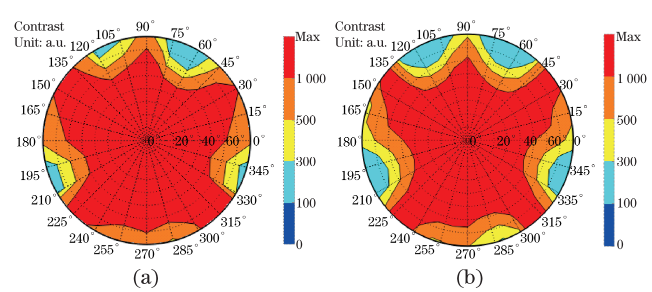

Fig. 4. Simulated iso-contrast contour plots for the (a) conventional and (b) proposed FR-IPS modes.

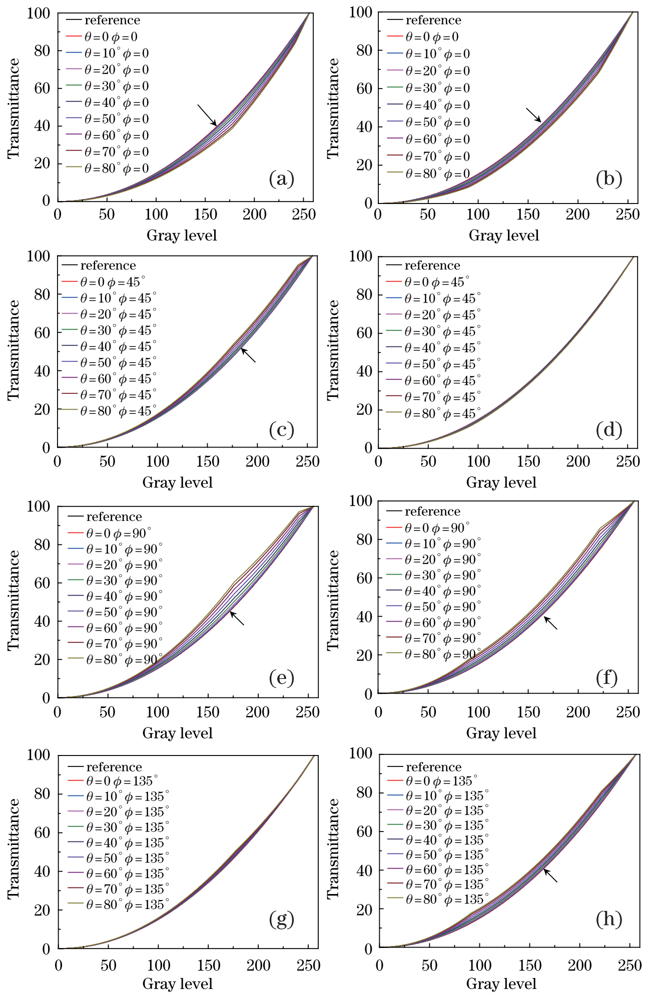

Fig. 5. Gamma shift curves: (a, c, e, g) conventional IPS mode; (b, d, f, h) proposed FR-IPS mode.

the conventional device in most viewing angles. Recently, Park *et al.* proposed a fast fringe-field-switching (FFS) LC cell with the protrusion inserted between the pixel electrodes[15], with the height and width of the protrusion being 0.4 and 1.0 μm, respectively. Considering the factual LCDs, the pixel electrodes of the two domains of FFS LCD have two directions; hence, the protrusion has two directions. However, the LC direction is only along one direction at the dark state; thus, the ups and downs of the protrusion affect the LC homogenous alignment. Light leakage cannot be ignored in the dark state; as a result, the CR is reduced. In our mode, the LC alignment is along the length direction of the protrusion, so the protrusion cannot induce light leakage in the normal or oblique viewing direction. The CR and viewing angle thus cannot be reduced. We believe that this mode is a good way to reduce response time.

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