Ultra-FFS TFT-LCD with super image quality, fast response time, and strong pressure-resistant characteristics

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Abstract — Fringe-field-switching (FFS) devices using liquid-crystal (LC) with a negative dielectric anisotropy exhibit high transmittance and wide viewing angle simultaneously. Recently, we have developed an "Ultra-FFS" thin-film-transistor (TFT) LCD using LC with a positive dielectric anisotropy that exhibits high transmittance, is color-shift free, has a high-contrast ratio in a wide range, experiences no crosstalk and has a fast response time of 25 msec. In this paper, the device concept is discussed, and, in addition, the pressure-resistant characteristics of the devices compared with that of the twisted-nematic (TN) LCD is discussed.

Keywords — *TFT-LCD, liquid crystal, fringe-field switching, wide-viewing angle.*

1 Introduction

Recently, the image quality of liquid-crystal displays (LCDs) has greatly improved because of several new technologies.[1] Among them, the fringe-field-switching (FFS) device exhibits high transmittance and wide-viewing angle at the same time.[2-8] In the FFS device, the fringe field was utilized to rotate homogeneously aligned LC molecules almost in the plane above the entire electrode surface, giving rise to a high light-transmitted area (TA), unlike the in-plane-switching (IPS) device as shown in Fig. 1. In the IPS device, the electrode width (w) and the cell gap (d) is always larger than the distance (l) between electrodes. Consequently, the in-plane field is generated between electrodes when a voltage is applied and the LC modulates light only in that area, giving rise to a limited transmission area. However, in the FFS device, the distance (l') between pixel electrodes only exists above the counter electrodes, creating a storage capacitance (C_{st}) in the light transmitted area. When a voltage is applied, fringe fields are generated, enabling the LCs to rotate above the electrodes so that high transmittance is achieved. In previous devices, LC with a negative dielectric anisotropy (–LC) was used. The response time was rather slow, 50 msec due to the relatively high rotational viscosity, and there was a color shift due to in-plane rotation in one direction with a single domain. The LC with a positive dielectric anisotropy (+LC) is rather inferior to the negative dielectric anisotropy in light efficiency though it has advantages in response time due to a low rotational viscosity and low driving voltage owing to high dielectric anisotropy, as summarized in Table 1. However, we have optimized the LC cell parameters to maximize the light efficiency by using the +LC and obtained a light efficiency of about 90% of that of negative LC. Furthermore, we optimized the pixel structure by using a wedge shape for the pixel electrode. In this way, the leakage of light between the data and pixel electrodes was suppressed automatically. Consequently, the device does not require a black matrix above the data lines. Thus, the aperture ratio can be increased, giving rise to the same luminance as that of negative LC and a fast response time of 25 msec. This concept referred to as Ultra-FFS was applied to our new 18.1- and 21.3-in. TFT-LCD modules, which show a high image quality comparable to that of a CRT. In this paper, the molecular dynamics of the device using +LC and the design concept consisting of cell parameters and one pixel structure are described in detail. Furthermore, the FFS device shows high stability of the molecular dynamics versus pressure compared to that of the TN device.[9] Because of this advantage, the FFS TFT-LCD is now being applied to even pen-based displays. This will also be briefly reviewed.

TABLE 1 — Comparison of the physical properties of the LC.

	–LC	+LC
Light efficiency	~90% of TN	Low
Rotational viscosity	>100 mPa-sec	<100 mPa-sec
Dielectric anisotropy	Low (high vop)	High (low vop)

2 Experimental and simulation results

The Ultra-FFS has the following characteristics:

- High transmittance.
- Color-shift free.
- Wide viewing angle (high contrast in a wide range).
- No crosstalk.
- Fast response time.
- Low power consumption.
- Highly pressure resistant.

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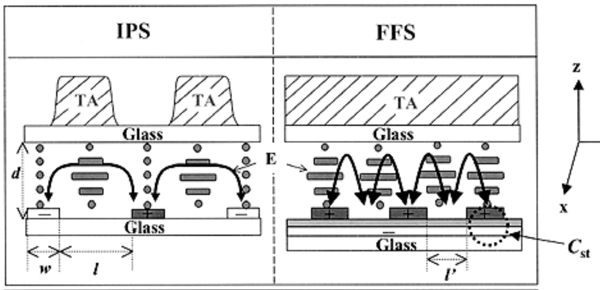

	IPS	FFS
l/d	>1	<1 or 0
l/w	>1	<1 or 0
Field	*Ey*	*Ey, Ez*
Electrodes	Metals or ITO	ITO

FIGURE 1 — Comparison of the cell structures of IPS and FFS modes.

To realize the above-mentioned characteristics, the cell and pixel designs must be optimized.

2.1 Cell and LC design

In the FFS device, the LC molecules are homogeneously aligned initially under crossed polarizers with the electrode structure generating a fringe field. Figure 2 shows the field distribution of vertical (E_z) and horizontal (E_y) fields along horizontal axis. Here, the detailed electrode structure is the same as that used in previous papers.[7] When the vertical distance (z) from electrode surface is 0.4 μm, a strong E_y exists near the edge of pixel electrodes and both E_y and E_z exist between the edge and the center of electrodes while E_y is zero above the center of the electrodes. At a vertical distance of 3 μm, both field intensities become very weak, and E_z is maximum at the center of electrodes and minimum at the edge. This field distribution causes the LC molecules to orient in an interesting way. Figure 3 shows the profile of the LC molecules of the white state in tilt (θ) and twist (Φ) angles inside cell gap (d) for the +LC, where A1, A2, and A3 indicate positions at the edge, between the edge and center, and at the center of the common electrodes. In this case, the rubbing angle (α) was defined as 78° for the +LC with respect to the horizontal component of the fringe field lines and the pretilt angle was 2°. According to Fig. 3, the LC molecules are tilted upwards in the bottom half of the layer and the maximum θ at A2 is much higher than those at other positions. In addition, the maximum θ at A2 is about –40° for the +LC material (the negative sign indicates θ in opposite direction to the initial one), due to the existence of a strong vertical field. For Φ, the +LC molecules are twisted by 68° from the initial alignment near the bottom surface of A1 such that the configuration of the LC molecules at A1 is similar to that for the low TN device. At A2 and A3, the maximum degree of twist is only about 50° and 30°, respectively. This indicates that the light transmittance in A1 is much higher than that in A3, and also the electro-optic characteristics of the FFS device with +LC mainly follows that of the low TN device. The high tilt angle in A2 (about 40°) means that the elastic force required to rotate the LC molecules in A3 is weaker than that of the device with negative LC, which is the origin of the lower light efficiency of the positive LC compared to that of the negative LC. Again, such a director profile implies that the electro-optic behavior is different from that of the FFS device with –LC and the IPS device. We found that the $d\Delta n$ value of the FFS cell with +LC for maximum light efficiency is much higher than that of the IPS and FFS devices with –LC and is between the first minimum of the TN and the IPS devices as shown in Fig. 4. We also found that the light efficiency of the FFS device with +LC is a function of the rubbing angle, as shown in Fig. 5.[7] For –LC in the FFS device, the maximum light transmittance does not changed, although the α changes from 12° to 30° but rapidly drops when a changes from 78° to 60° for +LC. This behavior is not observed in the IPS and the FFS devices with –LC. Of course, when α is 45°, the maximum transmittance is decreased since the maximum twist angle of the LC director can not be 45°. By understanding the relationship between the light transmittance and the cell parameters in the FFS device, such as rubbing angle and the retardation value of the cell, we could obtain a light efficiency for +LC of over 90% of that of –LC.

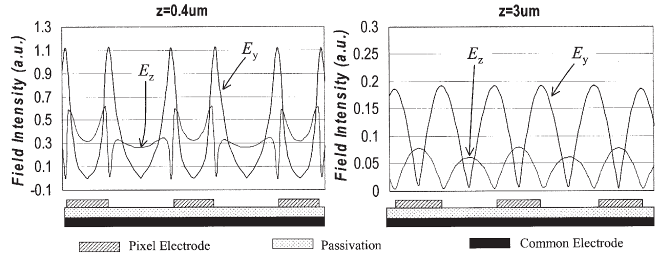

FIGURE 2 — Field distributions along the horizontal axis of the FFS device.

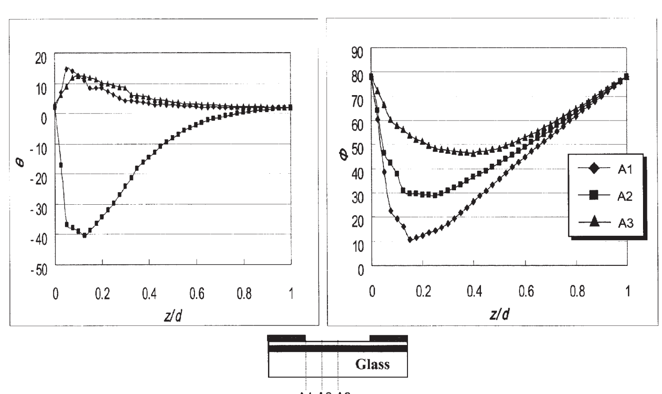

FIGURE 3 — Profile of the LC molecules in tilt angle (θ) and in twist angle (Φ) at three different positions.

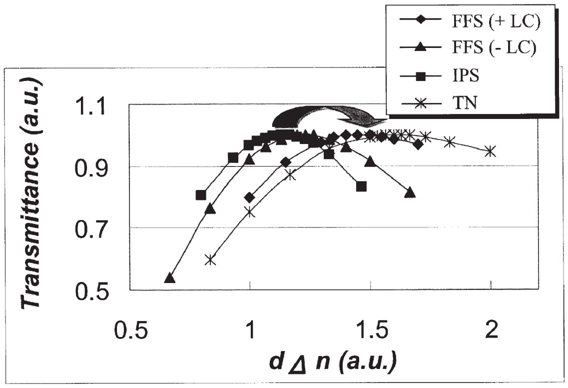

FIGURE 4 — Light transmittance as a function of retardation value of the cell in the FFS, the IPS and the TN devices.

2.2 Pixel structure of Ultra-FFS device

In the Ultra-FFS device, only the pixel electrode has a wedge shape such that the field direction in half of one pixel is different from that in the other half, as shown in Fig. 6. The IPS device cannot have this kind of shape because the transmittance will be greatly lowered if the pixel and the counter electrodes are patterned in such a shape. With such a structure, the LC molecules rotate clockwise and counter-clockwise in one pixel so that the shift of color coordinates as the viewing angle changes is minimized compared with that of the conventional FFS device that shows bluish and yellowish colors in certain oblique directions. For the FFS device, the degree of rotation of the LC director along the horizontal axis is alternating (see the configuration of the LC director of the white state in Fig. 6) and therefore, owing to the self-compensation effects, shows less of a color shift than that of the IPS device. Another advantage of using such a structure is leakage of light in the area between the pixel and data bus line does not occur because the field direction in that area is parallel to the LC director, *i.e.*, the noise field generated by data bus lines causes the LC director to align more perfectly to the initial rubbing direction, giving rise to a complete dark state as described in Fig. 6. Light leakage in that area is one of the major sources for crosstalk in low gray levels. Therefore, the Ultra-FFS device demonstrates low crosstalk without shielding the areas near the data bus lines. Therefore, the device does not need a

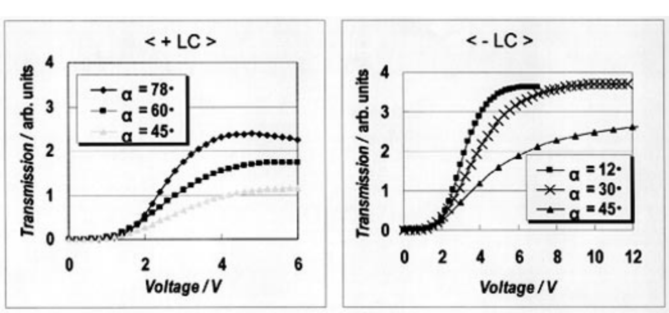

FIGURE 5 — Rubbing angle-dependent transmittance in the FFS device with +LC and –LC.

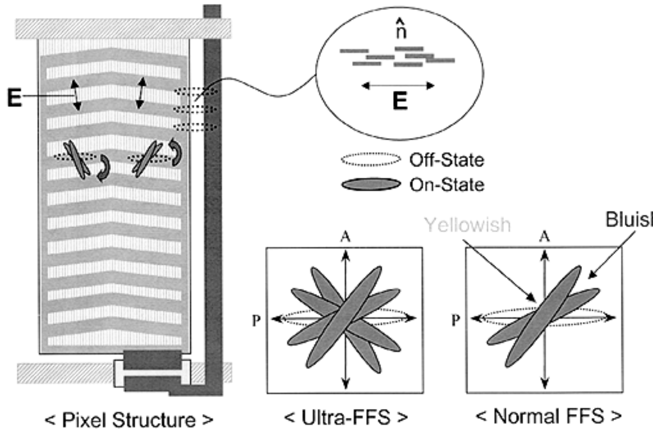

FIGURE 6 — Pixel structure of the Ultra-FFS device and configuration of the LC director in the white state.

black matrix (BM) on the color-filter side theoretically, and thus the aperture ratio can be increased to compensate for the decreased transmittance of the +LC compared to the –LC. Figure 7 shows the iso-contrast plot of the 18.1-in. Ultra-FFS TFT-LCD. As indicated, it shows a four-fold symmetric viewing angle and that the CR of greater than 100 extends to about 70° of the polar angle vertically and horizontally – with a minimum CR value of 13 in all azimuthal directions within a polar angle of 80°. We also measured the degree of color shift of the white state in conventional and Ultra-FFS panels, where the data were obtained by changing the azimuthal angle with increasing steps of 15° at polar angle of 60°. As can be shown in Fig. 8, in the Ultra-FFS device the color coordinates are almost constant although the viewing direction changes.

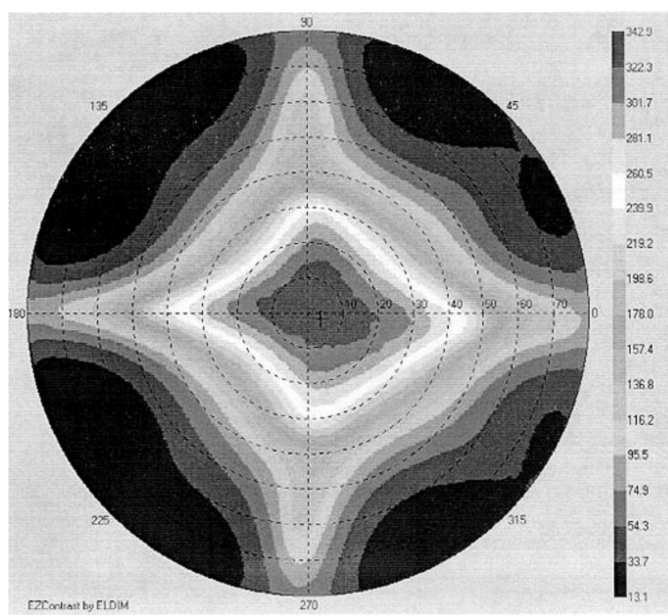

FIGURE 7 — Iso-contrast plot of the 18.1-in. Ultra-FFS TFT-LCD.

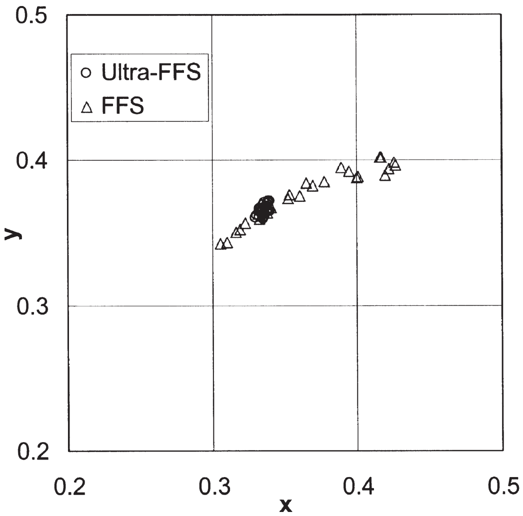

FIGURE 8 — Viewing-angle dependency of the color coordinates of the white state in normal and Ultra-FFS devices.

Overall, the Ultra-FFS device shows high transmittance and a perfect viewing angle with minimized color shift and no crosstalk.

2.3 Fast response time and low power consumption

At the present level, the rotational viscosity (γ) of the positive LC (<100 mPa-sec) is smaller than that of negative LC (>100 mPa-sec). In the IPS device, in order to achieve a fast response time, the reduction of d and γ is required. However, reducing d increases the driving voltage, so that an increase of Δε is inevitable in lowering the driving voltage, which increases γ of the LC unfortunately since the driving voltage is inversely proportional to d and proportional to l follows:

$$V_{th} = \pi l/d \times (K_{22}/\varepsilon_0\Delta\varepsilon)^{1/2},$$

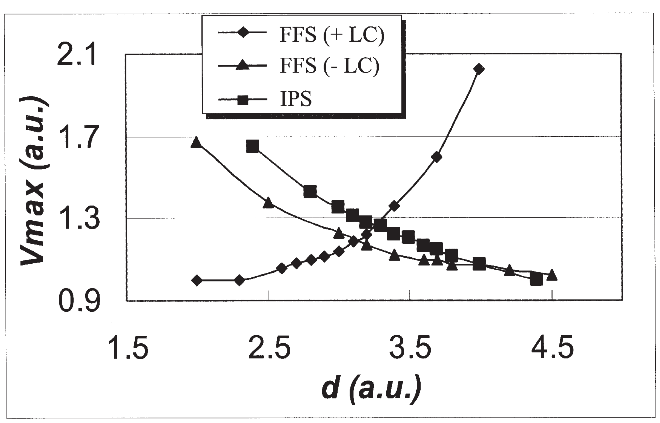

FIGURE 9 — Cell-gap-dependent driving voltage (V_{max}) in the IPS and the FFS devices.

TABLE 2 — Specification for the 18-in. Ultra-FFS TFT-LCD.

Diagonal size (in.)		18 in.
Resolution (pixels)		1280 (H) × 1024 (V) × (3)
Pixel pitch (mm)		0.95 (H) × 0.285 (V)
Brightness (nits)		220 (typical)
White chromaticity W (x, y)		x = 0.32, y = 0.34
Number of backlights		four CCFL
Color reproduction (%)		68 (typical)
Contrast ratio		300:1 (min.)
Viewing angle	(CR > 100)	130° (Horizontal, Vertical)
	(CR > 10)	>160° (Horizontal, Vertical)
Response time (msec)		25 (T_r = 11, T_f = 14)
Crosstalk (%)		<1 (Horizontal, Vertical)
Power consumption (W)		23

where K_{22} is the twist elastic constant and Δε is the dielectric anisotropy of the LC.[10] In the FFS device with –LC, the same rule is applied, *i.e.,* decreasing a cell gap will increase driving voltage because the LC director rotates almost in plane. However, in the FFS device with a +LC, the lower the cell gap the lower the driving voltage as indicated in Fig. 9. This is mainly due to the tilt effect of the LC molecules in A2.[11] Conclusively speaking, it is not necessary to increase Δε in order to lower the driving voltage when decreasing the cell gap so that the device is intrinsically advantageous for fast response time and also for low driving voltage since the absolute value of Δε is much higher for the +LC than the –LC.

2.4 Specifications of the Ultra-FFS device

By optimizing the cell parameters, materials, and shape of electrodes, *i.e.,* using the Ultra-FFS concept, we developed an 18.1-in. TFT-LCD. As shown in Table 2, the specifications of the device shows a high brightness of 220 nits using four lamps and a high color reproduction ratio of 68% with

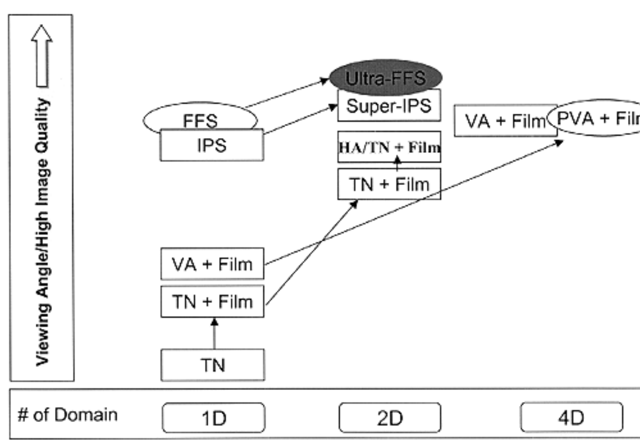

FIGURE 10 — Comparison of several display modes in terms of the number of domains and image quality.

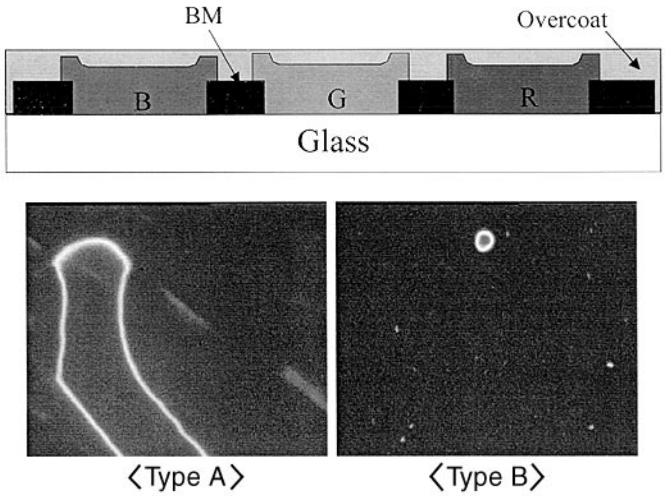

FIGURE 11 — Structure of color filter in the FFS device and photos showing the alignment characteristics of the cells depends on the type of OC layer used.

only a power consumption of 23 W since the operating voltage of the panel is less than 5 V. The response time is 25 msec without reducing the cell gap from normal FFS devices.

We compared several display modes with the Ultra-FFS device in terms of the number of domains, viewing angle, and image quality, as shown in Fig. 9.[12] Among singe-domain devices, the FFS and IPS devices exhibit the best image quality. Furthermore, among all display modes, we believe that Ultra-FFS devices exhibit the best viewing angle and image quality.

2.5 Pressure-resistant characteristic of the FFS device

We tested the pressure-resistant characteristics of the FFS and the TN devices by driving the TFT-LCD module with a pressure of 800–1000g force using a sharp stick pen with a diameter of 1 mm. In the dark state of the TN device (when an operating voltage is applied), when an external pressure is applied, the ripple and coloration grow more apparently than those in the white state. Not only the size of the ripple and coloration, but an unexpected mark of about 15 mm was observed. Furthermore, the mark that is a distorted image did not disappear and remained over 5 sec even though the pressure was released. This indicates that the display using the TN mode is not appropriate as a pen-based touch-panel display without the use of extra cover protection. However, in the FFS device, especially when using the –LC, the size of the mark was small and disappeared immediately at all gray levels when the external pressure was released. Because of such advantages, at present the 15.1-in. FFS TFT-LCD using the –LC was applied to pen-based touch-panel system for graphic use. The behavior is dependent on the type of the LCs as well as the structure of the pixel. This will be discussed elsewhere in detail.[9]

3 Process challenge

In the IPS and FFS devices, the top surface of the color filter substrate is overcoat (OC), which is an organic layer with thickness of about 1 μm, as shown in Fig. 11. We checked the possibility that this layer could act as an alignment layer, *i.e.*, whether it can replace the alignment layer on the color-filter side. We tested the aligning capability of two kinds of OC layers, type A and B. Under crossed polarizers with an homogeneously aligned LC cell with a normal alignment layer and an OC layer the bottom and top substrates respectively, the cell with type A showed a large disclination line, but the cell with type B showed relatively good alignment except for small spots with not enough alignment. This implied that it could replace an alignment layer with further improvement in the aligning characteristics of the OC layer and, this replacement will bypass the conventional coating and cure processes of the alignment layer, improving throughput greatly and removing PI coating defects. The development process is under way.

4 Summary

We have developed a FFS device utilizing LC with positive dielectric anisotropy. The Ultra-FFS TFT-LCD shows intrinsically high image quality comparable to that of a CRT display, and fast response time. We believe that this device will greatly impact on the image quality of the TFT-LCD with very low power consumption unlike conventional wide-viewing-angle TFT-LCDs. Furthermore, the FFS device can also be applied to position and pressure-sensitive touch-panel system owing to its intrinsic characteristic of stable dynamics against external pressure.

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