n-FFS vs. p-FFS: Who wins?

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Abstract

Both negative and positive dielectric anisotropy liquid crystals have been used in fringe field switching (FFS) display devices. We compare the electro-optic performances of single-domain p-FFS with two-domain n-FFS from device and material viewpoints. Quantum-dot backlight enhanced FFS shows vivid colors with negligible color shift, higher transmittance, and better sunlight readability.

Keywords

Fringe field switching (FFS); Liquid crystal displays (LCDs).

1. Introduction

Fringe field switching (FFS) liquid crystal display (LCD) has been widely used in mobile displays, such as smart phones and pads, because of its wide view, high transmittance, and robustness to external pressure for touch panels. Both negative and positive dielectric anisotropy ($\Delta\varepsilon$) LCs have been used in FFS [1-6]. Table 1 lists the two LC mixtures we employed for comparing the performances of n-FFS (negative $\Delta\varepsilon$ LC: JNC ZOC-7003) and p-FFS (positive $\Delta\varepsilon$ LC: UCF-L3) [7].

Table 1. LC parameters used in n-FFS and p-FFS LCDs; T=22°C and λ=550 nm.

	$\Delta\varepsilon$	Δn	γ_1 (mPas)	T_c ($^{\circ}$C)	E (meV)
ZOC-7003	-4.4	0.103	101	79	396
UCF-L3	+4.4	0.102	50	80	228

For a fair comparison, we use the same FFS device structures: electrode width 2.5 μm, electrode gap 3.5 μm, rubbing angle 7° for p-FFS and 83° for n-FFS, passivation layer 150-nm Si$_3$N$_4$, and wavelength λ=550 nm.

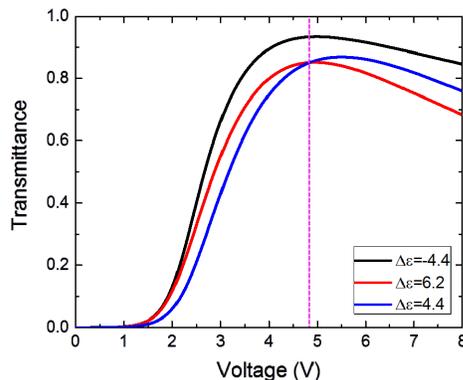## 2. Results and Discussion

A. Transmittance

Fig. 1. Voltage-dependent transmittance (VT) curves of n-FFS with $\Delta\varepsilon$=−4.4 and p-FFS with $\Delta\varepsilon$=4.4 and 6.2.

Figure 1 depicts the voltage-dependent transmittance (VT) curves of single-domain (1D) n-FFS (black line) and two p-FFS cells (red and blue lines). From Fig. 1, the n-FFS cell climbs up more

quickly and reaches the peak transmittance (93.5% vs. 87.1%) at a lower voltage (V_p=4.8V$_{rms}$ vs. 5.5V$_{rms}$) than the corresponding p-FFS with the same |$\Delta\varepsilon$| value. To reduce the V_p of p-FFS to 4.8V, we have to increase the +$\Delta\varepsilon$ value to 6.2 (red line). This is because the LC directors in n-FFS are reoriented more uniformly in terms of twist and tilt angles [5]. As a result, its effective birefringence is higher. This more uniform LC reorientation also explains why the required $d\Delta n$ (=320 nm) for n-FFS is smaller than that of p-FFS (340 nm), and n-FFS has weaker flexoelectric effect than p-FFS [5]. However, p-FFS with a lower +$\Delta\varepsilon$ LC leads to a higher peak transmittance. As a result, there is crossover point as shown in Fig. 1 where the blue and red lines have the same transmittance (85.3% at V_p=4.8V$_{rms}$). A lower $\Delta\varepsilon$ LC possesses lower γ_1 and smaller E, resulting in faster response time, especially at low temperature.

B. Response time

As listed in Table 1, the negative $\Delta\varepsilon$ LC mixture ZOC-7003 has a 2X higher rotational viscosity than the positive one, UCF-L3. As a result, its response time is slower. Figure 2 shows the measured decay time of n-FFS and p-FFS cells. At 20°C, the decay time is 22 ms for n-FFS and 12 ms for p-FFS. The ratio is ~1.8. But this ratio increases to 4 as the temperature decreases to −20°C. Slow response time causes motion picture image blurs.
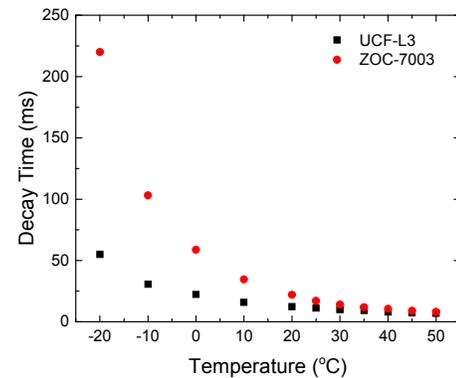

Fig. 2. Measured decay time of n-FFS with ZOC-7003 and p-FFS with UCF-L3.

The slower response time at lower temperature is attributed to the exponentially increased rotational viscosity [8, 9]:

$$\gamma_1 \sim S \cdot \exp(E / k_B T), \qquad (1)$$

$$K_{ii} \sim S^2, \qquad (2)$$

$$\gamma_1 / K_{ii} \sim \exp(E / k_B T) / S. \qquad (3)$$

where S is the order parameter, E the activation energy, and k_B the Boltzmann constant. From Eq. (3), activation energy plays a key role affecting the rising rate of response time in the low temperature region. Key parameters affecting activation energy include molecular structure and conformation, and intermolecular interactions. Low |$\Delta\varepsilon$| LCs exhibit three attractive features: ultra-

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low viscosity (Fig. 3) [7], small activation energy [10] which leads to a mild increase in viscosity at low temperature, and mitigated flexoelectric effect (because the LC tilt angles are more uniform spatially). But the drawback is increased voltage. The optimal $|\Delta\varepsilon|$ value depends on the intended operation voltage. For both p-FFS and n-FFS, the strategy is to use a minimally acceptable $|\Delta\varepsilon|$ in order to take advantages of ultra-low viscosity and small activation energy. In addition to γ_1, K_{22} also plays an important role because the response time is proportional to γ_1/K_{22}.
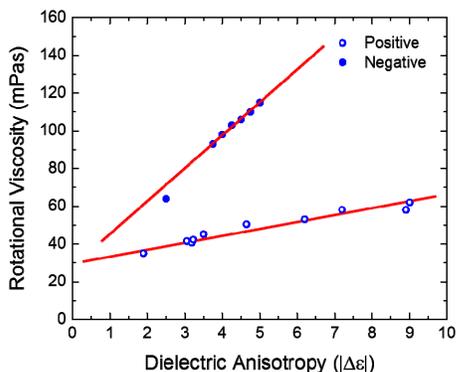

Fig. 3. Rotational viscosity vs. $|\Delta\varepsilon|$ of some LC mixtures with $\Delta n \approx 0.1$ and clearing point around 80^oC.
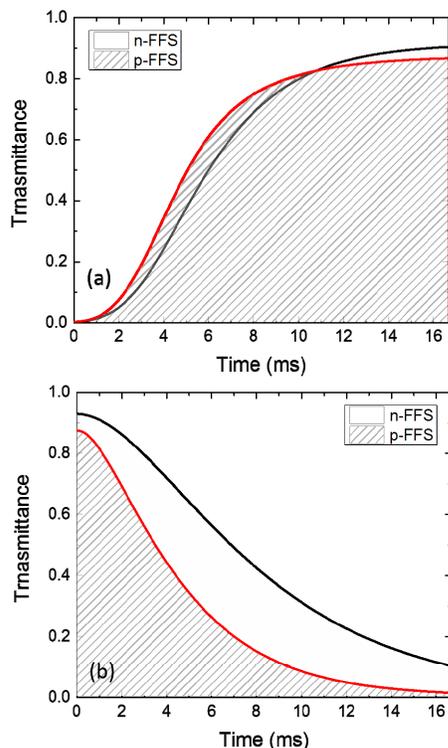
C. Effective transmittance

Fig. 4. (a) Rise time and (b) decay time of n-FFS and p-FFS cells at 60 Hz.

As Fig. 1 shows, n-FFS has ~10% higher transmittance than p-FFS at V_p=4.8V_{rms}. But this is in steady state (i.e., constant voltage). If we consider dynamic response for videos at 60Hz, then the effective transmittance should be the integrated area covered by the solid lines [Fig. 4(a)]. On the other hand, the slow decay process [Fig. 4(b)] causes undesirable crosstalk between

frames. For wearable displays using RGB LED field sequential colors, such as LCOS, slow decay time causes color mixing (crosstalk), which degrades the color gamut [11]. This problem gets worse at low temperature, in which the LC response time is slower. Thus, fast rise time increases display brightness, while fast decay time reduces crosstalk and improves image quality.

Based on this principle, we calculated the effective transmittance between different gray levels. We found the averaged [transmittance, crosstalk] is [7.87, 3.00] for p-FFS, and [7.62, 4.35] for n-FFS. That is to say, p-FFS has ~3% (7.87÷7.62) higher effective transmittance and much smaller crosstalk than n-FFS because of its faster response time.

D. Quantum-dot enhanced FFS

Grayscale inversion is noticeable for single-domain (1D) n-FFS at high gray levels (Fig. 5(a)), but it is more forgiven for 1D p-FFS (Fig. 5(b)). Therefore, if we want to use n-FFS for practical applications we have to consider 2D structure. This leads to reduced transmittance because of the dead zone at the center of zigzag electrodes. From Fig. 6, the steady-state transmittance at V_p=4.8V of 2D n-FFS is about the same as that of 1D p-FFS (85% vs. 85.5%). But when it comes to dynamic transmittance, 2D n-FFS is ~10% lower than 1D p-FFS.
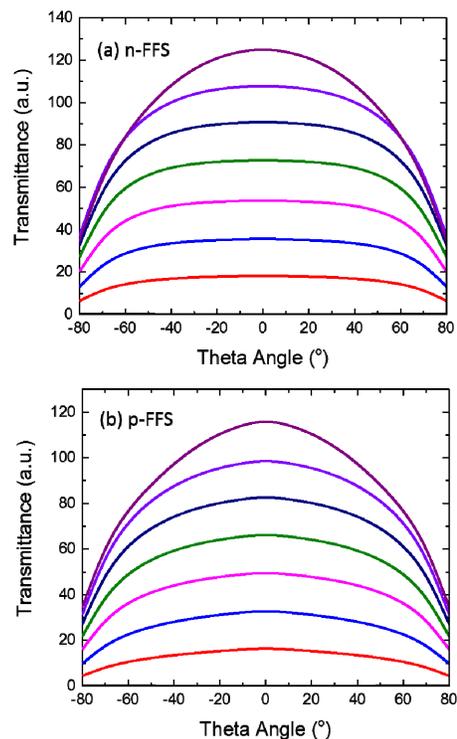

Fig. 5. Viewing angle dependent eight gray levels for film-compensated single-domain (a) n-FFS and (b) p-FFS.

Compared to 2D n-FFS, 1D p-FFS exhibits about the same transmittance, but its color shift, especially blue color, is $\Delta u'v'$= 0.024, which is barely noticeable when a white LED backlight is employed. To suppress color shift to unnoticeable level ($\Delta u'v'$<0.02) for 1D p-FFS, two approaches have been commonly considered: (1) to implement 2D structure, and (2) to use quantum-dot (QD) enhanced backlight [12]. Figure 7 shows the simulated color shift of QD-enhanced 1D p-FFS and 2D n-FFS. Their color shift is much smaller than 0.02, and is therefore indistinguishable to the human eye. Note: 1D n-FFS still exhibits

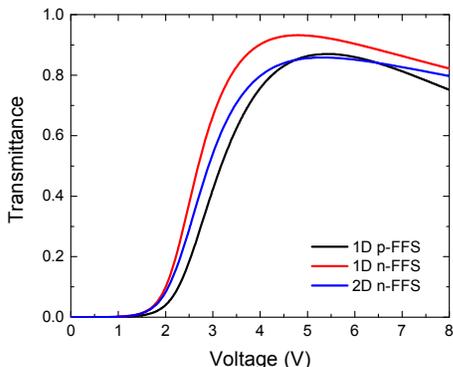grayscale inversion even a QD backlight is used. QD reduces the color shift, but not grayscale inversion.

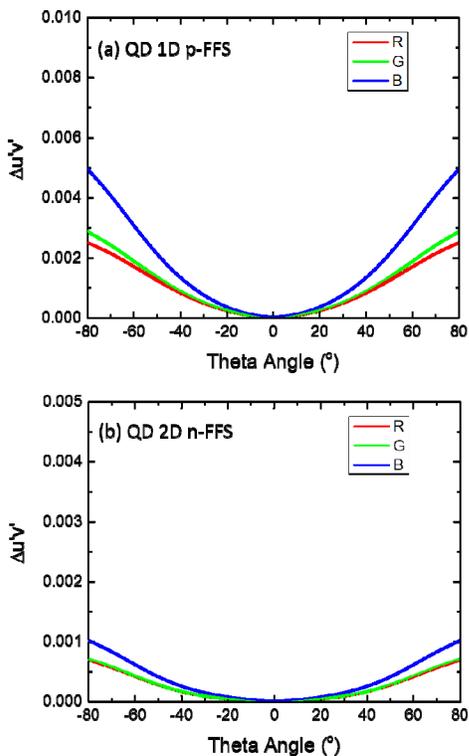**Fig. 6.** Voltage-dependent transmittance (VT) curves of 2D n-FFS and 1D p-FFS

Fig. 7. Simulated color shift of quantum-dots enhanced (a) 1D p-FFS and (b) 2D n-FFS.

E. Flexoelectric effect

Because of the non-uniform electric field, the splay deformation would occur in p-FFS and electric polarization is induced, which is known as flexoelectric effect [13]. The light transmittance would differ between negative and positive frames, resulting in a noticeable image flickering at low frame rate. This phenomenon is amplified especially when a large $\Delta\varepsilon$ LC is used, in which LC directors near the middle of electrodes and gaps tilt at a large angle. For n-FFS, the tilt angle is much less sensitive to the electric field [5], which in turn results in a much weaker flicker.

Next, we experimentally investigated how the $\Delta\varepsilon$ value affects image flicker. Figure 8 shows the measured transmittance profiles of two p-FFS ($\Delta\varepsilon$=10 and 4.4) and one n-FFS ($\Delta\varepsilon$= −4.4) cells.

Each positive and negative frame lasts for 16.6ms (upper traces), which is equivalent to 60Hz TFT driving. We define F=$\Delta T/T$ to quantify the transmittance change during frame inversion. For the p-FFS cell with $\Delta\varepsilon$=10, F~18%, but it drops to ~7% for $\Delta\varepsilon$=4.4. In contrast, F~4.0% for the n-FFS cell with $\Delta\varepsilon$ =−4.4. We found that when F<10% the image flicker is visually unnoticeable at 60Hz. Another method to suppress the image flicker of p-FFS is to dope ~2wt% bent-core LC molecules [14]. However, the tradeoff is increased viscosity because the bent-core molecules are quite bulky.
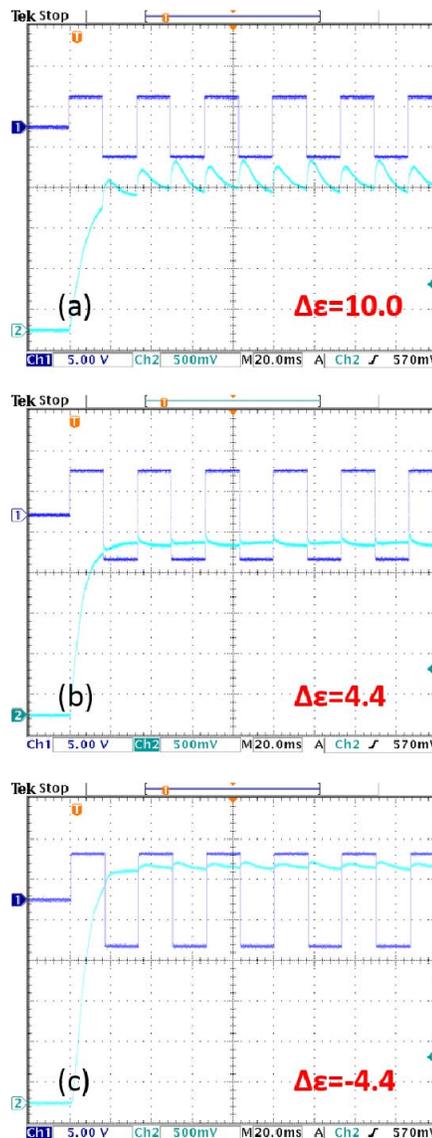

Fig. 8. Measured transmittance profile for FFS cells with different $\Delta\varepsilon$ LC mixtures: (a) $\Delta\varepsilon$= 10.0, (b) $\Delta\varepsilon$=4.4, and (c) $\Delta\varepsilon$=−4.4. Each positive and negative frame is 16.6ms.

3. Discussion

Table 2 summarizes the pros and cons of 2D n-FFS vs. 1D p-FFS as discussed above. Both modes work really well, but 2D n-FFS stands out in weaker color shift and image flickering. On the other hand, 1D p-FFS has faster response time, especially at low temperature, and higher dynamic transmittance and smaller crosstalk. They have comparable performance in static

transmittance, operation voltage, and viewing angle. Although p-FFS has a larger flexoelectric effect than n-FFS, the resultant image flickering remains unnoticeable to the human eye.

Table 2. Comparison between 2D n-FFS and 1D p-FFS

	2D n-FFS	**1D p-FFS**
Static transmittance	85.0%	85.5%
Operation voltage	4.8V	4.8V
Viewing angle	Excellent	Excellent
Color shift ($\Delta u'v'$) (WLED backlight)	0.005	0.024
Color shift ($\Delta u'v'$) (Quantum dot backlight)	<0.001	<0.005
Image flicker	Unnoticeable (4%)	Unnoticeable (7%)
Response time (20°C)	22 ms	12 ms
Response time (−20°C)	220 ms	52 ms

To avoid grayscale inversion and to eliminate color shift of 1D n-FFS and 1D p-FFS, we can integrate a quasi-collimated backlight with an engineered diffuser film. The technical details have been described in [15]. Here, we only present the isocontrast contours and gamma curves in Fig. 9. The gamma curves at off-axis angles (up to 60°) are indistinguishable for both 1D p-FFS and 1D n-FFS. Moreover, in this single-domain FFS-LCD systems, *no compensation film is needed*, and contrast ratio is over 3000:1 from almost all viewing directions.
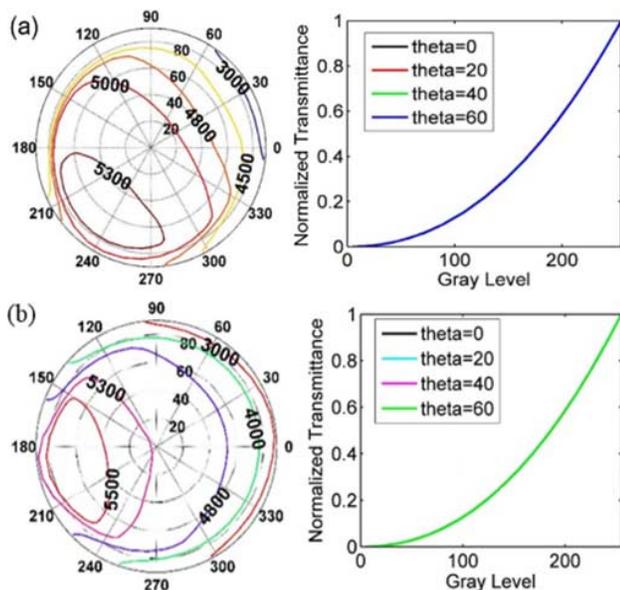

Figure 9. Simulated isocontrast contours and gamma curves of single-domain (a) n-FFS and (b) p-FFS with quasi-collimated WLED backlight and engineered diffuser film, as described in Ref. [15].

4. Conclusion

For p-FFS, the strategy is to optimize its single-domain structure with a minimally acceptable $\Delta \varepsilon$ for achieving high transmittance

and fast response time, while suppressing flexoelectric effect. For n-FFS, 2D structure is required in order to eliminate grayscale inversion. As a result, its static transmittance is reduced to the same level as 1D p-FFS. Similar to p-FFS, a delicate balance between $\Delta \varepsilon$ and viscosity for n-FFS should be practiced. Both n-FFS and p-FFS would benefit from quantum-dot backlight, as it helps to achieve wide color gamut (90% Rec 2020), suppress color shift to indistinguishable level, boost transmittance, and improve sunlight readability.

5. Acknowledgement

6. References

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