Display Technology Letters

Nematic Liquid Crystal Display With Submillisecond Grayscale Response Time

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***Abstract*—A nematic display with three electrodes and double fringing fields is proposed. Both top and bottom substrates have pixel and common electrodes to generate complementary fringing fields for achieving high transmittance. This mode exhibits submillisecond gray-to-gray response time and high contrast ratio. The effect of pixel misalignment on transmittance is discussed.**

***Index Terms*—Fast response, nematic liquid crystal, triode.**

I. INTRODUCTION

SUBMILLISECOND-RESPONSE liquid crystal not only reduces image blurs but also enables color-sequential display using RGB LED backlight with negligible color breakup [1]–[4]. The elimination of spatial color filters triples the optical efficiency and resolution density. For 3D displays, which demands higher frame rate than 2D displays, fast response time also helps to reduce crosstalk and residual images [5]–[7]. Hence, there is an urgent need to develop fast-response LCD to overcome the abovementioned problems.

For nematic LCs, the rise and decay times between gray level transitions can be written as [8]:

$$\tau_{rise} = \frac{\tau_o}{\left[\left(\frac{V}{V_{th}}\right)^2 - 1\right]} \tag{1a}$$

$$\tau_{decay} = \frac{\tau_o}{\left|\left(\frac{V_b}{V_{th}}\right)^2 - 1\right|} \tag{1b}$$

$$\tau_o = \frac{\gamma_1 d^2}{K\pi^2} \tag{1c}$$

where V is the applied voltage to the final gray level, $V_{\rm b}$ is the bias voltage of the initial gray level, $V_{\rm th}$ is the threshold voltage, γ_1 is the rotational viscosity, and K is the corresponding elastic constant which depends on the LC alignment. For example, for a vertical alignment (VA) cell, $K = K_{33}$, which is the bend elastic constant. From (1), rise time and decay time could be very slow when the grayscale voltages are close, especially in the vicinity of threshold.

To overcome this bottleneck, several approaches such as crossed-field effects [9]–[11], overdrive and undershoot voltage method [12], [13], thin cell gap with high birefringence and low viscosity material [14], and bend mode [15], [16] have been developed. In 2008, Jiao, *et al.* [17] reported a dual fringe field switching (DFFS) mode in a VA cell with a positive dielectric anisotropy $(\Delta\varepsilon)$ LC and achieved 1.88-ms averaged gray-to-gray (GTG) rise time and 1.68-ms averaged GTG decay time. However, this response time is still inadequate to completely eliminate the color breakup for color sequential displays. In this paper, we propose a triode DFFS mode to achieve submillisecond GTG response time.

II. DEVICE STRUCTURE

Fig. 1(a) and 1(b) shows the device structures, electric field directions, and LC director reorientations of the proposed triode DFFS mode in bright and dark states, respectively. The structure consists of four electrodes: top common, top pixel, bottom common and bottom pixel. Each substrate has a planar common electrode and stripe pixel electrodes, same as the conventional fringe field switching (FFS) structure [18].

In the proposed triode DFFS mode, a typical electrode width and electrode gap is 2–5 μm, while the LC cell gap is 10–14 μm, depending on the LC material employed. In order to compensate the dead zones on each side for obtaining high transmittance, the top and bottom pixel electrodes are shifted by half of a pixel width so that the edges of the top pixel electrodes are right above the center of the bottom pixel electrodes. The LC cell is sandwiched between two crossed polarizers and some compensation films are needed for wide-view applications [17].

The operation principle of the triode DFFS mode is described as follows. The LC directors are vertically aligned in order to achieve a good initial dark state. To obtain a bright state, we apply a high voltage (10.8 V to reach the highest gray level) to the top and bottom pixel electrodes while keeping both common electrodes at $V = 0$. The LC directors are reoriented by the in-plane electric field, as Fig. 1(a) shows. The incident linearly polarized light experiences phase retardation and is transmitted by the crossed analyzer. A unique feature of the DFFS mode is that the cell gap is intentionally set to be larger than the total penetrating depth of the fringing fields. Thus, the electric field near the substrate surface is much stronger than that in the middle of the cell. The middle bulk layers function as standing layers; only the boundary layers are reoriented.

During relaxation period, a voltage of 11 V is applied to the bottom common electrode as Fig. 1(b) depicts. The top common electrode is always grounded. The vertical field exerts a strong

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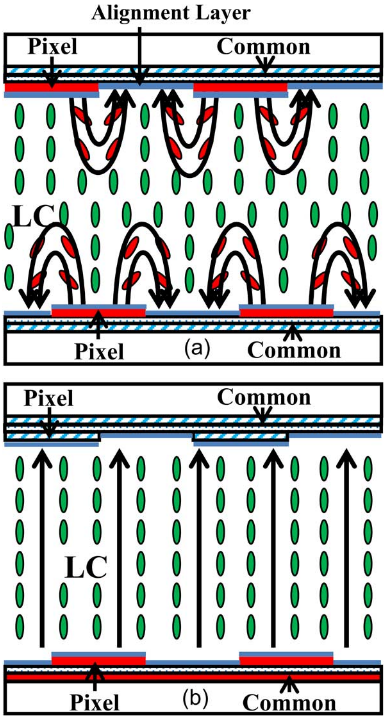

Fig. 1. Device structure of the triode DFFS mode in (a) bright state and (b) dark state. The LC employed has a positive $\Delta\varepsilon$.

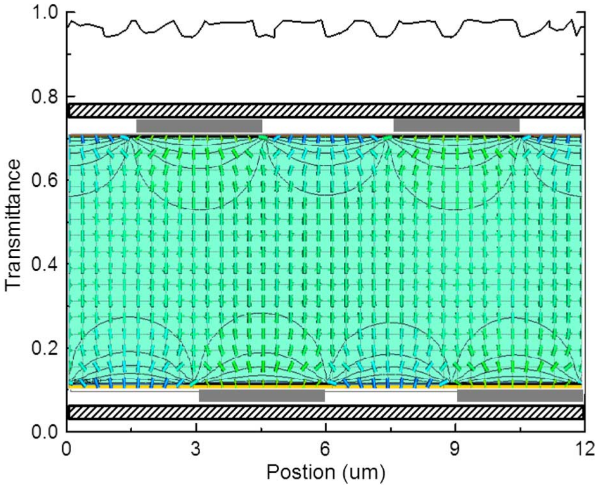

Fig. 2. Transmittance (upper), electric potential (lower) profiles and LC directors' orientation (color) of the triode DFFS at a bright state (10.8 V).

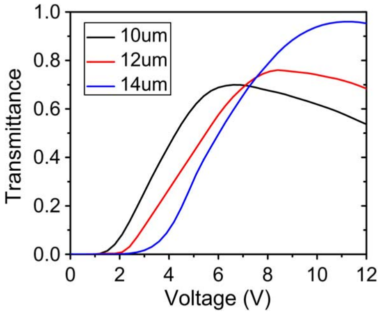

Fig. 3. Simulated VT curves of the proposed triode DFFS cell with $\mathrm{d} = 10\ \mu\mathrm{m}$, $12\ \mu\mathrm{m}$, and $14\ \mu\mathrm{m}$. $\lambda = 550\ \mathrm{nm}$.

torque to pull the LC directors back to the vertical direction in addition to the existing elastic restoring torque. Therefore, submillisecond decay time can be achieved. Also due to vertical alignment, a contrast ratio over 5000:1 can be obtained easily.

III. SIMULATION RESULTS AND DISCUSSION

The device configuration of the proposed triode DFFS mode are studied and optimized by using commercial simulation software Techwiz LCD (Sanayi System Company) and the electro-optic performance is calculated by the extended 2×2 Jones matrix method. To compare our results with [17], we chose the same electrode configuration: electrode width $W = 3\ \mu\mathrm{m}$, and electrode gap $G = 3\ \mu\mathrm{m}$. The LC material used here is a commercial mixture DAB-1711 (Poland) whose physical properties are listed as follows: $K_{11} = 17.2$ pN, $K_{22} = 8$ pN, $K_{33} = 20.4$ pN, $\Delta n = 0.247$, $\Delta\varepsilon = 10.8$, and $\gamma_1 = 148\ \mathrm{mPas}$. These parameters are very similar to those used in [17].

Fig. 2 depicts the LC directors' orientation and simulated transmittance (top) and potential (bottom) profiles of the proposed triode DFFS at 10.8 V. The transmittance profile is relatively flat, because the dead zones on both sides are well complemented.

Fig. 3 depicts the voltage-dependent transmittance (VT) curves of three cell gaps: $d = 10$, 12 and 14 μm. The 14-μm cell shows a transmittance >96% at 10.8 V. Here, we normalize the transmittance to that of two open polarizers. If the cell is too thin, in the on-state the reoriented upper and bottom layers would interfere and then push the middle LC layers to rotate, which leads to a slower GTG response time and lower transmittance. On the other hand, if the cell gap is too thick, the GTG response time would be slower since the vertical electric field is weaker and other problems such as narrow viewing angle and crosstalk between adjacent pixels would also occur. Therefore, we choose 14 μm as the optimum cell gap for the chosen LC mixture. Although the $\mathrm{d}\Delta\mathrm{n}$ value of the employed cell is relatively large, wide view can still be obtained by using phase compensation films, as reported in [17].

To evaluate the GTG response time, in simulations we divide the VT curve uniformly into 8 gray levels (1–8). As usual, the response time is defined as 10%–90% transmittance change. The commonly used overdrive and undershoot voltage method is also applied here in order to achieve fast GTG response time. A short pulse is applied to generate a vertical field to pull the LC directors back during a short period until the transmittance decays to the designated gray level. Then a bias voltage is applied to hold the transmittance at the targeted final gray level. Detail of this driving method has been reported in [19].

Table I summarizes the calculated rise and decay times for the 14-μm cell. All the GTG response time (except the rise time from gray level 1 to 2 which is 1.29 ms) is below 1 ms. The averaged rise time of all gray levels is 0.739 ms and decay time is 0.478 ms at $\sim 22^\circ$C, which is 2–3× faster than its counterpart cell 1 in [17] with similar LC material and same cell parameters. The response time can be further reduced if a lower viscosity LC material is used or higher overdrive and undershoot voltages are applied. These results are comparable to those of polymer-

TABLE I
CALCULATED GTG RESPONSE TIME (UNIT: ms)

	1	2	3	4	5	6	7	8
1		1.29	0.96	0.98	0.89	0.97	0.95	0.85
2	0.53		0.83	0.83	0.93	0.90	0.80	0.48
3	0.56	0.28		0.80	0.82	0.76	0.66	0.38
4	0.60	0.41	0.55		0.78	0.72	0.72	0.35
5	0.60	0.30	0.20	0.36		0.74	0.60	0.32
6	0.64	0.38	0.27	0.55	0.17		0.64	0.31
7	0.71	0.46	0.42	0.39	0.20	0.18		0.43
8	0.85	0.63	0.50	0.51	0.35	0.85	0.95	

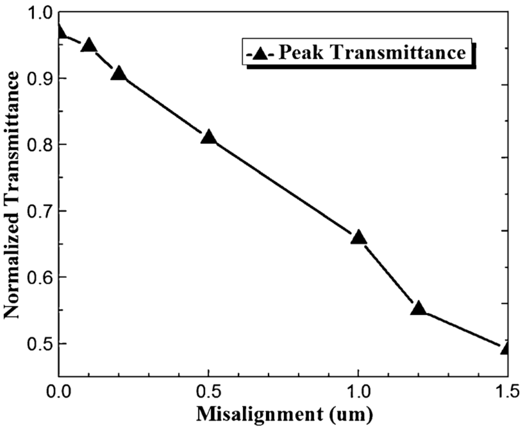

Fig. 4. Simulated peak transmittance for the triode DFFS under different misalignment conditions.

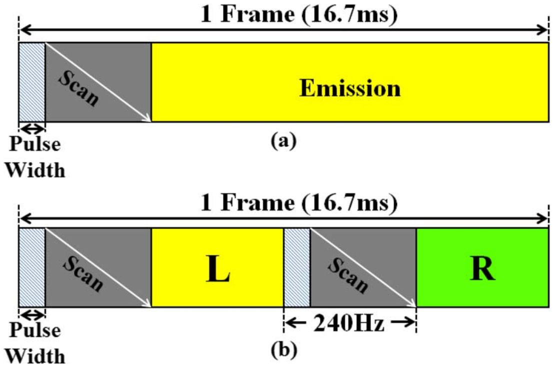

Fig. 5. Display driving methods for the triode DFFS using simultaneous emission in (a) 2D display (b) 3D display.

stabilized blue phase liquid crystals [20]–[22] but with a lower voltage.

IV. DISCUSSION

In the proposed triode DFFS mode, four electrodes are used and two TFTs are needed. The top common electrode is always connected to ground while the voltages on top and bottom pixels are controlled by TFTs. Since the voltage on bottom common electrode is either 11 or 0 V, it can be controlled by a simple electronic circuit.

The major challenge of this mode is on the need of precise registration between top and bottom pixel electrodes in order to keep high transmittance. Fig. 4 shows the peak transmittance under different electrode misalignment conditions. If the misalignment is within 0.5 μm, the peak transmittance is still above 80%. As misalignment increases, the dead zones on both sides are no longer well complemented, resulting in a decreased peak transmittance. For the worst scenario, i.e., the top and bottom pixel electrodes overlap perfectly (or misalignment is 1.5 μm), the peak transmittance drops to $\sim$49%.

With its submillisecond GTG response time, the proposed triode DFFS mode has potential applications in color sequential displays and 3D displays. Fig. 5(a) depicts the driving method for the application of triode DFFS mode for 2D display using simultaneous driving method. For decay process between gray levels, the frame time is composed of three periods: the first period is to generate vertical field, the second is for scanning row by row to input data voltage through driving TFTs, and the third period is for emission. Fig. 5(b) shows the driving method for the triode DFFS in 3D displays for reducing left–right crosstalk.

V. CONCLUSION

The proposed triode DFFS mode has some attractive features: submillisecond GTG response time, high transmittance and contrast ratio. It is a strong contender for color sequential displays and 3D displays. Through optimizing the cell gap, electrode structures, and LC parameters, its performance can be further improved. However, this device requires 2 TFTs and precise registration between the top and bottom pixel electrodes.

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