Passive-matrix-driven field-sequential-color displays

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Abstract — Passive-matrix-driven field-sequential-color (FSC) displays were successfully fabricated. It makes use of a new multiplex driving scheme that does not depend on voltage averaging. Instead, a transient response of the liquid crystal is employed. An addressing and response time of less than 70 μsec and 2.0 msec, respectively, are used. Scanning time compensation is also introduced to improve the brightness uniformity of the display.

Keywords — *Passive matrix, field-sequential color.*

1 Introduction

Field-sequential-color (FSC) displays have been studied as an alternative to subpixel area color for a long time.[1] For liquid-crystal displays, FSC offers many advantages such as much higher optical efficiency and better color saturation. With the advent of light-emitting-diode (LED) backlight units (BLUs), FSC looks more and more attractive and viable. However, FSC requires fast LCD modes. Currently, the most promising candidates are the bend cell or π-cell[1] and ferroelectric liquid crystals.[2] Liquid crystal in pure bend deformation is not stable under zero-voltage bias. The free elastic energy of splay deformation is always less than that of the bend mode for small pretilt angles. With high pretilt angles,[3,4] the bend mode can be stabilized at zero-voltage bias and is known as the no-bias bend (NBB) mode.[5]

All FSC studies thus far are based on active-matrix driving because fast scanning is necessary. A passive-matrix LCD is generally low cost and dominates the low-end market. PMLCDs with high multiplex ratios based on supertwisted-nematic (STN) mode can have decent resolutions. Color-STN (CSTN) displays are of reasonable quality. Unfortunately, CSTN is quite expensive due to the use of color filters. It is therefore of some practical interest to see if FSC can be achieved with passive-matrix driving. However, neither the π-cell nor the NBB mode is applicable to passive-matrix displays. Because in PMLCDs, time-averaged multiplexing is achieved by using the nonlinearity of the electro-optic characteristic (threshold V_{th}) of the liquid-crystal mode. In a π-cell, cross talk cannot be minimized. Active-matrix driving is required.[6,7]

Another important candidate for fast-switching LCDs is vertically aligned nematic (VAN) LCDs. Their response time can be reduced by decreasing the effective cell gap to 1.5 μm, and by using low-rotational-viscosity liquid crystals. A fast switching time of <2 msec has been achieved. VAN has the unique advantage of excellent contrast ratio (>1000:1). Unfortunately, such small cell gaps are difficult to manufacture. The transmission efficiency at such small cell thicknesses is also poor due to insufficient birefringence. Moreover, the threshold voltage and the steepness of the transmission *vs.* voltage curve (TVC) for the VAN mode is not suitable for passive addressing as well.

In this paper, we demonstrate passive-matrix driving of FSC displays. This is made possible by several new innovations. First of all, a new non Alt and Pleshko driving scheme is used. A fast LCD mode is also introduced that can work closely with this new driving scheme. Every pixel must fully present the correct gray scale within the subframe time (<5.5 msec). Fast relaxation within the subframe is required. Otherwise, color leakage occurs and the performance is degraded. Most importantly, the liquid-crystal mode should give good contrast and a high-enough-steepness TVC curve. The performance of this passive-matrix FSC LCD will be detailed here.

2 Non Alt and Pleshko driving method

The central idea of the traditional Alt and Pleshko driving or 3:1 driving method[8,9] is time-averaged multiplexing. By selecting the proper V_D data voltage and V_S scan voltage according to the TVC of the liquid crystal, the multiplexing number N or the resolution of such passive-matrix LCDs can be maximized. However, the typical response time for such a driving method is about 25–50 msec. Obviously, it is totally insufficient for FSC driving. Therefore, instead of maximizing the resolution N, we try to minimize the response time of the liquid crystal according to the gray-to-gray (GTG) response-time chart. Figure 1 shows an example of the response time from different start-voltage levels to different end-voltage levels, for a 90° TN cell with a 3-μm cell gap. Liquid-crystal MDA-2-3993 is used with a d/P ratio at 0.25.

The response time for 0 V → 12 V switching is only 150 μsec (red circles). Furthermore, the no-bias free relaxing time τ_D is found to be less than 2 msec for any driving voltage (blue circles). In other words, if the data voltage V_D and scanning voltage V_S can be selected according to this

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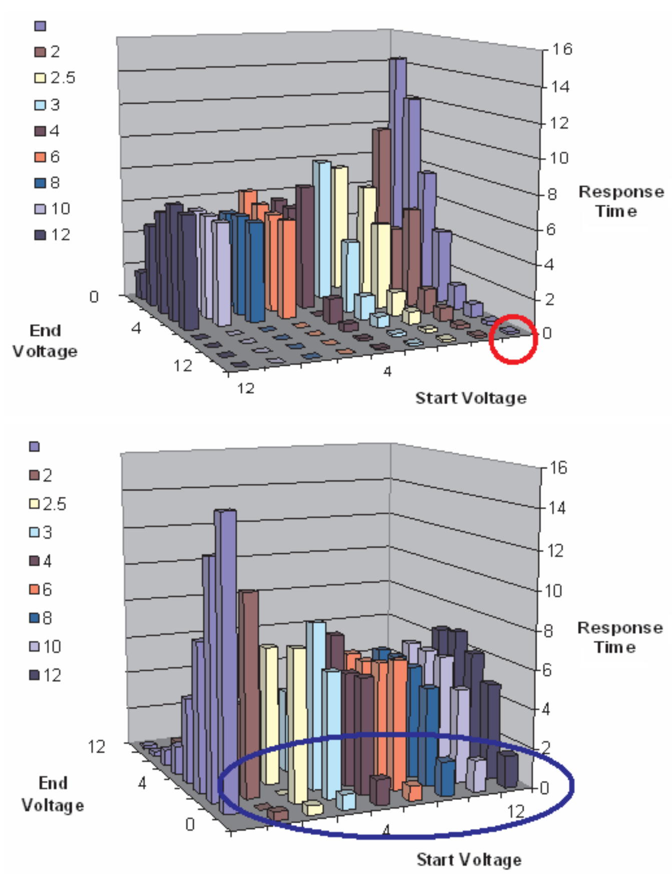

FIGURE 1 — GTG response time for an ordinary 90° twisted LCD.

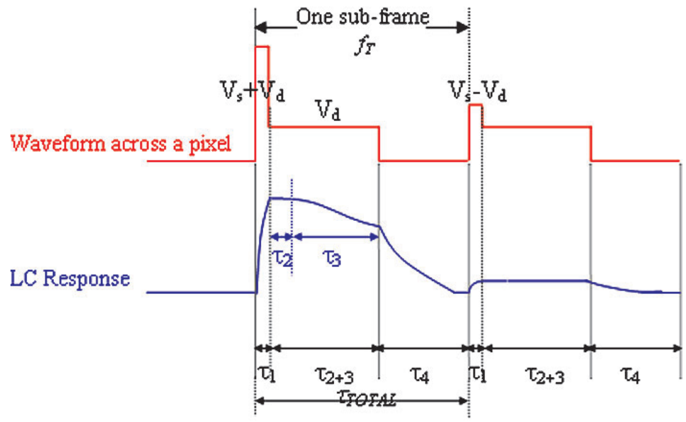

FIGURE 2 — Waveform across a pixel and corresponding optical response of this pixel.

criteria, the LC cell can be addressed and totally relaxed within about 2 msec. A modified driving method is therefore proposed and is depicted in Fig. 2. The total pixel response time, τ_{TOTAL}, contains three time individuals: τ_1, $\tau_2 + \tau_3$, and τ_4. τ_1 is the LC addressing time with the selection pulse $V_{SEL} = V_S + V_D$. For non-selection case, the pixel voltage $V_{NSEL} = V_S - V_D$ is applied. $\tau_2 + \tau_3$ is the relaxation time of the LC, during which the LC will relax from selection (or non-selection) voltage to data voltage V_D. When a sufficiently high selection pulse is applied during τ_1, hysteresis phenomena could be observed and will last for a time of τ_2, during which the LC does not respond to the voltage change immediately, but hold its director distribution for a time. The total scanning time, τ_S, is the sum of τ_1 and $\tau_2 + \tau_3$. τ_4 is the free relaxation time under zero-biased voltage. Driving is suspended at that moment, during which the LC molecule will relax under no external electric field. $\tau_{TOTAL} = \tau_4 \leq f_T$ is required to be less than the subframe time f_T. Here, we take $f_T = 5.5$ msec.

Using the example shown in Fig. 1, if τ_4 is 2 msec, then the total scanning time τ_S for the subframe is about 3.5 msec. In order to optimize the optical performance of the passive-matrix FSC, the scanning voltage V_S and data voltage V_D has to deal with the maximum contrast of the passive-matrix FSC displays. By varying the lighting time τ_L, the contrast of the displays can be maximized by further changing the select to the non-selection ratio during the free relaxation time, τ_{4SEL}/τ_{4NSEL}. Obviously, the most effective way to increase the ratio is to minimize the non-select free relaxation time τ_{4NSEL}. Additionally, it also implies that the average off-pixel voltage should be smaller than the threshold voltage of the device $\hat{V}_{OFF}^2 \leq V_{th}^2$. The average on-pixel voltage $\hat{V}_{ON}$ and off-pixel voltage $\hat{V}_{OFF}$ are given by

$$V_{th}^2 \approx \hat{V}_{OFF}^2 = \frac{(V_S - V_D)^2}{M} + \frac{(N-1)V_D^2}{M}, \tag{1}$$

$$\hat{V}_{ON}^2 \approx \frac{(V_S + V_D)^2}{M} + \frac{(N-1)V_D^2}{M}, \tag{2}$$

where $M = \tau_{TOTAL}/\tau_1$ and τ_1 is determined by $\tau_1 = (\tau_{TOTAL} - 4)/N$. The selection pulse V_{SEL} which is equal to $V_D + V_S$ is actually governed by the LC addressing time τ_1. τ_1 depends on the dynamics of LC molecule realignment in an external field. The dynamic behavior of the LC can be modeled and solved numerically using the Erickson–Leslie equations.[10] For low pretilt angle and low twisted, *i.e.*, 90°, liquid-crystal deformation, the addressing time[11] can be estimated using a more simplier analytical form as shown in Eq. (3):

$$\tau_1 = \frac{\gamma_1}{\Delta\varepsilon E^2/4\pi - K\pi^2/d^2}, \qquad K = \frac{4K_{11} - 2K_{22} + K_{33}}{4}, \tag{3}$$

where γ_1 is the rotational viscosity, K_{11}, K_{22}, and K_{33} are Frank elastic constants, and d is the cell thickness. Assuming that $\gamma_1 = 118$ mPa, $K = 15.9$ pN, $d = 3$ μm, $V_{th} = 1.57$ V. The simulated and measured results are shown in Fig. 3.

According to Fig. 2, a typical τ_4 is about 2 msec. It implies that $\tau_1 \sim 3.5/\mathrm{N}$ (unit: msec). V_{SEL} can be determined to be

$$V_{SEL} = V_{th}\sqrt{\frac{2N\gamma_1 d^2}{7K\pi^2} + 1}. \tag{4}$$

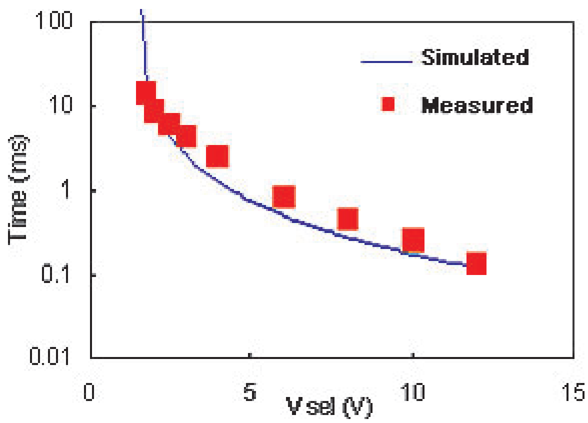

FIGURE 3 — Simulated and measured results for addressing time τ_1.

Using Eq. (4), V_D can be solved by using Eq. (1) as a quadratic function of V_{OFF}^2, N, and M. Figure 4 shows the experimental results using a 90° TN cell with a 3-μm cell gap and a d/P ratio of 0.25. Liquid crystal MDA-2-3993 from Merck is used. The upper curve is the optical response of the liquid crystal. The lower curve is the corresponding driving waveform. The optical response of the LCD under our suggested driving scheme fully fulfills the requirement of the FSC display. The pixel can fully relax within the frame time of 5.5 msec. The resultant pixel appearance is shown at the top right corner of the Fig. 4 as well.

The gray scale of the display is also adjustable. It can be obtained by pulse-width modulation during the scanning time τ_1. A set of experimental data is reported in Fig. 5. The scan pulse duration is 200 μsec. The highest contrast (27) can be obtained if the selection pulse duty ratio is 100%. If the duty ratio is reduced to <10%, the contrast ratio is only 1. Theoretically, there is a infinite number of gray levels. However, experimentally, only 16 repeatable gray levels are found. Therefore, the maximum number of colors is 4096.

3 BLU lighting control

The BLU plays an important role in FSC displays. Without the color filter, the maximum color gamut obtained is actu-

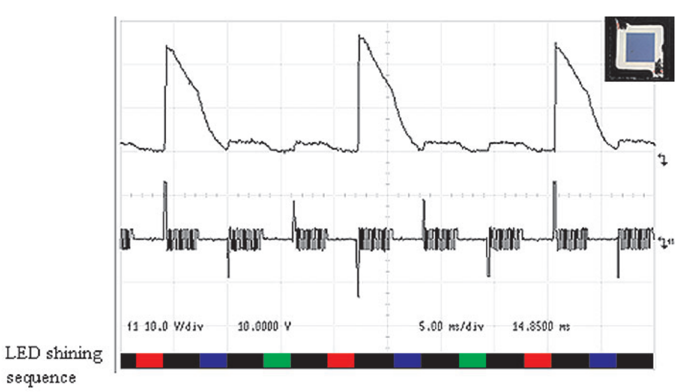

FIGURE 4 — The oscilloscope image shows the optical response of an LCD (top) and the corresponding driving waveform (bottom).

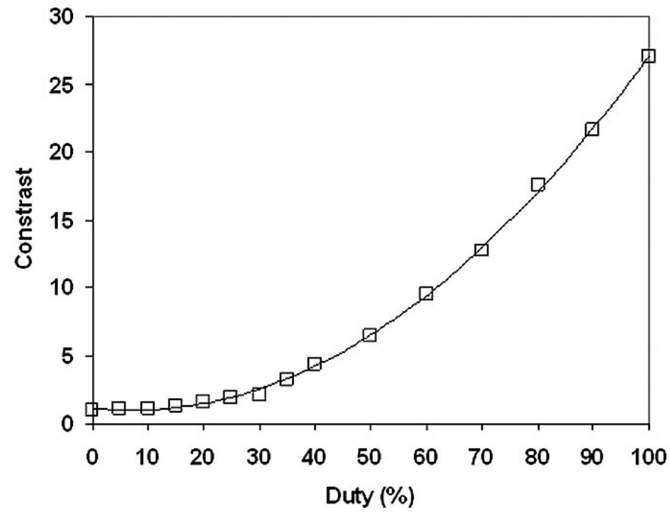

FIGURE 5 — The contrast (gray scale) of the display using the non Alt and Pleshko driving method with PWM.

ally determined by the BLU directly. Several publications[12–14] have already demonstrated the lighting method for color-filter-less displays. However, those methods can only be applied to active-addressing displays. For passive-matrix FSC, more requirements are needed. According to the passive-addressing driving scheme mentioned above, there is no time-integration effect. Instead, the subframe time is finite, typically <5.5 msec. Therefore, the addressing time for the first and the last row scanning is different from τ_S. It affects the brightness uniformity of the display panel. As shown in Fig. 6, owing to the scanning time delay, the LC transient for the first row does not perfectly overlap with the N-th row during the free relaxing time τ_4. Without using any BLU lighting compensation method, brightness non-uniformity will occur as a consequence. We propose an effective compensation method by promoting the BLU light up Δ time beyond τ_4.

Figure 7 shows an example of the Δ time determination. The effective intensity (integrated area beneath the transient curves) for different light up time is calculated according to the experimental data obtained from Fig. 6. There is only a moment such that both of them have equal brightness when the BLU is on. It is the equilibrium point

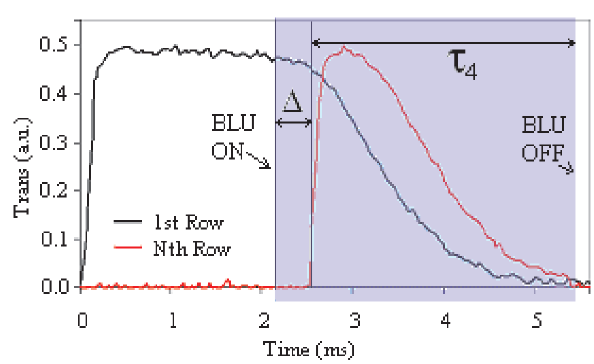

FIGURE 6 — Transient response of pixels at first row and N-th row.

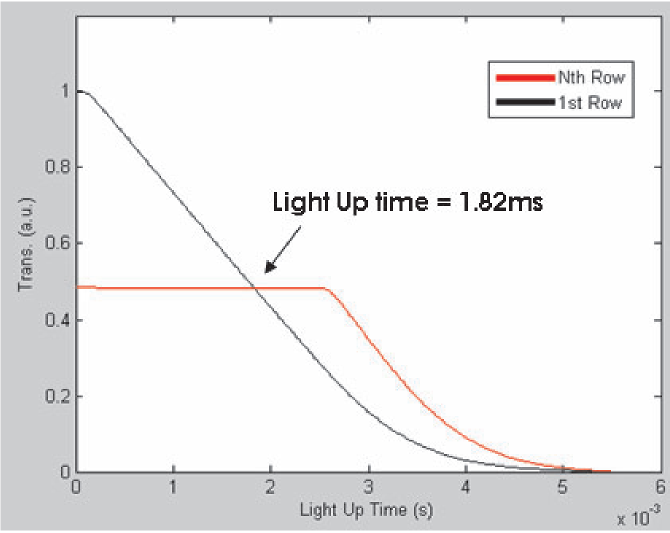

FIGURE 7 — Intensity dependence of the first and *N*-th row at different BLU light up time.

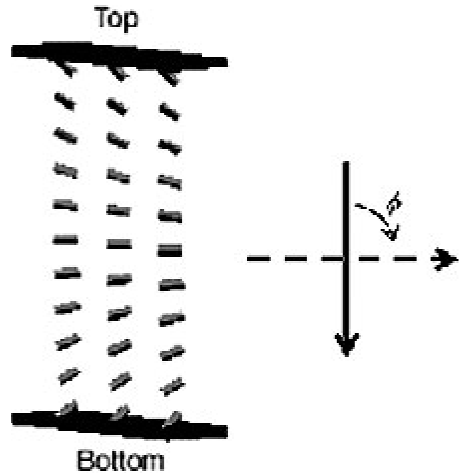

FIGURE 9 — SST mode 3-D deformation, the bottom rubbing direction, dash arrow; top rubbing direction: solid arrow. ϕ is the twist angle from bottom to top.

that the BLU must be turned on in order to preserve the brightness uniformity of the display panel.

Although the proposed scanning-time compensation method is useful, the LC relaxing time τ_3 under cross talk is not constant for all rows. It is therefore not possible to fully compensate all scanning rows to a perfectly uniform brightness for all viewing angles. Therefore, it is still very important to make the LC transient as close as possible during τ_4 for different scan rows. One solution can be τ_3 reduction. But it will affect the maximum transmission of the panels. Another solution can be found by examining τ_2. If the hysteresis τ_2 is prolonged, Δ time can be minimized. To increase hysteresis, some special LC deformation designs are required.

4 LC mode design

According to the non Alt & Pleshko driving method mentioned in the previous sections, the LC mode is required to be normally dark. Obviously, 90° TN at the Mauguin minima $\Delta nd = \lambda(P^2 - 1/4)^{1/2}$, where $P \in \{1,2,...\}$ with a parallel polarizer and analyzer provides good wide-viewing-angle normally dark displays. Figure 8 shows the dispersion of 90° TN, using $\Delta nd = 0.46$, which is much lower than for ECB modes.

To increase the duration of τ_2, we proposed a 90° TN-like deformation which is called the stressed splay twist deformation (SST) mode. Figure 9 shows a 3D SST mode LC deformation. The main difference between the 90° TN mode and the SST mode is the alignment direction. SST requires a reversed twist angle at –90°, while TN has a natural twist angle at 90°. The construction of the SST-mode display is shown in Fig. 10. The polarizer and analyzer are placed at 0° with the input director of the LC cell; 3-μm spacers are applied to the display. The liquid crystal is MDA-2-3993 with $\Delta n = 0.18$ and a d/P ratio of 0.25. Since the pretilt angle is only 2°, the optical performance of the SST mode is expected to be very similar to that of the TN mode. It also exhibits low dispersion in the normally dark state, as shown in Fig. 8. The hysteresis of the SST mode is measured and compared with that of normal 90° TN mode. As shown in Fig. 11, the SST mode has a longer τ_2 than for the 90° TN mode under any driving voltages by about

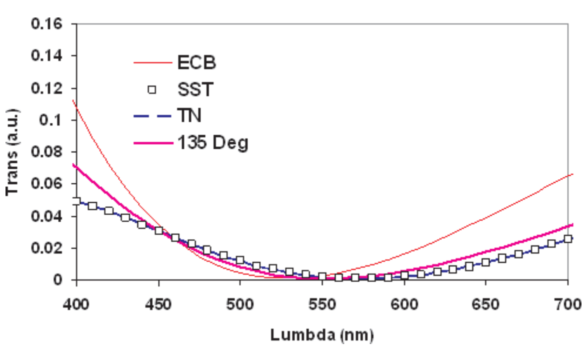

FIGURE 8 — Dispersion comparisons of different LC modes.

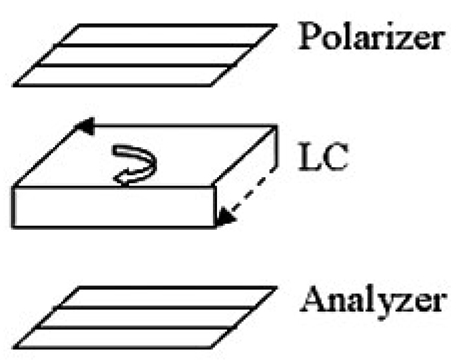

FIGURE 10 — Optical setup of the SST-mode LCDs. The direction of twist is shown as the block arrow; Polarizer is 0° with input LC director; dotted arrow is bottom rubbing direction and solid arrow is top rubbing direction; analyzer is 90° with output LC director.

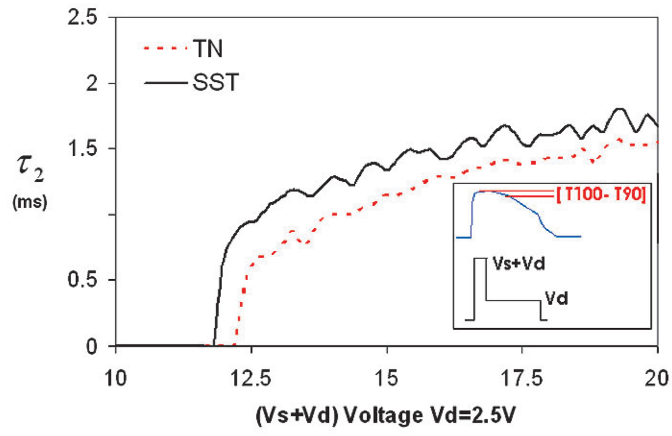

FIGURE 11 — τ_2 for TN and SST mode under different driving voltages.

400–700 μsec. This is a desirable property for passive-matrix FSC.

Using the non Alt and Pleshko method, the resolution N is limited by the single pulse addressing time τ_1. One can improve the resolution by further reducing the single pulse addressing time. Therefore, the response time for TN deformation at different twisted angles are simulated. The details of elastic-energy model calculation can be found in Refs. 15–18. Figure 12 shows the experimental results. It can be seen that the 135° TN mode can give the shortest addressing time.

For the other twist angles, higher stress induces longer times for single-pulse addressing. The simulation parameters are similar to those in Ref. 19: viscosity: α_1 = –0.11, α_1 = –1.59, α_1 = –0.02, α_1 = 0.75, α_1 = 1.02, cell gap d = 3 μm, K_{11} = 14.4 pN, K_{22} = 7.1 pN, K_{33} = 19.1 pN, $\varepsilon_{\|}$ = 11.1, $\varepsilon_{\perp}$ = 3.9. Based on these results, the Mauguin parameter $X = \phi(1 + u^2)^{1/2}$, $u = \Gamma/2\phi$ is fixed where Γ is retardation and ϕ is twisted angle. The cell gap d of the LCDs is 3 μm, thus the free relaxing time can be as short as about 2 msec. The only parameters for the normally dark transmission are angles of polarizer α and analyzer β. A calculation using the parameter space method is used.[20] The results are shown in Fig. 13. It can be seen that the best values are α = –82° and analyzer γ = –8° (red dots). The resultant dispersion is found to be a little worse than that of the SST mode or 90° TN mode and much better than that for the ECB mode. The dispersion properties of the various modes are compared in Fig. 8 using Eq. (5):

$$T = \frac{1}{2}\left\{ \begin{matrix} \cos^2(\alpha+\beta) + \cos^2\chi\cos 2\alpha\cos 2\beta \\ \left(\tan 2\alpha - \frac{\phi}{x}\tan\chi\right)\left(\tan 2\beta - \frac{\phi}{\chi}\tan\chi\right) \end{matrix} \right\}. \tag{5}$$

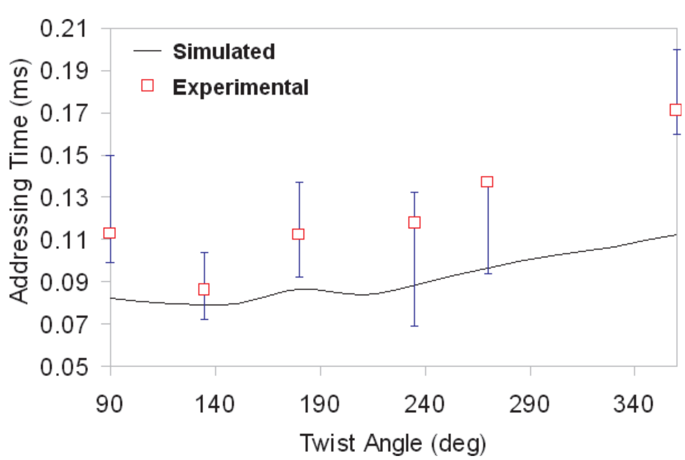

FIGURE 12 — Simulation and experimental results of τ_1 at different twisted angles.

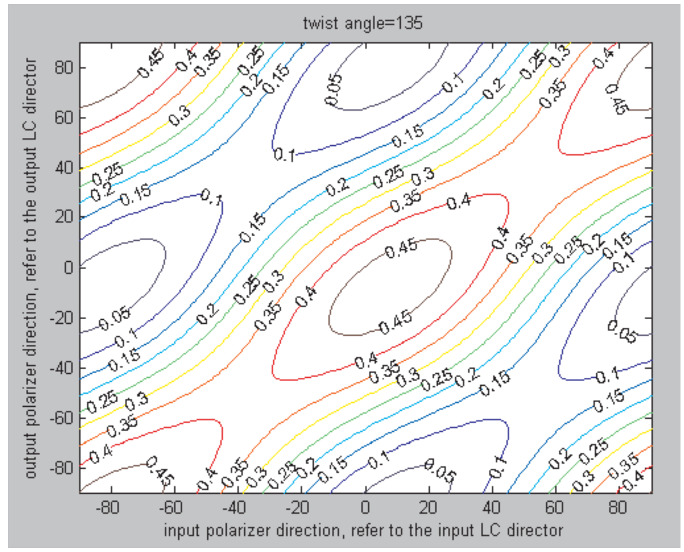

FIGURE 13 — Parameters space for 135° TN; red dot shows the solution for α and β.

FIGURE 14 — A demonstration unit with 48 × 64 resolution. Pixel size, 0.5 × 0.5 mm.

Figure 14 shows a 64 × 48 passive-matrix FSC display using the 135° TN deformation. The control unit consists of commercial STN drivers with a RGB LED backlight unit. It shows good color saturation and video rate.

5 Conclusion

In this paper, a passive-matrix-driven field-sequential-color display is proposed and demonstrated. There are three main enhancements. Firstly, a non Alt and Pleshko method is proposed. Based on GTG optimization, a fast addressing time <70 μsec and relaxing time <2 msec can be obtained. The scanning-time compensation method is proposed, also with BLU lighting control. It ensures brightness uniformity of the passive-matrix FSC panel. Finally, different twisted-nematic normal dark deformations are investigated and compared for this application.

The aim of this passive-matrix FSC device is not to obtain the maximum resolution, but to provide an alternative to spatial color for passive-matrix LCDs. It is shown that a passive-matrix FSC is capable of video rate display with 80% NTSC color. This solution is suitable for low-resolution color-text displays because the aperture ratio of passive-matrix FSC displays is almost 95%, as shown in Fig. 13, while color STN (CSTN) displays will only have a maximum of 33% for showing pure color (the other two subpixels are shut off). Passive-matrix FSC displays are a good alternative to CSTN displays.

Acknowledgments

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