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A Full-Color Matrix Liquid-Crystal Display with Color Layers on the Electrodes

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***Abstract*—A full-color matrix liquid-crystal display panel with color stripe layers of red, green, and blue on the *Y*-electrodes is proposed. The color stripe layers of 300-μm pitch are made by photolithography. The color purities of greenish, bluish, and purplish colors obtained by the liquid-crystal display panel are as good as those of typical printed inks, while those of yellowish and reddish colors are poor at present.**

In addition, effects of the color layers on the display properties are discussed.

I. Introduction

Twisted nematic liquid-crystal displays (TN-LCD's) [1] are increasingly being used for numeric displays and matrix displays. According to expansion of their applications, color LCD's are desired in some fields because novelty, viewability, and variety of display are expected. Especially for the latter two items, a multicolor or full-color display is considered to be necessary. Among various color LCD's, however, an electrically controlled birefringence cell (ECB-cell) [2]-[4] is the only LCD that can display multicolor by itself, while the other LCD's such as a TN-cell using a dichroic filter or a birefringent film [5], [6], a guest-host cell (GH-cell) [7], [8] and a cholesteric-nematic phase change cell using optical rotatory dispersion [9] are all monochrome or two-color displays. The ECB-cell has the disadvantages of narrow viewing angle, poor purity in some colors, and difficulty in controlling displayed color because it is sensitive to cell gap and temperature. Therefore the authors [10] have investigated a multicolor LCD with color layers on the electrodes as shown in Fig. 1. The liquid crystal itself acts as a light value, so that the twisted nematic mode (TN-mode) with parallel polarizers or the guest-host mode (GH-mode) with black color can be used for this device as shown in Fig. 2. In both cases, incident light is cut off at off state. When a voltage is applied to a segment, the light passes through the segment and is colored by the color layer on the electrode. By applying this system to usual

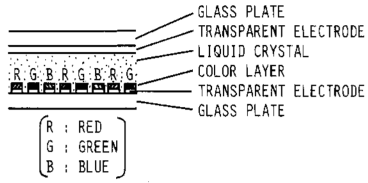
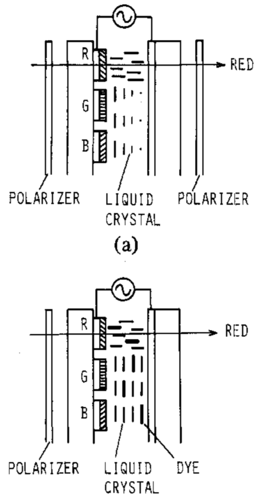


Fig. 1. Cross section of the multicolor LCD.



(a)

(b)

Fig. 2. The multicolor LCD using (a) TN-mode and (b) GH-mode.

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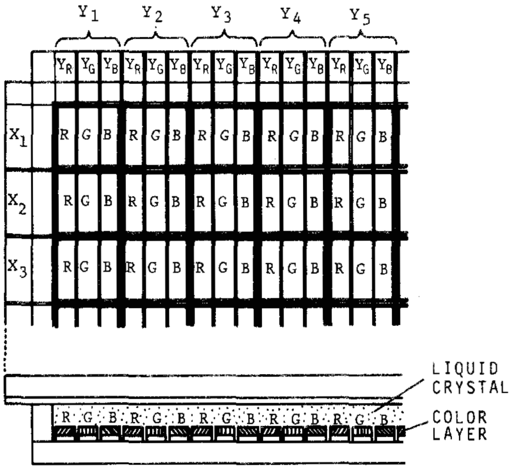

Fig. 3. The color matrix LCD.

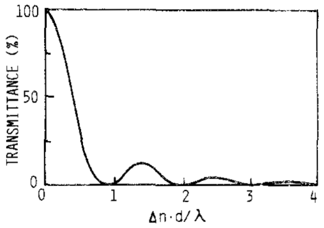

Fig. 4. Transmittance of the TN-cell with parallel polarizers at off state as a function of $\Delta n \cdot d/\lambda$ [11].

matrix LCD's as shown in Fig. 3, full-color images can be displayed in the same manner as the color CRT. This system can also be applied to active matrix LCD's with switching arrays.

Advantages of this system are as follows: 1) full-color display is easily realized by a simple structure; 2) when viewed from an oblique direction, neither parallax nor color shift occurs 3) the TN-mode with high multiplexibility can be used for usual matrix LCD's; 4) the GH-mode with wide varying angle can be used for active matrix LCD's.

In the previous paper [10], the author suggested this multicolor LCD and reported basic characteristics of a primitive cell with color stripe pattern of rough pitch (1 mm). In this paper, the authors report a full-color matrix LCD using the TN-mode. The color stripe layers of red, green, and blue are made by using the photolithographic technique instead of the screen-printing used in the previous experiment, because a fine pattern is necessary for visual mixing of the three primary colors. In this paper, the effect of the color layer on matrix driving property is also discussed.

II. CHARACTERISTICS REQUIRED FOR LIQUID CRYSTAL

As the TN-mode of negative image display is used for this color LCD reported in this paper, leakage of transmitted light at off state must be suppressed as much as possible. The transmittance at off state is a function of $\Delta n \cdot d/\lambda$ as shown in Fig. 4 [11], where Δn is optical anisotropy, d is cell gap, and λ is wavelength. Practically satisfied condition obtained by experiment was

$$\Delta n(550) \cdot d \geqq 1.4 \quad (\mu\text{m}) \tag{1}$$

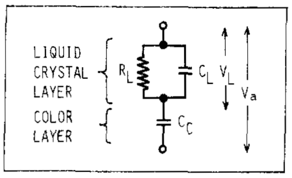

Fig. 5. Equivalent circuit of the color LCD.

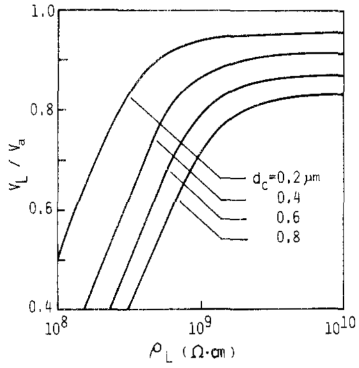

Fig. 6. ρ_L dependence of V_L/V_a.

where $\Delta n(550)$ denotes the optical anisotropy at a wavelength of 550 nm. Therefore, in the typical case of $d = 8$ μm a liquid crystal with $\Delta n(550)$ larger than 0.175 is required.

Next, the condition required for the resistivity of the liquid crystal is examined. The equivalent circuit of the color LCD can be described as Fig. 5, where R_L and C_L are, respectively, resistance and capacitance of the liquid crystal layer and C_C is capacitance of the color layer. The ratio of voltage applied to the liquid crystal layer V_L to that applied to the LCD V_a is written as

$$\frac{V_L}{V_a} = \left\{ \left(1 + \frac{\epsilon_L d_C}{\epsilon_C d_L}\right)^2 + \left(2\pi f \epsilon_C \epsilon_0 \rho_L \frac{d_L}{d_C}\right)^{-2} \right\}^{-1/2} \tag{2}$$

where f is the frequency of the applied voltage, ϵ_L is the average specific dielectric constant of the liquid crystal layer, ϵ_C is the specific dielectric constant of the color layer, ϵ_0 is the dielectric constant of space, d_L and d_C are, respectively, thickness of the liquid-crystal layer and the color layer, and ρ_L is the resistivity of the liquid crystal. Fig. 6 shows the ρ_L dependence of V_L/V_a calculated by substituting typical values of $f = 50$ Hz, $\epsilon_C = 5$, $\epsilon_L = 10$, and $d_L = 8$ μm into (2). In order to neglect voltage drop by the resistance of the liquid-crystal layer, the following inequality must be satisfied:

$$\rho_L \gg \{2\pi f \epsilon_C \epsilon_0 (d_L/d_C + \epsilon_L/\epsilon_C)\}^{-1}. \tag{3}$$

Substituting the above mentioned typical values and $d_C = 0.65$ μm, $\rho_L \gg 5 \times 10^8$ Ω · cm is obtained.

The other conditions required for the liquid crystal are as follows: 1) having no absorption in the visible region, and 2) having sharp threshold of optical property of the TN-cell. Liquid crystal TU-03 of Chisso Corporation satisfies all conditions mentioned above. Fig. 7 shows the optical property of the TN-cell using TU-03 and Table I shows characteristics of this liquid crystal.

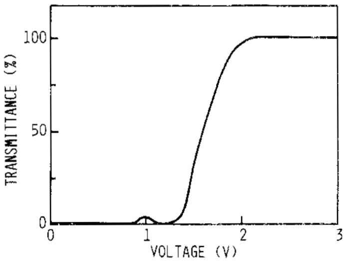

Fig. 7. Optical property of the TN-cell using TU-03 (Cell gap: 8 μm).

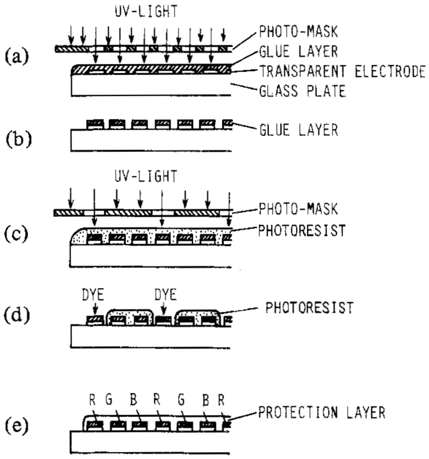

Fig. 8. Process of making color layers. (a) Coating of aqueous solution of glue doped with a sensitizer by a spinner and drying it followed by UV-light exposure. (b) Removing unexposed parts of the glue layer. (c) Coating positive photoresist and UV-light exposure. (d) Removing exposed parts of the photoresist and dyeing the glue layer red followed by removing the photoresist, repeating (c) and (d) for dyeing the glue layer green and blue. (e) Coating a protection layer.

TABLE I

CHARACTERISTICS OF LIQUID CRYSTAL TU-30 OF CHISSO CORPORATION

• Principle specific dielectric constant:	$\varepsilon_{\parallel} = 17.14$
	$\varepsilon_{\perp} = 5.74$
• Resistivity:	$\rho = 2.15 \times 10^{10}$ Ω·cm
• Viscosity:	$\eta = 53$ cP
• Optical anisotropy at 550 nm:	$\Delta n(550) = 0.206$
• Voltage for 10% transmittance*:	V(10) = 1.40 V
• Voltage for 90% transmittance*:	V(90) = 1.86 V
• Threshold sharpness*:	V(90)/V(10) = 1.34

* measured by TN-cell with parallel polarizers and cell-gap of 8 μm.

III. DISPLAY CONSTRUCTION AND RESULTS

As mentioned previously, the color layers were made by using the photolithographic technique. The process is shown in Fig. 8. Transparent glue (gelatin) doped with sensitizer is coated and it is patterned by photolithography as shown in Fig. 8(a), (b). Then the glue is dyed red, green, and blue through photoresist masks (Fig. 8(d)). Finally, a protection layer was coated (Fig. 8(e)). This layer acts as not only a protector of the color layers but also an alignment layer for liquid crystal. The thickness of the color layer made in the experiment was 0.57-0.73 μm including the protection layer.

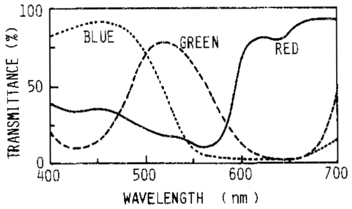

Fig. 9. Transmissive spectra when each primary color dot is excited.

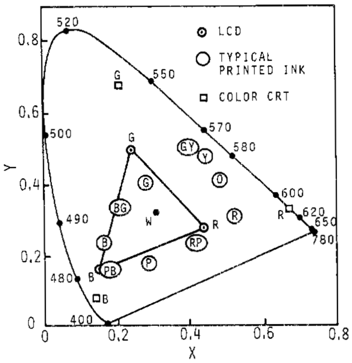

Fig. 10. Color coordinates of the color LCD, the fluorescence of the color CRT, and typical printed inks on the 1931 CIE chromaticity diagram (R: red, O: orange, Y: yellow, GY: greenish yellow, G: green, BG: bluish green, B: blue, PB: purprish blue, P: purple, RP: reddish purple, W: white).

TABLE II

CHARACTERISTICS OF THE COLOR LAYERS

Color	Dominant wavelength	Color purity	X+Y+Z
Red	- 495 nm	38.5%	1.12
Green	524 nm	34.0%	0.93
Blue	478 nm	76.5%	1.27

The color matrix LCD with 56 × 56 dots and the dot pitch of 300 μm was made as a trial. Fig. 9 shows transmissive spectra when each primary color dot is excited. Their color coordinates on the 1931 CIE chromaticity diagram are shown in Fig. 10. Table II shows their dominant wavelength, color purity, and the sum of tristimulus values, $X + Y + Z$. Though $X + Y + Z$ of three colors are almost well balanced, the color purities of red and green are not sufficient at present.

In this color matrix LCD, if the transmissive spectra of red, green, and blue as shown in Fig. 9 are respectively denoted by $T_R(\lambda)$, $T_G(\lambda)$, and $T_B(\lambda)$, and the voltage dependence of trans-

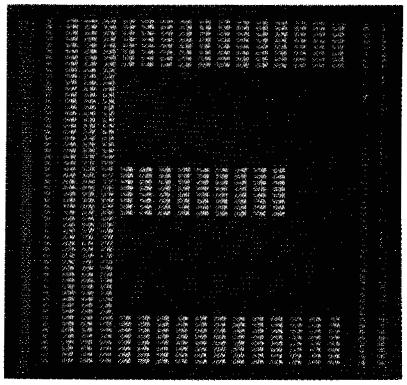

Fig. 11. An example of displayed pattern by the 56 X 56 color matrix LCD. Red and blue elements are excited.

mittance of the TN-cell as shown in Fig. 7 is denoted by $T(V)$, the spectrum of the mixed color is given by

$$T(\lambda) = \{T_R(\lambda) \cdot T(V_R) + T_G(\lambda) \cdot T(V_G) + T_B(\lambda) \cdot T(V_B)\}/3. \tag{4}$$

In this equation, V_R, V_G, and V_B denote voltages applied to red, green, and blue elements, respectively. Equation (4) indicates that any color in the triangle shown in Fig. 10 can be displayed by adjusting V_R, V_G, and V_B. The coordinates of fluorescence of the color CRT and typical printed inks are also shown in Fig. 10 for comparison. The color purities of greenish, bluish, and purplish colors obtained by the LCD are almost the same as those of the printed inks, while those of yellowish and reddish colors are poor at present.

Fig. 11 shows the letter "E" displayed by the color matrix LCD with 56 X 56 elements driven by 1:7 multiplexing. In this case, red and blue elements are excited and hence purple pattern can be observed when viewed more than about 50 cm away from the LCD.

IV. Effect of the Color Layer on Display Properities

The effect of the capacitive color layer on the properties of the matrix display is discussed in this section. When the inequality (3) is satisfied, (2) is written as

$$V_L/V_a = (1 + \epsilon_L d_C/\epsilon_C d_L)^{-1}. \tag{5}$$

Here, let $V_a(10)$ and $V_a(90)$ be voltages applied to the LCD when the transmittance becomes 10 and 90 percent of saturated value, respectively. In the same manner, let $V_L(10)$ and $V_L(90)$ be voltages applied to the liquid crystal layer, and $\epsilon_L(10)$ and $\epsilon_L(90)$ be average specific dielectric constants of the liquid-crystal layer in the same conditions. Then, $V_L(10)$ and $V_L(90)$ are written as

$$V_L(10) = V_a(10)/\{1 + \epsilon_L(10)\, d_C/\epsilon_C d_L\} \tag{6}$$

$$V_L(90) = V_a(90)/\{1 + \epsilon_L(90)\, d_C/\epsilon_C d_L\}. \tag{7}$$

Therefore, practical threshold sharpness is given by

$$\frac{V_a(90)}{V_a(10)} = \frac{\epsilon_C d_L + \epsilon_L(90) d_C}{\epsilon_C d_L + \epsilon_L(10) d_C} \cdot \frac{V_L(90)}{V_L(10)} \equiv \alpha \frac{V_L(90)}{V_L(10)}. \tag{8}$$

For the TN-cell with $d_L = 8$ μm using TU-03, experimental values of $\epsilon_L(10)$ and $\epsilon_L(90)$ are 9.16 and 11.45, respectively

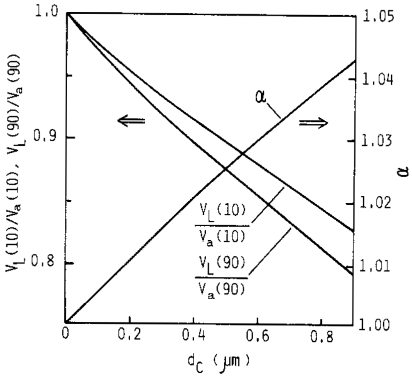

Fig. 12. d_C dependences of $V_L(10)/V_a(10)$, $V_L(90)/V_a(90)$, and α.

By using these values and $\epsilon_C = 5$, $V_L(10)/V_a(10)$, $V_L(90)/V_a(90)$, and α are calculated. The result is shown in Fig. 12. As a typical example, substituting $d_C = 0.65$ μm into (6)-(8), the following values are obtained:

$$V_L(10)/V_a(10) = 0.87 \tag{9}$$

$$V_L(90)/V_a(90) = 0.84 \tag{10}$$

$$V_a(90)/V_a(10) = 1.03\, V_L(90)/V_L(10). \tag{11}$$

Namely, voltage drop by the color layer is 13 to 16 percent and threshold sharpness becomes worse by a factor of 1.03.

Next, the allowed value of irregularity in the thickness of the color layers, Δd_C, is examined. This irregularity causes difference of the voltage applied to liquid crystal layer, ΔV_L. Assuming $\Delta V_L/V_L \leqq 0.02$ for relatively high-duty matrix driving, the allowed value of Δd_C is given by (5) as

$$\Delta d_C \leqq (\epsilon_C d_L/\epsilon_L + d_C)/49. \tag{12}$$

Substituting $\epsilon_C = 5$, $\epsilon_L = 10$, $d_L = 8$ μm, and $d_C = 0.65$ μm into (12) as typical values, $\Delta d_C \leqslant 0.09$ μm is obtained. In the color LCD made as a trial, $\Delta d_C = 0.17$ μm and $\Delta V_L/V_L = 0.03$, and hence it is somewhat insufficient for the above mentioned condition at present. However, it is considered to be possible to be improved.

V. Conclusion

A 56 X 56 matrix LCD panel with color stripe layers of red, green, and blue on the Y-electrodes was constructed. The TN-mode with parallel polarizers was used in this panel. Pitch of the stripe layers was 300 μm, but it is not difficult to be decreased to less than 50 μm because the color layers are made by using the photolithographic technique.

The adjacent colors were visually mixed when observed more than about 50 cm away from the LCD, and hence it was shown that a full-color display could be realized by this system. The sums of tristimulus values, $X + Y + Z$, of the three primary colors were almost well balanced. The color purities of greenish, bluish, and purplish colors obtained by the LCD were as good as those of the typical printed inks, while those of yellowish and reddish colors were poor.

In addition, effects of the color layers on the display properties were examined. As a result, required conditions of optical anisotropy and resistivity of liquid crystal and the allowed value of irregularity in the thickness of color layer were clarfied.

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The Direct-View Matrix-Addressed Smectic A LCD Panel: Dynamic Behavior

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***Abstract*—We present an analytical solution of the heat-flow equation applied to a direct-view thermally matrix-addressed smectic LCD panel. Using experimental values of the operating parameters of an actual panel, we compute the corresponding temperature profiles in the liquid-crystal layer. These theoretical results are compared with temperature measurements on a test cell to verify the model. Finally, we show how the thermal analysis can improve the understanding of the behavior of the smectic display, and thus to optimize the cell design for the widest possible operating margin.**

I. INTRODUCTION

IT IS a well-known fact that matrix addressing of liquid-crystal displays is a very difficult problem. This is due to the insufficient nonlinearity of the electrooptic effects and the lack of an intrinsic memory which limits the number of addressable lines. The authors [1], [2] and more recently Lu *et al.* [3], have shown that this limitation can be overcome by using two different effects to address the rows and the columns of a smectic A liquid-crystal display: thermal addressing for one set of electrodes and electric-field effect for the other.

It has been proved that such a scheme can lead to displays with very high information content ($>10^5$ pixels). Fig. 1 shows a picture of such a panel with its main characteristics written on the screen itself. Fig. 2 illustrates its implementation in a flat-screen fully-interactive portable terminal which has recently been reported by the authors [2].

These results have been obtained by an optimization of the thermal design of the cell. Two theoretical methods have been used: a numerical one, using finite differences, and an analytical solution of the heat flow equation. In this paper, we present the analytical approach applied to the direct-view matrix-addressed display. We give some results of the calculations for various parameters and compare these with measurements on an actual cell.

II. THEORETICAL MODEL

A large number of parameters have to be taken into account in such an analysis. They can be divided into two groups:

1) structural parameters such as the nature, thickness, composition of the walls of the cell, the thickness of the liquid crystal, etc., and

2) operational parameters such as peak power, pulse length, duty cycle, ambient temperature, etc.

We consider a structure consisting of three regions: a semi-infinite substrate, the liquid-crystal layer of thickness l and a

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