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Reflective Multicolor Liquid-Crystal Display

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Abstract—**A reflective multicolor matrix LCD with micro color filters is investigated. In order to improve the brightness of the LCD, contrast and brightness of various liquid-crystal display modes are analyzed. This analysis suggests the choice of the phase-change-type guest-host mode. The optimal parameters for this mode are derived. In addition, the transmission spectrum of the micro color filters is investigated and the optimal doping concentration of the dye in the color filters is determined. This results in a reflective color LCD with acceptable brightness.**

I. Introduction

DEVELOPMENT of the flat-panel displays with large information content is progressing to the point where some of these have already seen practical application. One of the future trends of research and development of flat-panel displays is the full-color display. As for liquid-crystal displays (LCD's), the authors have proposed a full-color display using micro color filters as shown in Fig. 1, where the color filters are placed inside of the cell and the liquid crystal acts as a black shutter [1]–[3]. Applications of this system to active matrix or direct matrix LCD's, pocket color televisions or color graphic displays have been made for experiments and some of these have appeared as commercial products [4]–[6].

The color LCD using micro color filters is one of the most practical color displays among flat-panel displays; however, one disadvantage of the color LCD is the necessity of a back light since most of the incident light is absorbed by the color filters and the polarizers. Therefore, power consumption of the back-lit color LCD becomes almost the same as that of color CRT's, and therefore the usual LCD advantage of low power consumption is lost.

In order to solve the above-mentioned problem, the authors have investigated a reflective-type color LCD without the back light. A key to practicallity is to increase the reflected light level as high as possible. In this paper, the brightness of various LCD modes are compared and the brightest mode is chosen. In addition, properties of the brightest LCD mode are analyzed in detail and the optimal design condition of the parameters is clarified. Finally, the properties of the reflective multicolor LCD's fabricated according to the optimal design condition are discussed [7]. Shortly after our report [7], Morozumi *et al.* [8] have independently reported on a transmissive full-color LCD with the phase-change-type guest-host mode, which we have used in the reflective color LCD. However, they have not analyzed the optical properties in detail nor optimized it from the viewpoint of the reflective type.

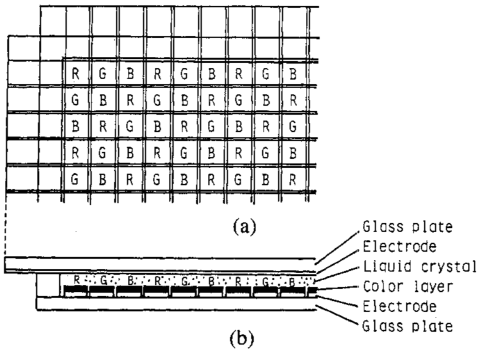

Fig. 1. Color LCD using micro color filters. (a) Top view. (b) Sectional view.

II. Evaluation of Various LCD Modes

LCD modes that can be used as a black shutter for the color LCD are as follows:

1) twisted-nematic mode (TN mode);
2) Heilmeier-type guest-host mode (GH mode) [9];
3) double-layered guest-host mode (DGH mode) [10]; and
4) phase-change-type guest-host mode (PCGH mode) [11].

Here, there are two types for the PCGH mode, that is, short pitch type with homeotropic surface alignment and long pitch type with homogeneous surface alignment. In this paper, the former is discussed because if has higher contrast and brightness than the latter. In addition, the series of guest-host modes of 2)–4) are assumed to have black color because they are used as a black shutter.

Brightness and contrast of the four LCD modes were analyzed. The results are shown in Fig. 2 [12]. The abscissa indicates transmittance when the LCD's are driven to the bright state by application of 10 V. The transmittance is a function of the concentration of dichroic dyes in the polarizers for the TN mode and that in the liquid crystal for the DGH mode and the PCGH mode. In the case of the GH mode, the transmittance is related to both the concentrations of dye in the polarizers and in the liquid crystal.

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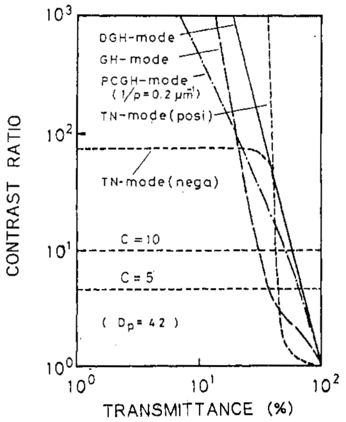


Fig. 2. Comparison of contrast ratio and brightness of various LCD modes.

It is seen from Fig. 2 that the DGH mode is the brightest and the PCGH mode is the next in the range of contrast between 5 and 10. For active matrix driving, the PCGH mode is more suitable than the DGH mode because of its simpler structure. Therefore, the PCGH mode was selected for further study as a reflective color LCD.

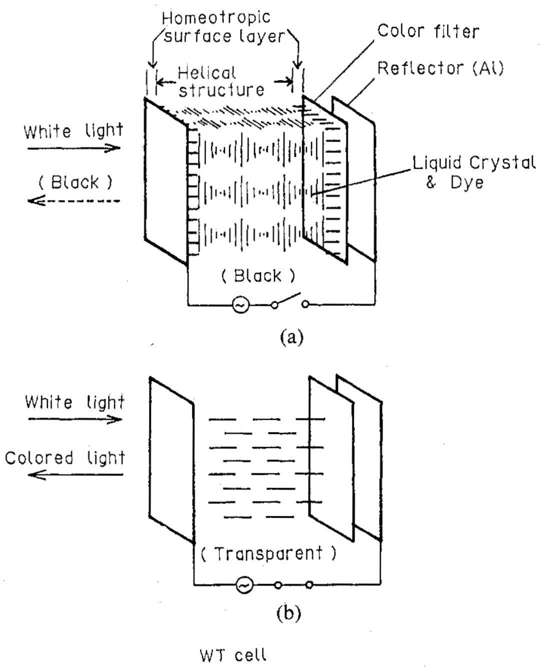


Fig. 3. Structure of reflective multicolor LCD using the PCGH mode. (a) V(OFF). (b) V(ON).

III. Analysis of the Reflective LCD Using the PCGH Mode

Fig. 3 shows the structure of the reflective multicolor LCD using the PCGH mode. In the actual active color matrix LCD, Fig. 3 corresponds to one of the micro color dots, each of which has a thin-film transistor. In this section, however, the color layer is neglected to analyze the properties of the liquid-crystal layer itself. In the analysis, it is assumed that the reflector has 100-percent reflectance and the reflected light is nondepolarized since deposited metal is used as the reflector as well as the back electrode.

Modifying White and Taylor's analysis [11] by taking into account the homeotropically aligned surface layer as shown in Fig. 3, reflectances of the cell at OFF- and ON-states are written as follows:

$$R_{\mathrm{OFF}} = \tfrac{1}{2} \exp\left[-2\{\alpha_1(d - d_s) + \alpha_\perp d_s\} q\right] + \tfrac{1}{2} \exp\left[-2\{\alpha_2(d - d_s) + \alpha_\perp d_s\} q\right] \quad (1)$$

$$R_{\mathrm{ON}} = \exp(-2\alpha_\perp d q). \quad (2)$$

Here, R_{OFF} and R_{ON} correspond to the brightnesses of the display in the two states, q is the concentration of dye, $\alpha_\perp$ is the attenuation constant perpendicular to the molecular axis, d is the cell gap, and d_s is the thickness of the homeotropic surface layers, which is given by the following equation by experiment on optical rotatory power [13]:

$$d_s = 0.4P \quad (3)$$

where P is the helical pitch of the liquid crystal, α_1 and α_2 in (1) denote attenuation constants of the two elliptical polarized light modes as defined by White and Taylor [11, eq. (6)], α_1 and α_2 are functions of $n_\parallel$, $n_\perp$, λ, $\alpha_\parallel$, $\alpha_\perp$, and p, where $n_\parallel$ and $n_\perp$ are the principal refractive indices of the liquid crystal, λ is the wavelength of light, and $\alpha_\parallel$ is the attenuation constant parallel to the molecular axis.

From (1) and (2), the constrast ratio C is given by

$$\begin{aligned} C &= R_{\mathrm{ON}}/R_{\mathrm{OFF}} \\ &= 2/[\exp\{-2(\alpha_1 - \alpha_\perp)(d - d_s)\} \\ &\quad + \exp\{-2(\alpha_2 - \alpha_\perp)(d - d_s)\}]. \end{aligned} \quad (4)$$

The other relating parameters are the dichroic ratio D and the birefringence Δn defined as follows:

$$D = \alpha_\parallel/\alpha_\perp \quad (5)$$

$$\Delta n = n_\parallel - n_\perp. \quad (6)$$

Phase change voltage V_{pc} is given by

$$V_{pc} = \pi^2 \frac{d - \beta}{P} \left(\frac{K_{22}}{\Delta\epsilon}\right)^{1/2} \quad (7)$$

where K_{22} is the twist elastic constant, $\Delta\epsilon$ is the dielectric anisotropy, and β is a function of the thickness of the surface layer and is experimentally given as

$$\beta \cong 0.55P. \quad (8)$$

From (1)–(8), the brightness R_{ON}, contrast ratio C, and phase change voltage V_{pc} are expressed by Δn, $n_\perp$, D, $\alpha_\perp q$, λ, P, d, and $K_{22}/\Delta\epsilon$. Furthermore, if $C = 5$, $V_{pc} = 10$ V, $\Delta n = 0.15$, $\lambda = 550$ nm, $d = 8$ μm, and $D = 10$ are assumed as typical values, and $\alpha_\perp q$ and P are optimized to maximize R_{ON}, then R_{ON} becomes a function of only Δn and $K_{22}/\Delta\epsilon$. Fig. 4 shows the relation between R_{ON}, Δn, and $K_{22}/\Delta\epsilon$. Here, Δn and $K_{22}/\Delta\epsilon$ are both material parameters of the liquid crystal, so that liquid crystals can be evaluated by plotting their parameters on Fig.

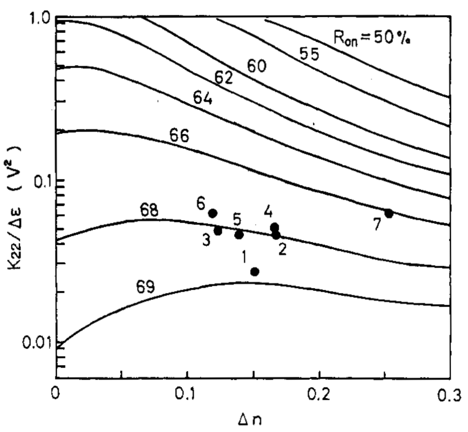


Fig. 4. Relation among brightness R_{ON}, $K_{22}/\Delta\epsilon$, and Δn.

TABLE I
MATERIAL PARAMETERS OF VARIOUS LIQUID CRYSTALS

No.	Liquid crystal	$\Delta\varepsilon$	Δn(550nm)	K_{22} [14]
1	RO-TN-701	22.5	0.151	5.40×10^{-12} N
2	RO-Tr-2934	13.9	0.167	5.50
3	RO-TN-703	12.9	0.123	5.47
4	RO-Tr-3021	12.8	0.166	5.20
5	RO-TN-615	12.7	0.139	5.25
6	RO-Nr-3102	9.4	0.119	5.20
7	GR-41	14.6	0.253	7.95

No.1~6 : Hoffman-La Roche Ltd.
No.7 : Chisso Corporation

4, and then noting the attained brightness. It is seen from Fig. 4 that among the typical liquid crystals shown in Table I, no. 1 (RO-TN-701 of Hoffman-La Roche Ltd.) is the best material, and it achieves a reflectance of about 69 percent.

IV. PROPERTIES OF THE REFLECTIVE LCD

The reflective LCD was made according to the optimal design condition of the PCGH mode mentioned in the previous section. Contrary to the previous analysis at 550 nm, the actual LCD must have a flat spectrum over a whole range of visible light for both the ON- and the OFF-states. Therefore, it is necessary to choose several suitable dyes whose absorbing regions cover the whole visible light range and with dichroic ratios that are well balanced. The properties of many azo- and anthraqinone-dyes were measured, and suitable combinations and concentrations of them were examined with the aid of a computer. From this study, four suitable dyes with absorption coefficients as shown in Fig. 5 were chosen.

These dyes and chiral materials (cholesteryl nonanoate were added to liquid crystal no. 1 according to the optimal condition. Reflectances for the ON- and OFF-states of this LCD are calculated as shown in Fig. 6.

The validity of these calculations has been confirmed by the fact that similar calculations for a transmissive cell agree very well with the measured values for the whole range of visible light. However, direct measurement for the reflective cell has not yet been made since the exact value is very difficult to obtain due to the diffusion of the reflective light and other problems. These problems are under investigation and will be reported in the near future.

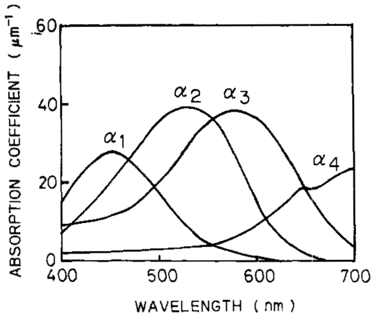


Fig. 5. Absorption spectra of four dichroic dyes used for the PCGH mode.

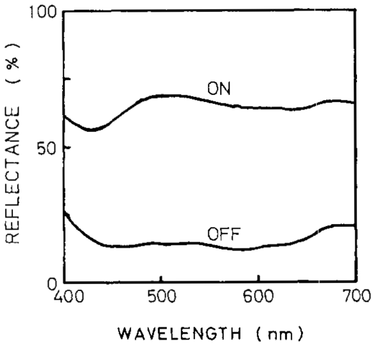


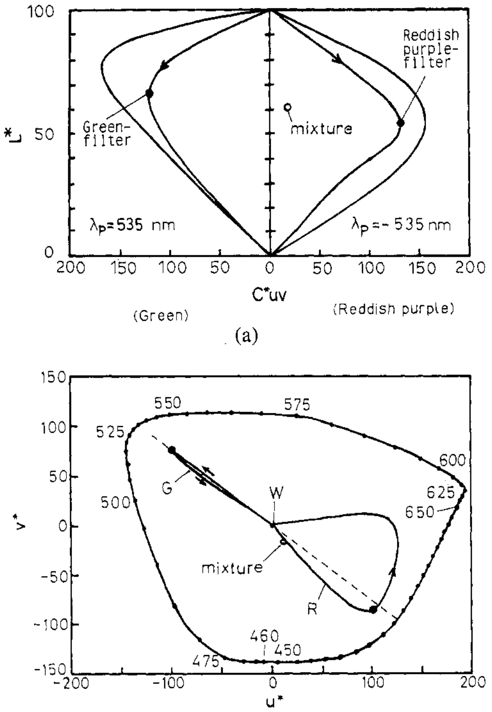
Fig. 6. Properties of the reflective LCD without color filters.

The R_{ON} value shown in Fig. 6 at 550 nm is slightly lower than the previously expected value (69 percent). This is due to a slightly lower dichroic ratio of the chosen dye, that is, 9.34 at 550 nm instead of 10 as assumed in the previous analysis.

V. SPECTRA OF THE MICRO COLOR FILTERS

Micro color filters of two colors, reddish purple and green, were investigated for the color LCD instead of the three primary colors because the two-color system has a higher brightness in the sense that the spatial occupation of each color dot is 50 percent larger than that of the three-color system. The reddish purple and the green colors are chosen as striking colors among several combinations of complimentary colors. The fabrication process of the filters is the same as for the previous report [3].

In order to determine the concentrations of dyes in the filters, the color properties of the filters as a function of the dye concentration are analyzed by using the $L^*u^*v^*$ chromaticity diagram shown in Fig. 7. Here, L^* corresponds to lightness; the magnitude of the vector sum of u^* and v^* ($C^*uv = (u^{*2} + v^{*2})^{1/2}$) corresponds to chroma and its angle to hue. Fig. 7(b) shows a locus of color coordinates of the filters projected on the u^*v^* plane when the dye concentration is changed. Fig. 7(a) shows the locus projected on a plane perpendicular to the u^*v^* plane including the broken line in Fig. 7(b). This figure



(a)

(b)

Fig. 7. Locus of the chromaticity coordinates of two color filters in a $L^*u^*v^*$-chromaticity diagram when their dye concentrations are changed. Solid circles indicate the coordinates of the color filters of green and reddish purple used in the reflective color LCD. The open circle indicates the mixture of the two colors. (a) Projection on the plane perpendicular to u^*v^*-plane for primary wavelengths λ_p of 535 and -535 nm. (b) Projection on u^*v^*-plane.

shows that when the dye concentration of the color filter is zero, the lightness is highest ($L^* = 100$), but chroma C^*uv is zero. As the concentration increases, the chroma increases, but the lightness decreases. For further concentration increases the chroma becomes maximum and then decreases again because the lightness decreases too much. It should be noted in this condition that the color purity continuously increases; however, the chroma is more important in the case of the reflective display because of the brightness importance. From the results, the concentrations of the dyes are determined to maximize chroma as shown by solid circles in Fig. 7. The open circle in Fig. 7 indicates the coordinates of their mixture. Fig. 8 shows their spectra.

VI. The Experimental Reflective Color LCD

According to the optimal design conditions of the parameters of the liquid crystal and the spectra of the color filters mentioned in the previous sections, a reflective color LCD was made as a test. The LCD is a matrix display with dot size of 95 μm × 2 mm, 432 × 24 number of dots, and a 48 × 48 mm display area. Fig. 9 shows a displayed pattern, where the LCD is statically driven to stimulate the active matrix driving. The brightness of the white part, which is mixture of reddish purple and green, was 19 percent in reflectance, which is calculated from the product of 29 percent from the color filters and 66 percent of the liquid-crystal layer. The brightness is a little lower than that of the usual black and white TN-LCD whose brightness is typically 25 percent; however, it is acceptable as a practical display. The viewing angle of this LCD is nearly 180 degrees.

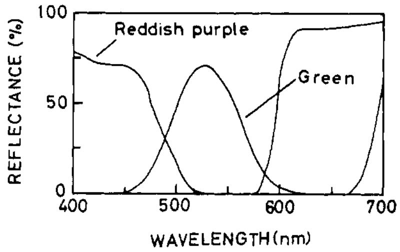


Fig. 8. Reflective spectra of the two color filters used in the reflective color LCD.

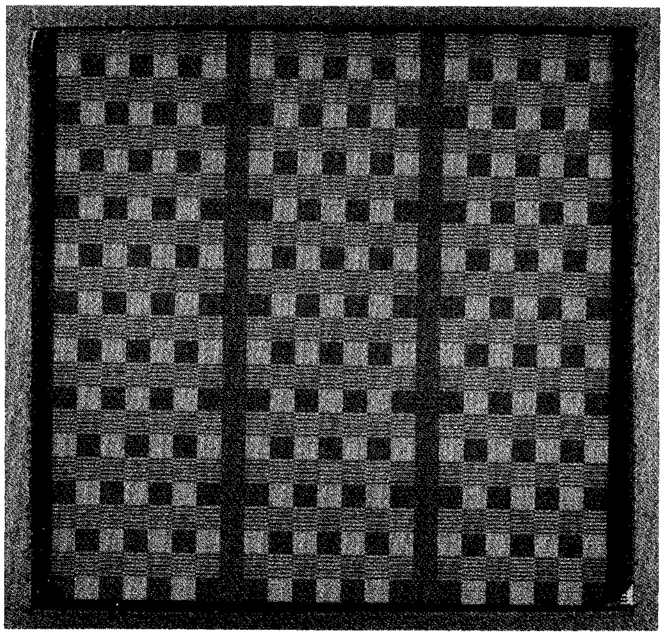


Fig. 9. A displayed pattern of the reflective multicolor matrix LCD.

VII. Conclusion

A reflective multicolor LCD using micro color filters has been realized. By using the phase-change-type guest-host mode, and optimizing the parameters, relatively high brightness can be obtained. The reflectance for the white state is 19 percent which is a little lower than that of the usual black and white TN-LCD's, which makes it acceptable for a practical display. The brightness will be further improved by optimizing the spectra of the color filters.

For the reflective LCD examined here, with color filters of reddish-purple and green, only four colors including black and white can be displayed. A full-color display is feasible with this system if color filters of the primary three colors are used. However, the brightness will be decreased by about 30 percent so that further improvement in the brightness is highly desirable.

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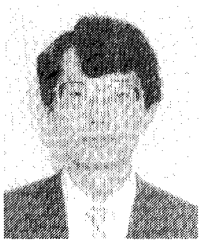

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