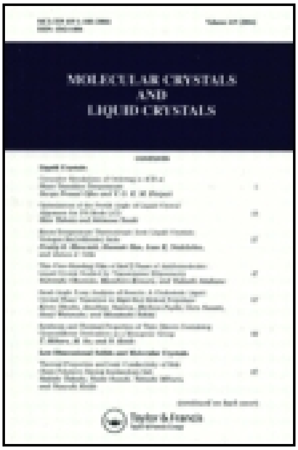

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Viewing Angle Characteristics of ECB Type Multi-Colored LCD with Non-Twist

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Viewing Angle Characteristics of ECB Type Multi-Colored LCD with Non-Twist

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A simplified analysis is made on the viewing angle characteristics of ECB type multi-colored LCDs having no twist, under the assumption that the incident light beam is applied obliquely to the plane including the directors. In addition to making $\Delta n \cdot d$ small, a symmetric configuration of molecular orientation is found theoretically to be favorable for any applied voltages to improve the viewing angle characteristic. The symmetric configuration means a symmetry which is like a mirror image with respect to the midplane in the layer of a liquid crystal. This has been experimentally confirmed by the use of a double-layered cell having such symmetric configuration. In fact, the widest viewing angle range of $\sim \pm 40°$ has been obtained in a double-layered pretilted HAN cell.

It is revealed experimentally that, when the incident light beam lies in the plane normal to the plane including the directors, the purity of displayed color tends to decrease in the cell having the symmetric configuration, as the incident angle is increased.

Keywords: multi-colored LCD, electrically controlled birefringence effect, viewing angle characteristics of LCD, non-twisted LCD, optically anisotropic medium

I. INTRODUCTION

There have been a number of reports[1-12] on the multi-colored display devices utilizing the ECB (electrically controlled birefringence) effect since a pioneer work by M. F. Schiekel and K. Fahrenschon. M. F. Schiekel and K. Fahrenschon[1] reported on the voltage controlled color formation (VCCF) with negative dielectric anisotropy. H. Mada and S. Kobayashi[3] reported on the VCCF using a twisted nematic liquid crystal with positive dielectric anisotropy and investigated the optimum condition for them. T. Shimomura, H. Mada and S. Kobayashi[4,8] reported on the spectral resolution and viewing angle characteristics in addition to the VCCF of twisted nematics with twist angles less than 90 degree. S. Matsumoto, M. Kawamoto and K. Mizunoya[5] proposed the HAN cell (hybrid aligned nematic cell) and reported on their VCCF. S. Satoh and M. Wada[6] reported on the ECB effect of nontwisted nematics for an obliquely incident light beam. T. Shimomura, H. Mada and S. Kobayashi[7] reported on the viewing angle characteristics of the VCCF with some pretilted nematics.

The narrow viewing angle characteristics of the VCCF used with the ECB effect, however, limited their application area.

In this paper, the influence of optical parameters of LC materials and of the configuration of molecular orientation on the viewing angle characteristics of multi-colored LCDs using nontwisted nematics are investigated both theoretically and experimentally. Additionally, the possible methods of improving them are described.

II. ANALYTICAL CONSIDERATION

Consider a nematic layer of thickness d confined between the planes $z = 0$ and $z = d$ of a Cartesian coordinate system (x, y, z), as shown in Figure 1. The director always lies in the x-z plane. The tilt angle between the director and the x-y plane is denoted by θ. It is assumed that the light beam lies in the x-z plane, and incidents are at an angle ϕ_i to the normal line of the x-y plane. This assumption makes it possible to simplify the present problem on the basis of geometrical optics, because in such a case the ordinary wave and the extraordinary wave always lie in the x-z plane.

After a rather complicated analysis, one obtains the following expression for the phase difference between the ordinary wave and the extra-ordinary wave:

$$\delta_\lambda = \frac{2\pi}{\lambda} d \left[\frac{1}{d} \int_o^d \frac{1}{n^2} \{ n_o n_e (n^2 - \sin^2\phi_i)^{1/2} - (n_e^2 - n_o^2) \sin\theta \cos\theta \sin\phi_i \} dz - (n_o^2 - \sin^2\phi_i) \right] \quad (1)$$

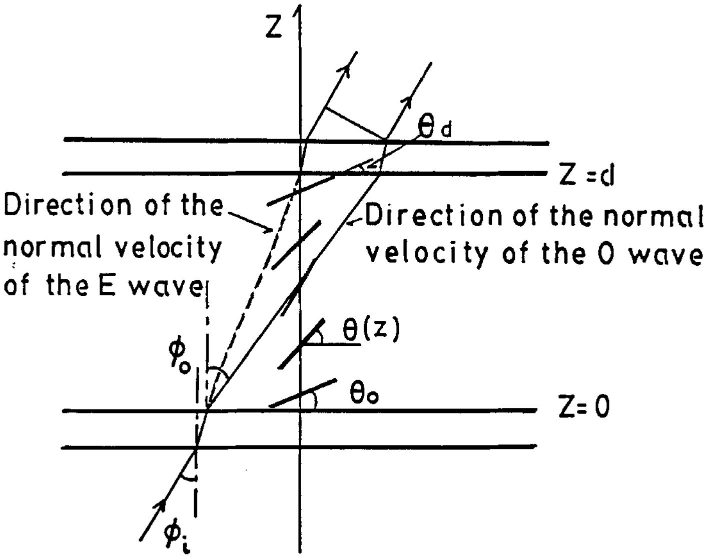


FIGURE 1 Analytical model.

where

$$n^2 = n_o^2\cos^2\theta + n_e^2\sin^2\theta \tag{2}$$

λ is the wave length, d is the cell thickness and n_o and n_e are the refractive indices of the ordinary wave and the extra-ordinary wave, respectively.

When $\Delta n = n_e - n_o \ll 1$, Eq. (1) is approximated as

$$\delta_\lambda = \frac{2\pi}{\lambda}\Delta n \cdot d[\{(1-\xi^2)^{-1/2} - 2(1-\xi^2)^{1/2}\}I_1 - \xi I_2 + (1-\xi^2)^{1/2}] \tag{3}$$

where

$$\xi = \sin\phi_i / n_o \tag{4}$$

$$\left.\begin{aligned} I_1 &= \frac{1}{d}\int_o^d \sin^2\theta dz \\ I_2 &= \frac{1}{d}\int_o^d \sin 2\theta dz \end{aligned}\right\} \tag{5}$$

As is well known, the optical transmittance T_λ is given as follows, under the condition of crossed polarizers.

$$T_\lambda = T_p \sin 2\varphi \sin^2\left(\frac{\delta_\lambda}{2}\right) \tag{6}$$

where T_p is the transmittance of polarizers and φ is the angle between the direction of the polarizer and the direction of the director projection to the surface of the first electrode. Hereafter, $T_p = (2/\pi)^2$ and $\varphi = 45°$ are assumed.

2.2. Influence of various parameters on viewing angle characteristics

The variation of δ_λ with the incident angle of the light ϕ_i may directly affect the viewing angle dependence of the displayed color. Thus, in this section, the various parameters making effects on the viewing angle characteristics will be discussed in some detail with the use of Eq. (3).

Hereafter, only the case of materials having positive dielectric anisotropy is discussed.

2.2.1. *Effects of* Δn*(550)* · d *and* n_o

It is easily noticed from Eq. (3) that if $\Delta n \cdot d$ is made small, the amount of variation of δ_λ with ϕ_i can also be made small. Taking into account the relation of $\xi = \sin\phi_i / n_o$, a large value of n_o is found to result in a small variation of the phase difference δ_λ with ϕ_i varied. A significant improvement of the viewing angle characteristics, however, can not be expected by the use of materials having a large value of n_o, because the value of n_o of typical LC materials, which has been widely used, lies within a range from 1.4 to 1.5.

It should be remembered that if $\Delta n(550) \cdot d$, which is the value of $\Delta n \cdot d$ for the wave-length of $\lambda = 550$ nm, is made too small, the range of color which can be displayed is limited. From the purpose of realizing a multi-colored LCD, it arouses interest to know the minimum value of $\Delta n(550) \cdot d$, denoted by $\Delta n(550) \cdot d_u$, above which all hues can be displayed by varying the applied voltage, under the condition of normal viewing. As was described in our previous report, all of the hues with high purity can be displayed when the retardation for $\lambda = 550$ nm, denoted by Γ_{550}, varies over the range from Γ_1 to Γ_2, by changing the applied voltage. The value of Γ_1 lies in the range of 0.80 μm to 0.85 μm, and that of Γ_2 lies from 0.2 μm to 0.25 μm, depending on the materials. Hence, it is reasonable to evaluate $\Delta n(550) \cdot d_u$ as

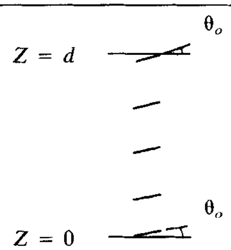
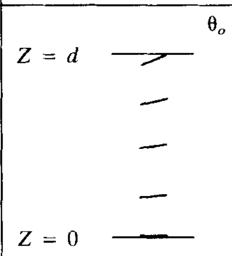
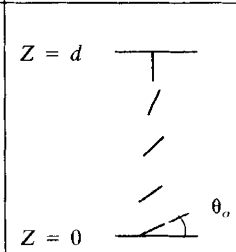
$$\Delta n(550) \cdot d_u = \Gamma_1/(1 - I_1(0)) \tag{7}$$

where $I_1(0)$ is the value of I_1 for no applied voltage, depending on the configuration of molecular orientation, as shown in Table I. The

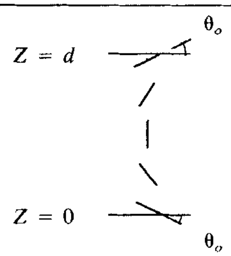
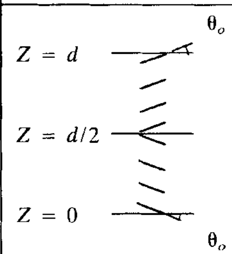
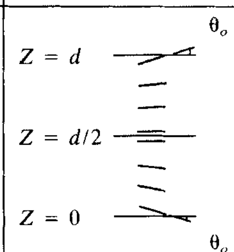
TABLE I

$I_1(0)$ and $I_2(0)$ for some types of configurations of molecular orientation

(a) Cases of $I_2 \neq 0$

	Pretilt cell	Pretilted HAN cell (1)	Pretilted HAN cell (2)
Molecular Orientation			
$I_1(0)$	$\sin^2\theta_o$	$\frac{1}{2}\left(1 - \frac{1}{2\theta_o}\sin 2\theta_o\right)$	$\frac{1}{2}\left(1 - \frac{1}{\pi - 2\theta_o}\sin 2\theta_o\right)$
$I_2(0)$	$\sin 2\theta_o$	$\frac{1}{2\theta_o}(1 - \cos 2\theta_o)$	$\frac{1}{\pi - 2\theta_o}(1 + \cos 2\theta_o)$

(b) Cases of $I_2 \equiv 0$

	Reversely pretilted cell	Double-layered pretilted cell	Double-layered pretilted HAN cell
Molecular Orientation			
$I_1(0)$	$\frac{1}{2}\left(1 + \frac{1}{\pi - 2\theta_o}\sin 2\theta_o\right)$	$\sin^2\theta_o$	$\frac{1}{2}\left(1 - \frac{1}{2\theta_o}\sin 2\theta_o\right)$
$I_2(0)$	0	0	0

values of $\Delta n(550) \cdot d_u$ are plotted in Figure 2 as a function of θ_o for some configuration types of molecular orientation.

From these results, a double-layered pretilted HAN cell, a reversely pretilted cell, a pretilt cell and a double-layered pretilted cell having a small pretilt angle are found to have the possibilities of giving relatively good viewing angle characteristics.

2.2.2. Effects of the configuration of molecular orientation

From the second order approximation of Eq. (3) with respect to ϕ_i, one obtains

$$\delta_\lambda = \frac{2\pi}{\lambda}\Delta nd\left[(1 - I_1) - I_2\left(\frac{\phi_i}{n_o}\right) + \frac{1}{2}(3I_1 - 1)\left(\frac{\phi_i}{n_o}\right)^2\right] \tag{8}$$

The first term of Eq. (8) is the contribution of normal viewing. The second and third terms represent the amount of the variation of phase difference with the angle of incidence ϕ_i.

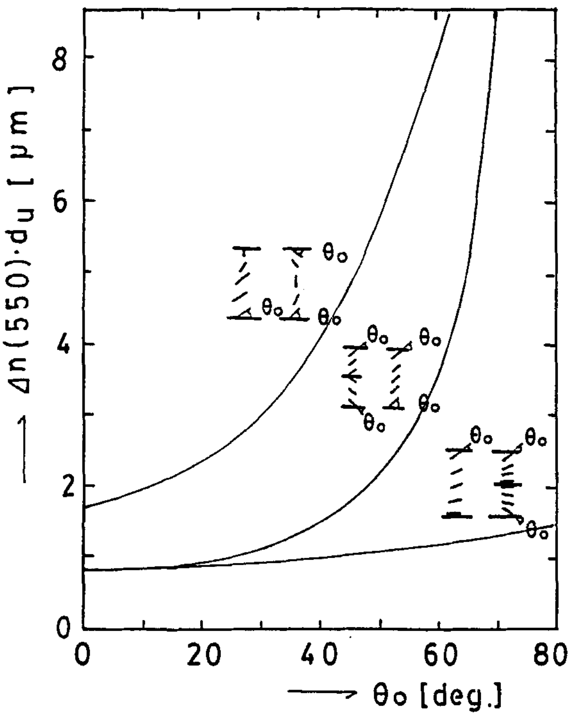


FIGURE 2 Values of $\Delta n(550) \cdot d_u$ for some kinds of configurations of molecular orientation with varied pretilt angles. $\Gamma_1 = 0.80$ μm, $k_{11} = k_{22} = k_{33}$.

A. The case of $I_2 \equiv 0$: It should be noted that if I_2 is identically equal to zero, δ_λ becomes independent of ϕ_i at $I_1 = 1/3$, predicting that if these conditions are satisfied, extremely wide viewing angle characteristics may be obtained. In order to satisfy that $I_2 = 0$ for any applied voltages, the molecular orientation must have a symmetric configuration like a mirror image with respect to the midplane in the layer of a liquid crystal for any applied voltages, as is known from the definition of I_2. A reversely pretilted cell, a double-layered pretilted cell and a double-layered HAN cell as shown in Table I(b) are the case. In order to satisfy that $I_1 = 1/3$, the value of I_1 for $V = 0$, denoted by $I_1(0)$, must be less than or equal to 1/3 in the case of Np–LC. In that case, I_1 increases monotonically with an increase of applied voltage.

Figure 3 shows the variation of $I_1(0)$ with the pretilt angle θ_o for various types of cells, as illustrated in the figure. The calculations

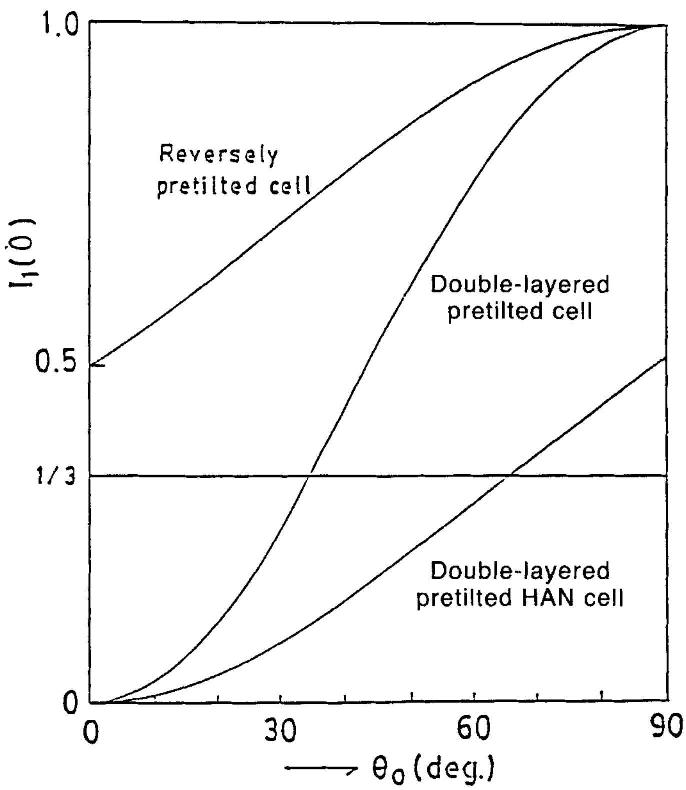


FIGURE 3 Relations between $I_1(0)$ and θ_o for three types of symmetric configuration like a mirror image with respect to the midplane in the layer of liquid crystals.

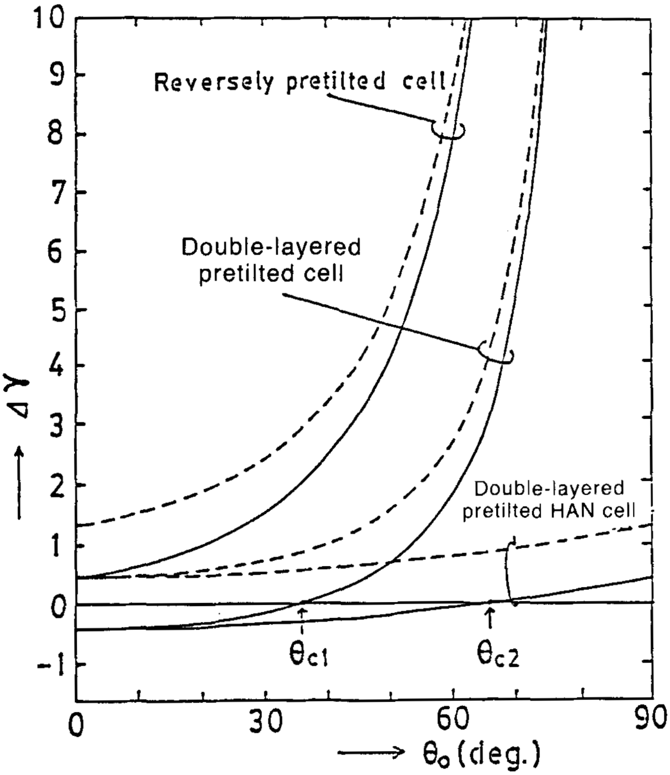


FIGURE 4 Values of $\Delta\gamma$ with θ_o for three types of configuration satisfying $I_2 = 0$ for any applied voltages. Solid lines are $\Delta\gamma_1$. Dotted lines are $\Delta\gamma_2$.

were made on the assumption that $k_{11} = k_{22} = k_{33}$. It is known from this figure that a double-layered pretilt cell with a lower pretilt angle than $\theta_{c1} = 35°$ and a double-layered pretilted HAN cell with a lower pretilt angle than $\theta_{c2} = 65°$ satisfy both conditions mentioned above. The reversely pretilted cells satisfy $I_2 = 0$, but cannot satisfy $I_1 = 1/3$, as shown in Figure 3.

From Eq. (8), the value of $\Delta\gamma = \Delta n(550) \cdot d_u \cdot (3I_1 - 1)/2$ is found to be an appropriate measure for the comparison between those cells having the respectively different $\Delta n(550) \cdot d_u$. It is easily known that $I_1 = I_1(0)$ for $\Gamma_{550} = \Gamma_1$ and $I_1 = 1 - \Gamma_2/\Delta n(550) \cdot d_u$ for $\Gamma_{550} = \Gamma_2$. The values of $\Delta\gamma$ are plotted in Figure 4 for the three types of cells mentioned above. In this figure, the solid curves, indicated by $\Delta\gamma_1$ correspond to the case of $\Gamma_{550} = \Gamma_1$, and the dotted curves, indicated by $\Delta\gamma_2$ correspond to the case of $\Gamma_{550} = \Gamma_2$. The values of $\Delta\gamma$ increase from $\Delta\gamma_1$ toward $\Delta\gamma_2$, as the applied voltage is increased from zero.

From those results, it is expected that a remarkable improvement can be achieved by the use of a double-layered pretilted HAN cell and a double-layered pretilted cell with a low pretilt angle.

B. The case of $I_2 \neq 0$: A pretilt cell, a pretilted HAN cell (1) and a pretilted HAN cell (2), as shown in Table I(a), are the case. For these types of cells, the third term in Eq. (8) may be negligible in the neighborhood of $\phi_i = 0$. Thus, in this neighborhood, a relatively good viewing angle may be obtained by a cell having a small value of I_2. Comparison is made between cells with fixed values of $\Delta n(550) \cdot d$ and n_o. On the other hand, if the comparison is made between cells having the respectively different values of $\Delta n(550) \cdot d_u$ defined as in Eq. (7), a smaller value of $I_2/(1 - I_1(0))$ results in

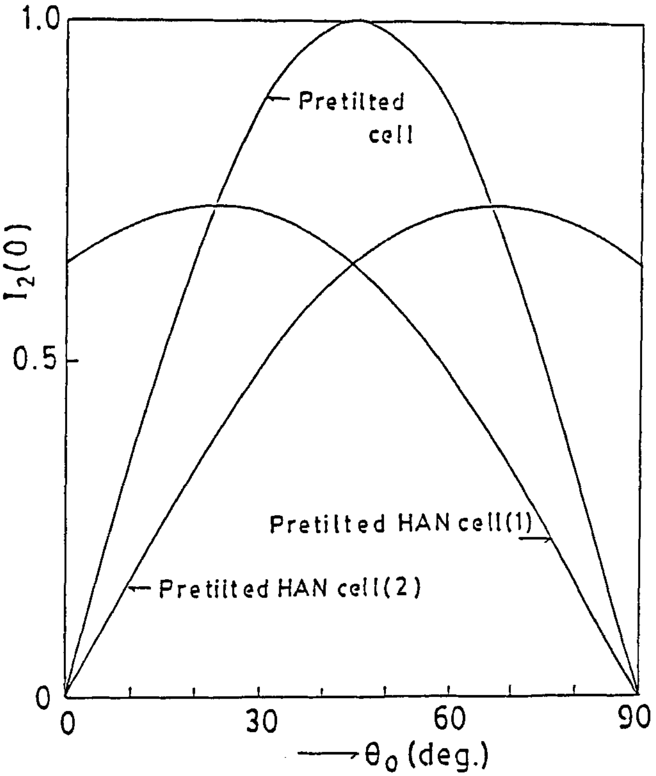


FIGURE 5 Variation of $I_2(0)$ with θ_o for three types of configuration of molecular orientation.

better viewing angle characteristics in the neighborhood of $\phi_i = 0$. The values of $I_2(0)/(1 - I_1(0))$ are plotted in Figure 6 as a function of θ_o for these three types of cells. Among those three types of cells, the pretilted HAN cell (1) with a low pretilt angle is expected to give relatively good viewing angle characteristics.

2.3. Results of numerical calculation

The variation of chromaticity with incident angle ϕ_i calculated on the basis of the CIE (1931) standard colorimetric system are shown in Figure 7 for four types of cells. In Figure 7 are shown the results for (a) the S–P cell with $\theta_o = 2°$, (b) the S–HAN cell (2) with $\theta_o = 90°$, (c) the S–RP cell with $\theta_o = 20°$ and (d) the D–PHAN cell with $\theta_o = 2$. The constants used in these calculations are listed in Table II. Those

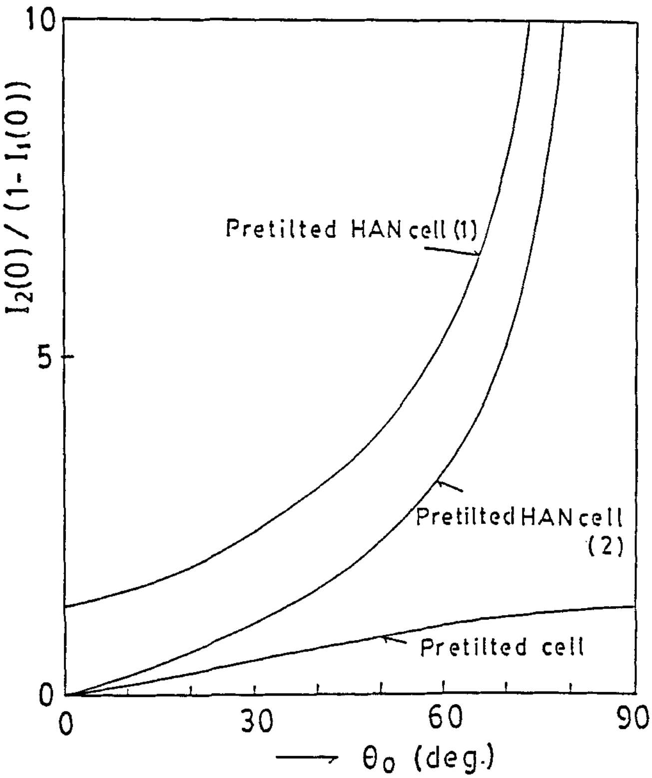


FIGURE 6 Relations between $I_2(0)/(1 - I_1(0))$ and θ_o for three types of configuration as shown in Table I (a).

TABLE II

Constants used in calculations

$\Delta n(550) = 0.209$	$\epsilon_{\parallel} = 9.9$
$n_o = 1.5$	$\epsilon_{\perp} = 3.6$
$a_o = 12800$ [nm²]	$K_{11} = 11.0 \times 10^{-12}$ [N]
$b_o = 0.154$	$K_{22} = 8.0 \times 10^{-12}$ [N]
$\lambda_o^2 = 91600$ [nm²]	$K_{33} = 16.0 \times 10^{-12}$ [N]

The Drude type dispersion relation $\Delta n = a_o/(\lambda^2 - \lambda_o^2) + b_o$ was assumed to be the birefringent index $\Delta n(\lambda)$.

TABLE III

Samples prepared in this experiment

Types of cell		Name	$\Delta n(550)$	d (μm)
Single-layer	Pretilted cell	S–P07–17	0.070	17.1
		S–P07–20	0.070	19.7
		S–P07–33	0.070	33.0
		S–P209–14	0.209	13.6
		S–P253–9	0.253	9.1
	Reversely pretilted cell	S–RP209–12	0.209	12.0
	Pretilted HAN cell	S–PH209–19	0.209	19.1
	HAN cell	S–H209–15	0.209	14.7
Double-layer	Double-layered pretilt cell	D–P07–19	0.070	19.2
	Double-layered pretilt HAN cell	D–PH07–16	0.070	16.4

are the values for the materials M3 as shown in Table IV. The values of $\Delta n(550) \cdot d_u$ given by Eq. (7) were used for the respective cells as indicated in the figure caption. In these figures, the dotted lines represent the loci of chromaticity with a continuous variation of applied voltage under the condition of $\phi_i = 0$.

It should be noted that the D–PHAN cell has the best viewing angle characteristics among these four types of cells. When a comparison is made between three single-layer cells, the S–RP cell is found to have relatively good viewing angle characteristics.

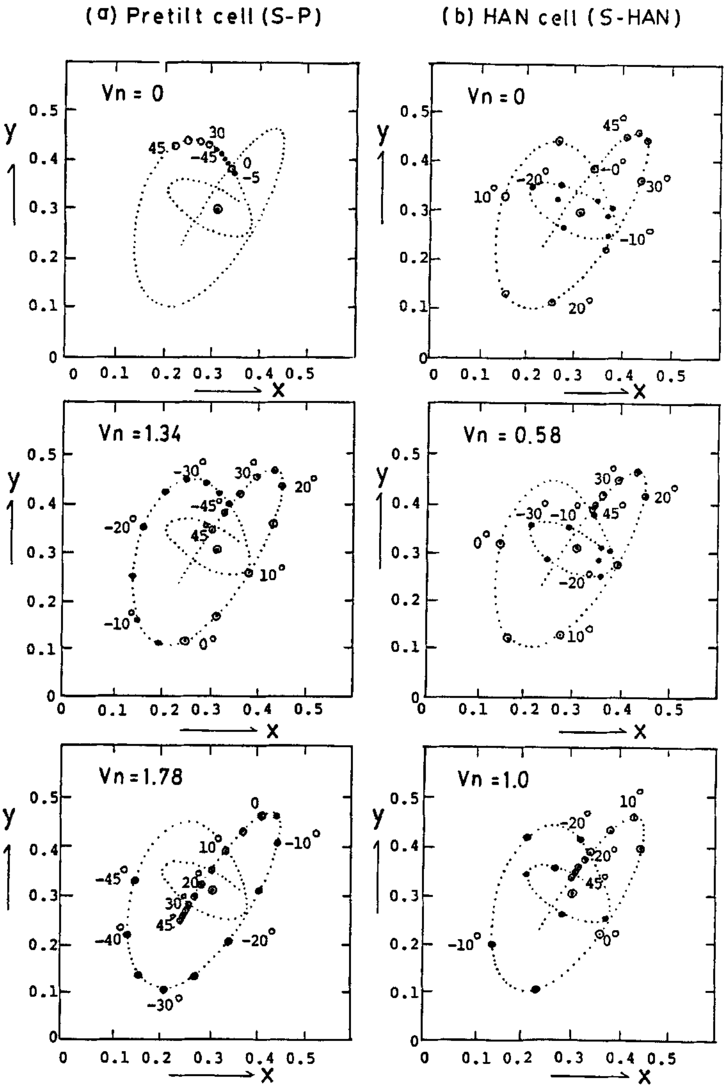


FIGURE 7 Variation of chromaticity with ϕ_i which were calculated theoretically for three types of cells. (a) $\Delta n(550) \cdot d_u = 0.85$ μm, (b) $\Delta n(550) \cdot d_u = 1.77$ μm

III. EXPERIMENTALS

3.1. Experimental apparatus and procedure

The samples prepared for the present experiments are listed in Table III. Three kinds of Np–LC materials, as shown in Table IV,

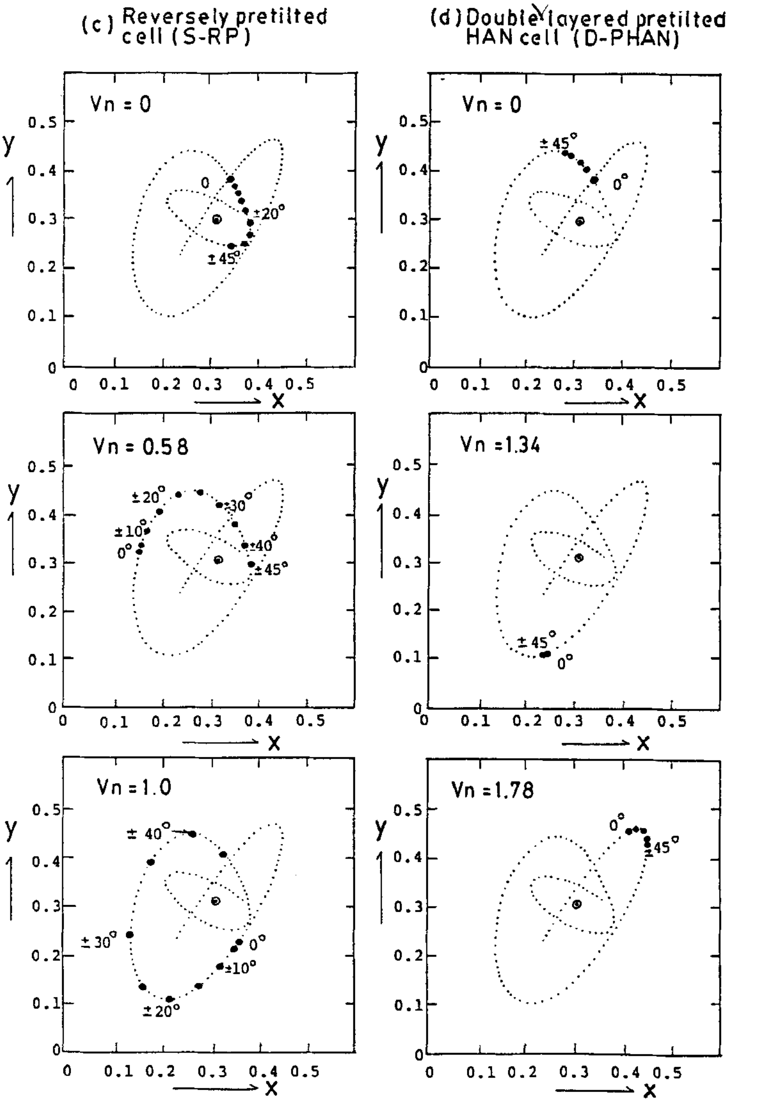


FIGURE 7 (continued) (c) $\Delta n(550) \cdot d_u$, = 2.40 μm, (d) $\Delta n(550) \cdot du$ = 0.84 μm

were used. The birefringent indices of those materials, M1, M2, and M3 are 0.07, 0.209 and 0.253, respectively. Oblique evaporations of SiO_x with the incident angles of 60° and 80° were made to obtain parallel and pretilted molecular orientations on the surfaces, respectively. The pretilt angle obtained by the oblique evaporation with the incident angle of 80° was 20° ± 2°. The method of coating a stearato-

TABLE IV

Materials used in experiments

LC materials				$\Delta n(550)$	$n_o(550)$
M1	Ester	ZLI–1800–001	Merck Co., Ltd.	0.070	1.475
M2	Shiff	MBBA + BBCA (4:1)	Fujishikiso Co., Ltd.	0.209	1.584
M3	Biphenyl	GI–41	Chisso Co., Ltd.	0.253	1.501

chromicchrolide was used to align the molecules perpendicular to the surfaces. Mylar films with thicknesses of 4 μm, 9 μm, 12 μm and 25 μm were used as spacers. By assembling these electrodes, the materials and the spacers, some types of cells, shown in Table III, were constructed.

The experimental set-up is shown in Figure 8. At first, the relations of transmitted light intensity I_t vs applied voltage V were measured under the light of $\lambda = 550$ nm, the incident angle of which is normal to the LC surface. A sinusoidal applied voltage of 1 kHz was used. Next, the variation of transmitted light intensity I_t with an incident light angle ϕ_i was measured under the condition of a fixed applied voltage. From those results with Eq. (6), the ϕ_i vs δ_λ relations were evaluated. Finally, a spectral transmittance T_λ within the visible light range was measured under the condition of a fixed voltage and of various incident angles ϕ_i. Processing these data in a personal

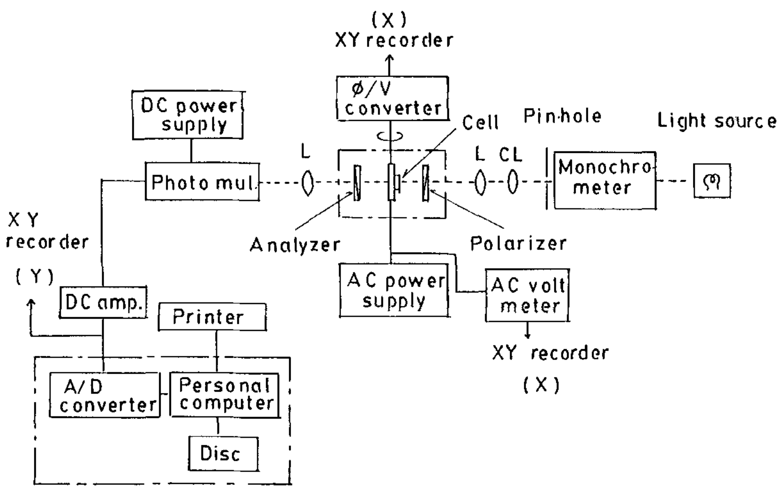


FIGURE 8 Experimental setup.

computer, the chromaticities were calculated with the CIE (1931) standard colorimetric system.

3.2. Experimental results

3.2.1. Variation of δ_λ with ϕ_i

(1). Δn(550) and d dependences.

The δ_λ vs ϕ_i relations for S–P07–17 and S–P07–33 are shown in Figure 9. Both cells are the pretilt cells in which the same material M1 was used. The thicknesses of S–P07–17 and S–P07–33 are 17.1 μm and 33.0 μm, respectively. The former cell is found to have apparently better viewing angle characteristics than the latter cell.

The δ_λ vs ϕ_i relations for the same thickness of 13.6 μm are plotted in Figure 10. In this figure, (a), (b) and (c) are the curves for S–P07–17, S–P209–14 and S–P253–9, respectively. Note that the data plotted in Figure 10 are those actually obtained values multiplied by 13.6/(the actual thickness) for the respective cells. All of these

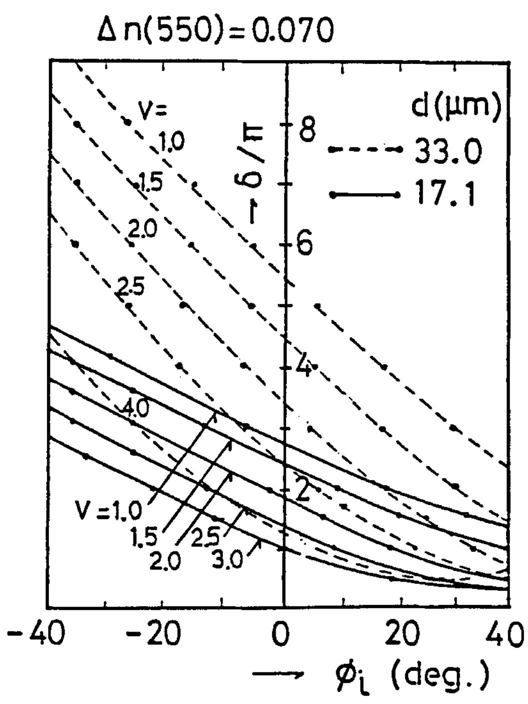


FIGURE 9 δ_λ vs ϕ_i for S–P07–33 and S–P07–17. Comparison of influences of cell thickness.

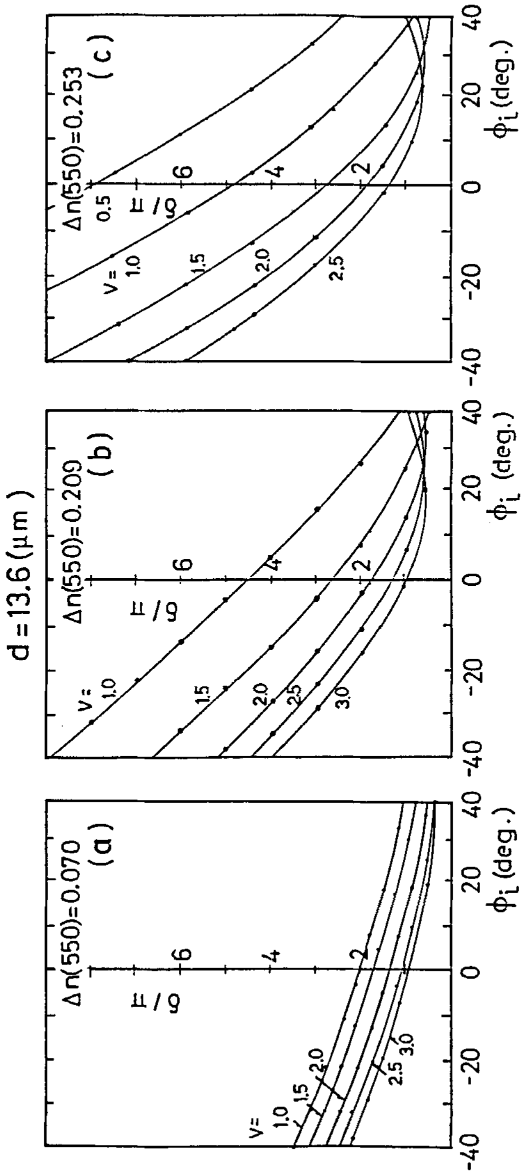


FIGURE 10 δ_λ vs ϕ_i with $\Delta n(550)$ varied for the same thickness of 13.6 μm. Compare the influence of $\Delta n(550)$.

cells are pretilt cells. The values of $\Delta n(550)$ in (a), (b) and (c) are 0.07, 0.209 and 0.253, respectively. From these results, it was found that the smaller $\Delta n(550)$ yields better viewing angle characteristics.

These results agree well with the theoretical considerations mentioned in the previous section.

(*II*). *Influence of the configuration of molecular orientation.*

A. Single-layer cell: The δ_λ vs ϕ_i relations for the cells having different configurations of molecular orientation are shown in Figure 11. In this figure, (a), (b), (c) and (d) correspond to the pretilt cell (S–P209–14), the pretilted HAN cell (S–PH209–19), the HAN cell (S–H209–15) and the reversely pretilted cell (S–RP209–19), respectively. All of those cells are single-layer cells, and the material M2 was used in common. The data plotted in Figure 11 are those actually obtained values multiplied by 13.6/(the actual thickness) for respective cells.

No significant difference between (a), (b) and (c) seems to exist. This agrees well with the theoretical prediction described in the previous section, since the values of $I_2(0)$ estimated from Figure 5 for these cells are almost the same.

It should be noticed that the curves for S–RP–209–19 are symmetric with respect to the vertical axis, and that this type of cell results in relatively better viewing angle characteristics than the other three. This fact also agrees well with the theoretical prediction.

B. Double-layered cell: The δ_λ vs ϕ_i relations for D–PH07–16 are shown in Figure 12. The variation of δ_λ with ϕ_i in this type of cell is found to be extremely small in comparison with the four types of cells shown in Figure 11. The sign of curvature of the variation of δ_λ with ϕ_i is found to change from negative to positive at 2.3 [V] when the applied voltage is increased from zero. This means that the value of $I_1(0)$ for this cell is smaller than 1/3, as was mentioned in the previous section.

3.2.2. *Variation of chromaticity with* ϕ_i

The variation of chromaticity with ϕ_i is shown in Figure 13. In this figure, (a) and (b) are the results for S–P07–17 and S–P253–9, respectively. Both cells are single-layer pretilt cells, employing the same material, M3. Although the thickness of S–P07–17 is thicker than that of S–P07–17, the former cell has better viewing angle characteristics than the latter cell. This is because the value of

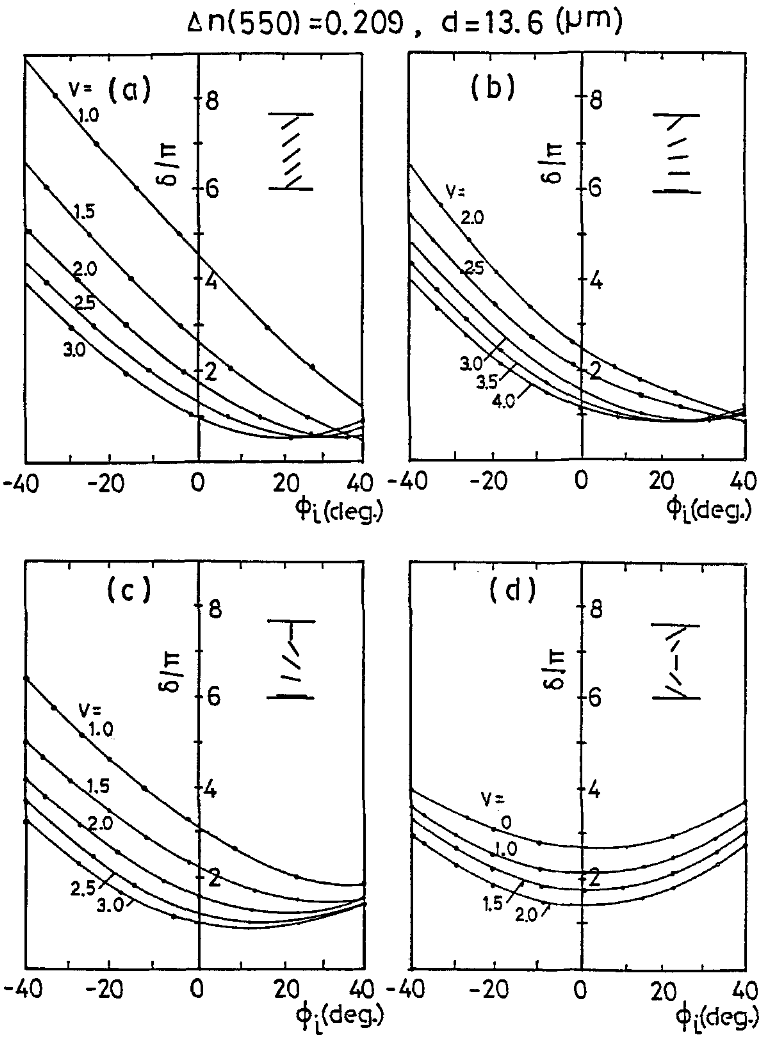


FIGURE 11 δ_λ vs ϕ_i for four types of cells having different configurations.

$\Delta n(550) \cdot d$ for the former cell is smaller than the latter cell. This agrees well with the theoretical prediction. In Figure 13, (c) and (d) are the results for D–PH07–16 and S–RP–209–12, respectively. The former cell, which is the double-layered pretilted HAN cell, is found to have the best viewing angle characteristics among these four types. The latter cell has relatively good viewing angle characteristics. In

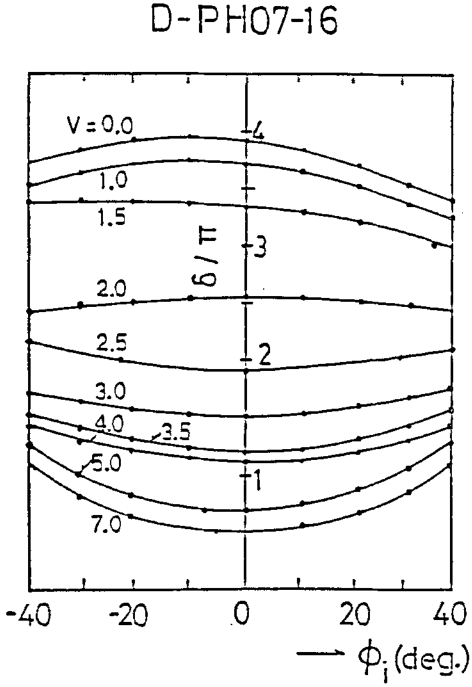


FIGURE 12 δ_λ vs ϕ_i for double-layered pretilted HAN cells (D–PH07–16).

this type of cell, however, the variation of chromaticity with ϕ_i tends to become large as the applied voltage is increased.

The previous experimental investigations, as well as the theoretical discussions, are to be limited only to the case in which the incident light beam lies in the plane including the directors. Now, let's show some interesting results observed when the incident light beam lies in the plane normal to the plane including the directors, particularly in the cell having a symmetric configuration, like a mirror image.

The variation of chromaticity with the light incident angle ϕ_i obtained in the way just mentioned above is shown in Figure 14. In this figure, (a), (b), (c) and (d) are the results for S–P07–17, S–P253–9, D–PH07–16 and S–RP209–12, respectively. It is found from these results that the chromaticities for D–PH07–16 and S–RP209–12 tend to approach the point of white as the incident light angle is increased. On the other hand, such a tendency is not observed in S–P07–17 and S–P253–9. These facts cannot be explained on the basis of the theory described in the previous section.

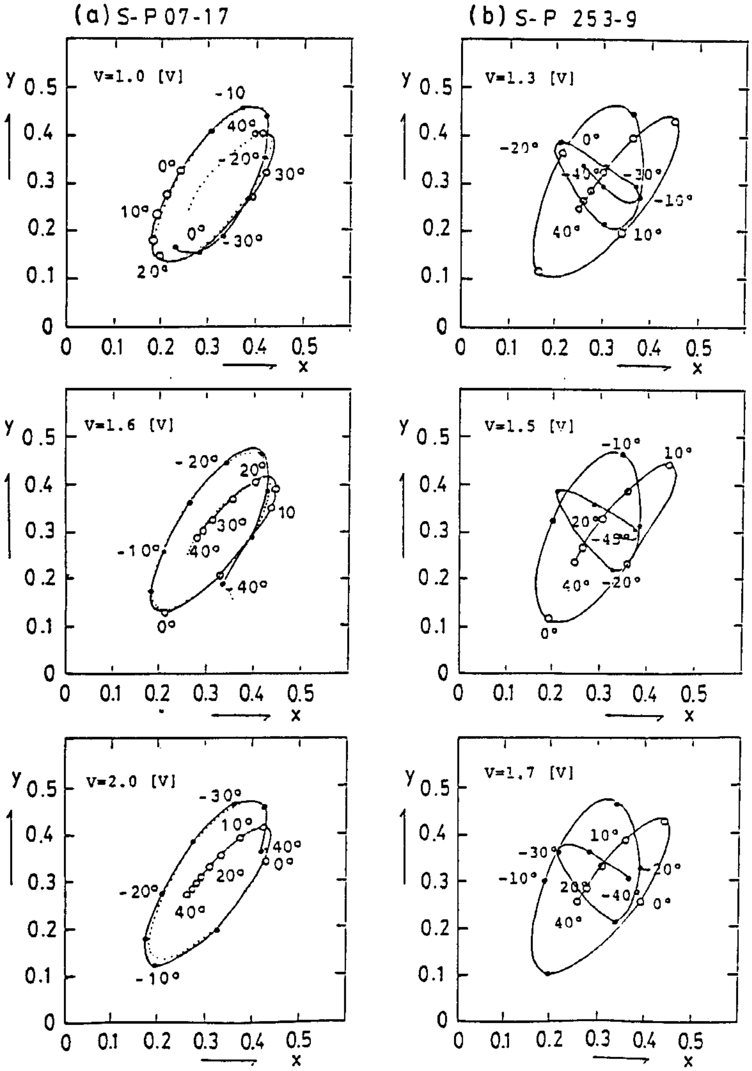


FIGURE 13 Variation of chromaticity with ϕ_i for four types of cells. In this case the light angles ϕ_i were varied in such a way that the light beam lies in the plane including the directors.

IV. CONCLUSION

The validity and usefulness of equation (3) was confirmed experimentally under the condition that the incident light beam lies in the plane including the directors.

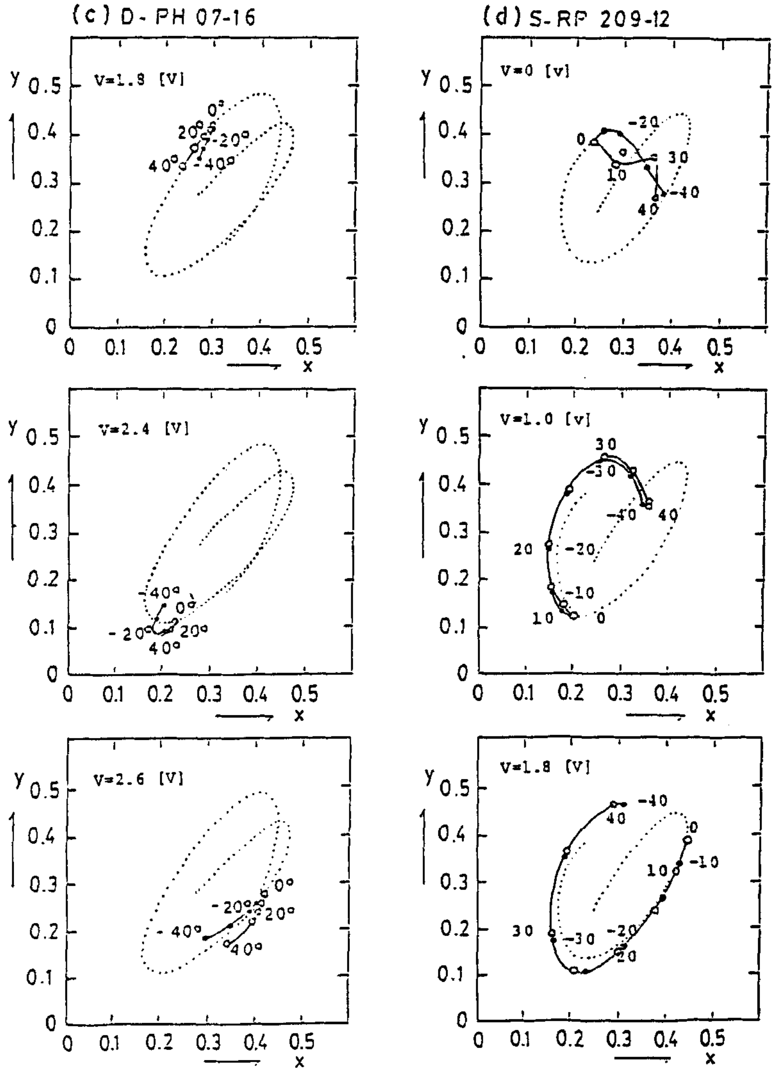


FIGURE 13 (continued)

It was revealed both theoretically and experimentally that a small $\Delta n(550) \cdot d$ and a symmetric configuration of molecular orientation like a mirror image with respect to the midplane in the layer of a liquid crystal are favorable in improving the viewing angle characteristics of ECB type multi-colored LCDs. Actually, the double layered pretilted HAN cell was found to have the widest viewing angle range.

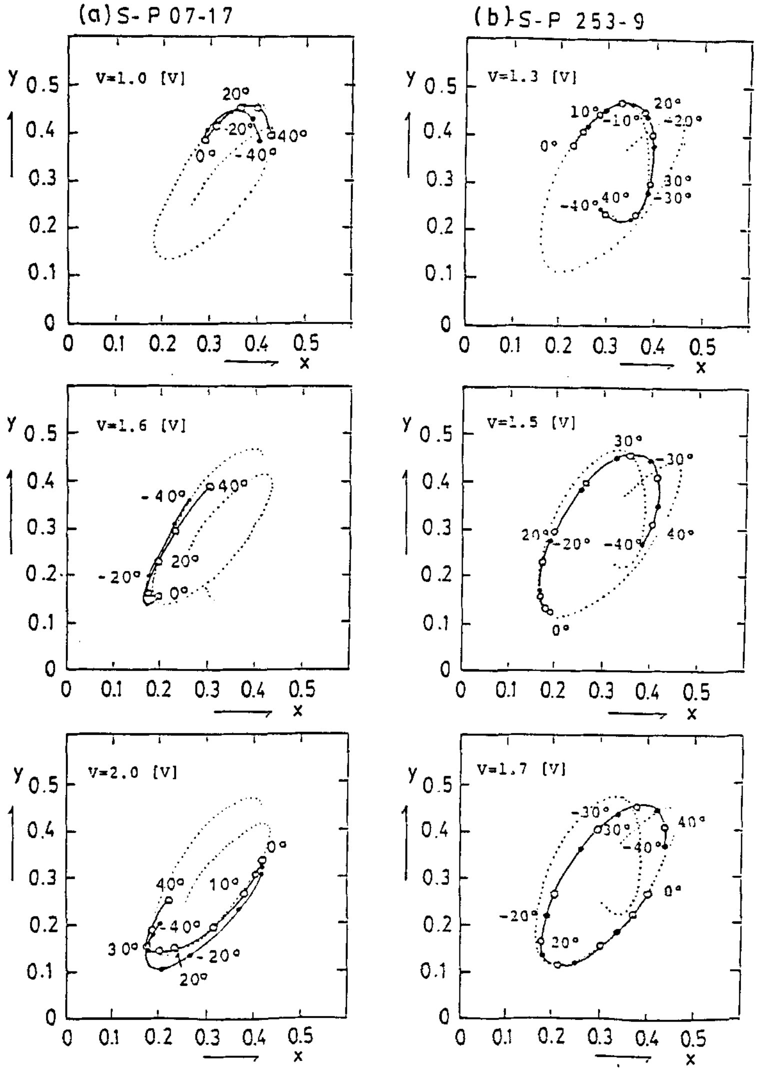


FIGURE 14 Variation of chromaticity with ϕ_i which were varied in a plane normal to the plane including the directors.

It was found experimentally that when the incident light beam lies in the plane normal to the plane including the directors, the purity of displayed color tends to decrease in the cell having a symmetric configuration like a mirror image, as the incident angle is increased.

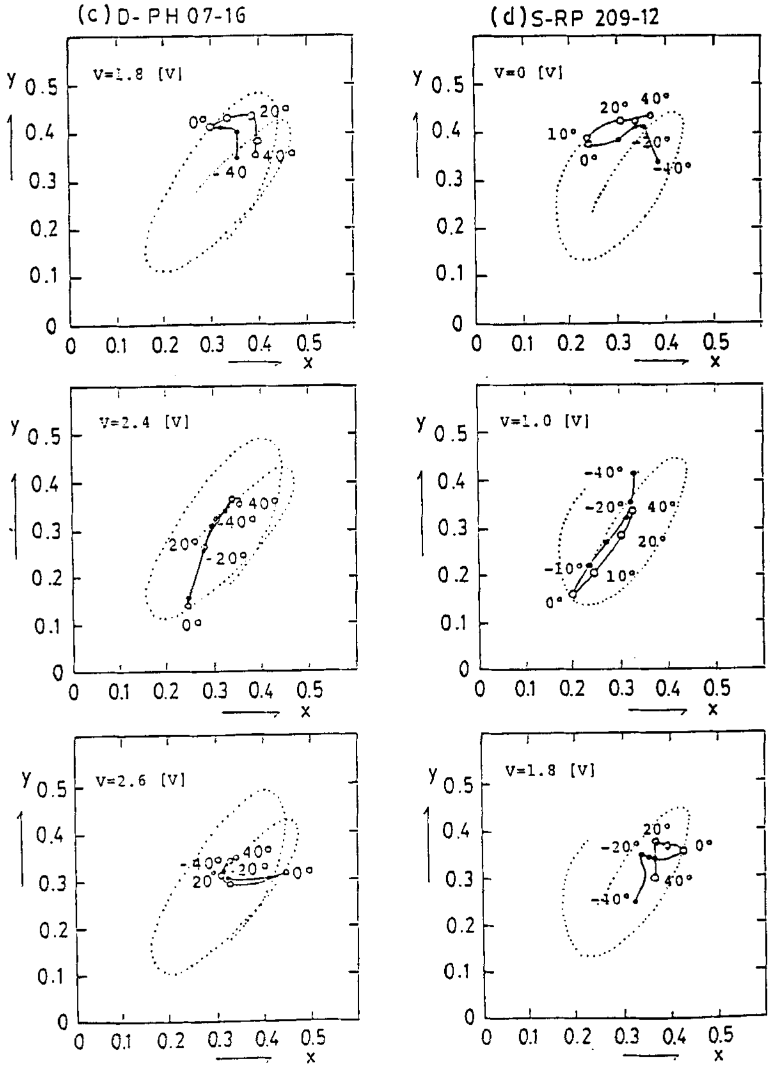


FIGURE 14 (continued)

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