Molecular Crystals and Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl16

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Version of record first published: 28 Mar 2007.

To cite this article: T. Uchida , C. Shishido & M. Wada (1977): Liquid Crystal Color Display Devices with phase Transition, Molecular Crystals and Liquid Crystals, 39:1-2, 127-138

To link to this article: http://dx.doi.org/10.1080/15421407708083915

Mol. Cryst. Liq. Cryst., 1977, Vol. 39, pp. 127–138

Printed in Holland

Liquid Crystal Color Display Devices with Phase Transition

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(*Received May 27, 1976; in final form October 26, 1976*)

The liquid crystal cell used a cholesteric-nematic mixture with positive dielectric anisotropy (CN cell) has a cholesteric phase at the off-state when molecules of liquid crystals near the electrode surfaces were aligned perpendicular to them by using surface treatment.

The cholesteric phase at the off state has rotatory dispersion, characteristic of the cholesteric phase. Then, by putting the CN cell between two polarizers, transmitted light is colored. On the other hand, the CN cell is clear (and optically inactive) at the on-state.

Thus, by stacking the CN cell and the usual twisted nematic cell, a combination of the on- and the off-state of two cells can display two colors, black and white. This paper describes the experimental results of the new devices.

1 INTRODUCTION

As is generally known, liquid crystal cells with the cholesteric–nematic phase transition (hereinafter abbreviated as CN cell) change their own states corresponding to the applied voltage V_l below or V_h above the threshold voltage as shown in Figure 1.

When the electrode surfaces of liquid crystal cells are previously treated so as to obtain parallel or perpendicular molecular alignment (abbreviated

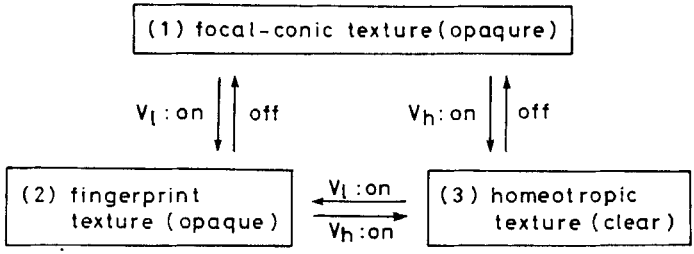

FIGURE 1 State changes of the former phase-transition-type cell.

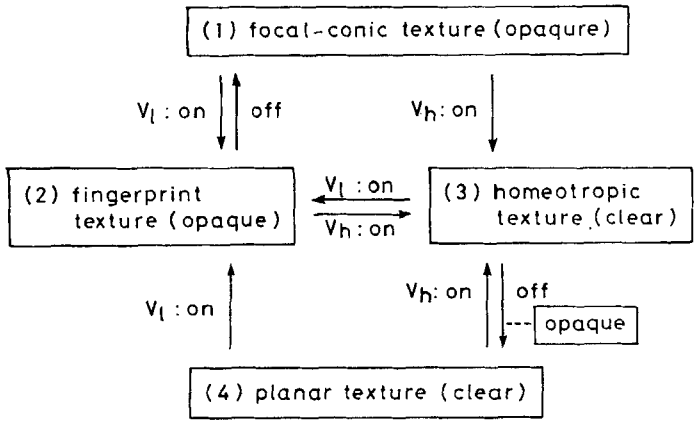

FIGURE 2 State changes of the parallel treatment cell.

V_l: A voltage below the threshold voltage for phase transition
V_h: A voltage above the threshold voltage for phase transition

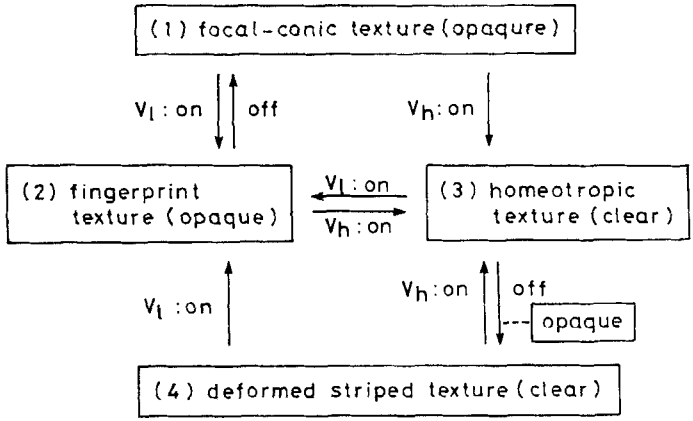

FIGURE 3 State changes of the perpendicular treatment cell.

V_l: A voltage below the threshold voltage for phase transition
V_h: A voltage above the threshold voltage for phase transition

as parallel-treatment cell and perpendicular-treatment cell, respectively), these liquid crystal cells have four states as shown in Figures 2 and 3.[1,2] In the state (4) in Figure 3, a vortical domain pattern can be seen, and the molecular alignment near the electrode surfaces seems to be a deformation of the striped texture reported by Cladis and Kleman.[3] Therefore, we call this state deformed striped texture.

As described in the previous papers,[1,2] both cells show two states, (1) and (4), are stable at the off-state. State (1) is opaque and state (4) is clear. Thus the change of the states is applicable to a memory-type display device. But after the applied voltage V_h is removed in state (3) in both cells, they switch over to state (4) through an opaque state. The switching time from state (3) to state (4) in the parallel-treatment cell is several tens times longer than that in the perpendicular-treatment cell.

Then in this paper a new color display device is proposed by using existence of optical activity in the clear states (3) and (4) in the perpendicular-treatment cell.

2 OPERATION PRINCIPLE

In the CN cell containing a cholesteric–nematic mixture with positive dielectric anisotropy, the state (4) shown in Figure 3 has an optical activity which is characteristic of the cholesteric phase, and its rotation angle is dependent on the wavelength of incident light as shown in Figure 4.

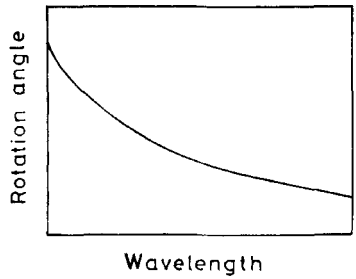

FIGURE 4 Wavelength dependence of rotation angle in the CN cell.

When this CN cell is inserted between two polarizers P_1 and P_2 as shown in Figure 5, the transmittance changes oscillatorily with the wavelength of incident light. The maximum and the minimum of the transmittance appear at the wavelengths given by the following relations:

$$\alpha(\lambda) = \theta + n\pi \quad \text{for maximum,} \tag{1}$$

$$\alpha(\lambda) = \theta + (n + \tfrac{1}{2})\pi \quad \text{for minimum,} \tag{2}$$

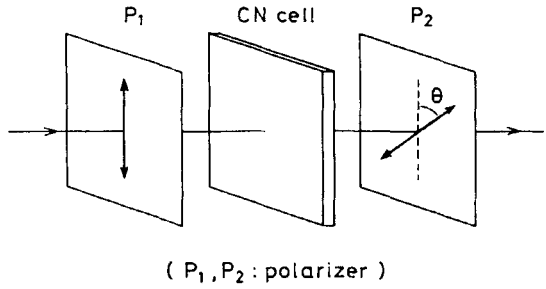

FIGURE 5 Arrangement of CN cell and polarizers.

where $\alpha(\lambda)$ is the rotation angle at the wavelength λ, θ is the angle between the directions of polarization of the two polarizers and n is an integer.

These relations suggest feasibility of a color display device and its displayed color depends upon the angle θ. Multicolor display is possible by combining a CN cell and a TN cell which can effectively switch the angle θ by applying voltage.

As is well known, the structure of the TN cell is such that without the applied voltage, the surface layers of the liquid crystal are homogeneously aligned, but there is a twist angle of 90° between the two surfaces, as shown in Figure 6(a). Then, polarization of incident light is rotated by 90° by transmitting through the TN cell. An applied voltage above the threshold voltage causes the nematic directors to be untwisted and to align parallel to the applied field as shown in Figure 6(b). Thus the incident light can transmit through the TN cell without rotation of its polarization.

Therefore, we can obtain a two color display device because the on-state and the off-state effectively correspond to $\theta = 0°$ and $\theta = 90°$, respectively. When the CN cell is in the state (3) shown in Figure 3 under the applied field, it has no optical activity and so black-and-white display can be obtained similar to that given by the TN cell only.

Multicolor displays can also be realized by combining a CN cell and TN cells with different twist angles.

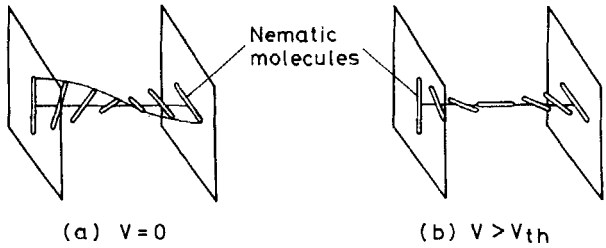

FIGURE 6 Schematic view of twisted nematic effect.

3 EXPERIMENTAL RESULTS AND DISCUSSION

3.1 CN cell

The following mixture of liquid crystals was used in the CN cell:

p-methoxybenzylidene-*p'*-*n*-butylaniline	45.0 wt%
p-ethoxybenzylidene-*p'*-*n*-butylaniline	31.5 wt%
p-ethoxybenzylidene-*p'*-aminobenzonitrile	13.5 wt%
cholesteryl oleyl carbonate	10.0 wt%

The electrode surfaces of the cell were coated with lecithin to obtain perpendicular alignment. The cell was of sandwich-type with the spacer of mylar 12 μm thick. The threshold voltage was about 30 volts for the cholesteric–nematic phase transition.

The wavelength dependence of the rotation angle measured in this cell is shown in Figure 7. When this cell was inserted between two polarizers

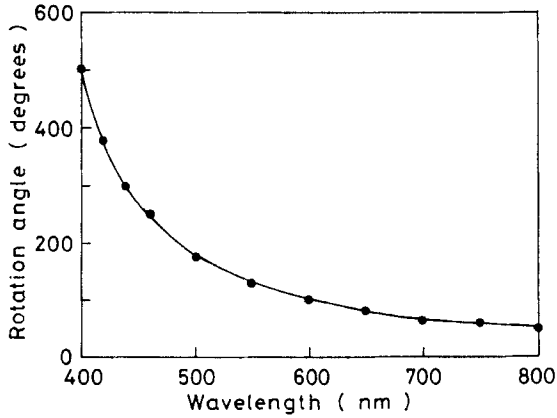

FIGURE 7 The experimental result of wavelength dependence of rotation angle.

P_1 and P_2 as shown in Figure 5, the relation between transmittance and wavelength was measured for several parameters of θ as shown in Figure 8. Figures 7 and 8 support Eqs. (1) and (2). Displayed colors for each value of θ are summarized in Table I.

3.2 Color display characteristics of the composite cell

A composite system of a CN cell and a TN cell with 90°-twist angle (abbreviated as TN_{90} cell) shown in Figure 9 gives a characteristic shown in Figure 10 when white light was applied to it. In this figure, the solid lines 1 and 2 are at

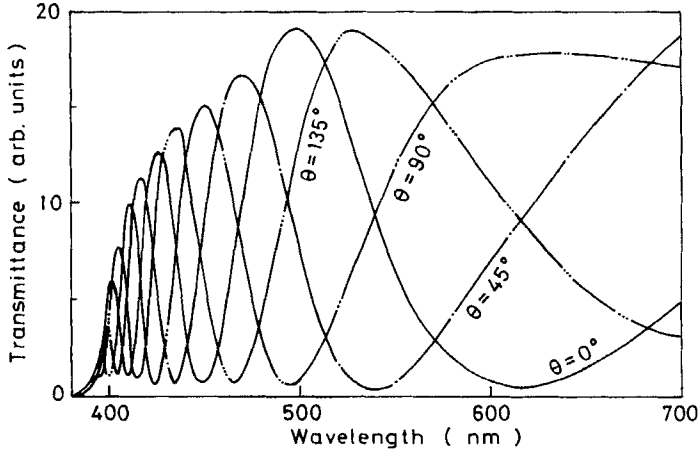

FIGURE 8 Wavelength dependence of transmittance.

TABLE I

Relation between θ and displayed color.

θ	Displayed color
0°	greenish blue
45°	pink
90°	yellowish orange
135°	yellowish green

the off-state of the CN cell and correspond to the characteristic lines $\theta = 0°$ and $\theta = 90°$ in Figure 8.

For an example of multicolor display devices, Figure 11 shows a composite system consisting of a CN cell and two TN cells with 45°-twist and 90°-twist angles. The TN cell with 45°-twist angle is denoted by the TN_{45} cell. In the composite system the TN cells must be carefully arranged, because they can

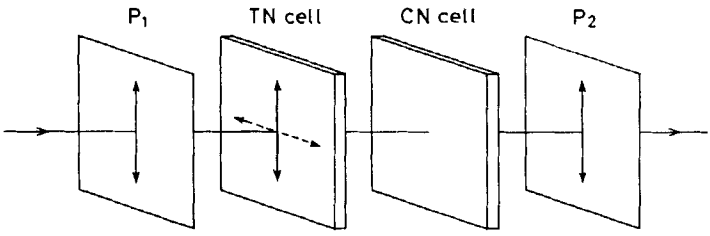

FIGURE 9 A combined system composed of a CN cell and a TN cell.

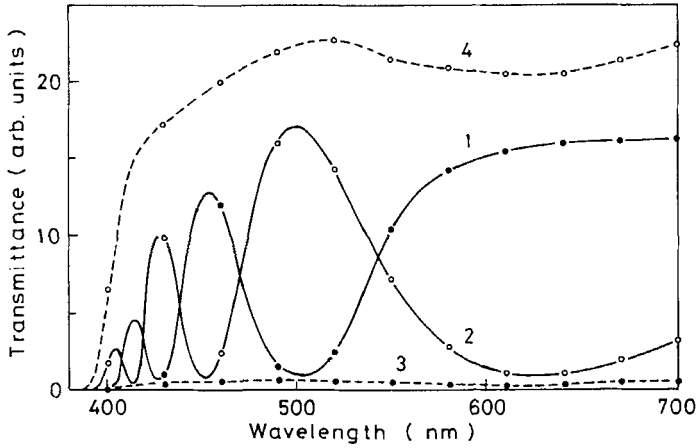

FIGURE 10 Spectral transmittance of the combined system with TN_{90} cell.

Curve	CN cell	TN cell	Displayed color
1	off	off	yellowish orange
2	off	on	greenish blue
3	on	off	black
4	on	on	white

rotate the polarization plane of the incident light as much as their twist angles only when the direction of polarization is parallel or perpendicular to the molecular alignment on the substrate at the incident side.

This composite system effectively has four values of θ as shown in Table II. Figure 12 shows spectral transmittance characteristics of this composite system. Four characteristic curves 1, 2, 3 and 4 correspond to those 135°, 90°, 45° and 0° in Figure 8, respectively. Little fluctuations can be seen in Figure 12, which seem to be due to birefringence. In this composite system, black-and-white display can also be obtained by applying a voltage to the CN cell.

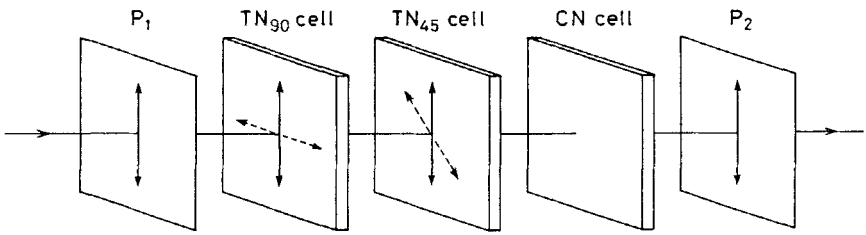

FIGURE 11 Combined system composed of two TN cells.

TABLE II

Total twist angle of incident polarized light at on- and off-states of TN cells.

TN_{90} cell	TN_{45} cell	Total twist angle	Effective θ
off	off	45°	135°
off	on	90°	90°
on	off	135°	45°
on	on	0°	0°

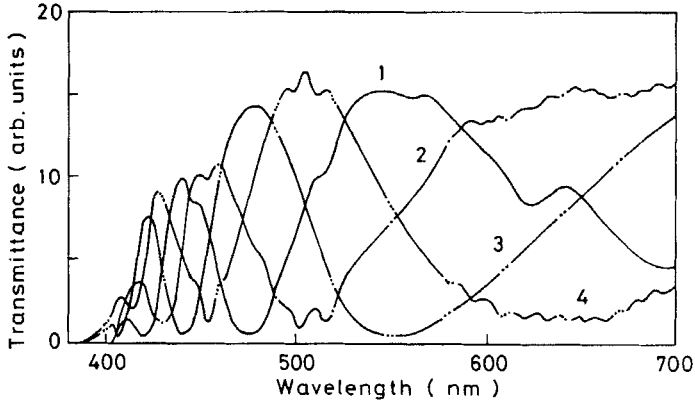

FIGURE 12 Spectral transmittance of the combined system with two TN cells. (CN cell: off).

Curve	TN_{90} cell	TN_{45} cell	Displayed color
1	off	off	yellowish green
2	off	on	yellowish orange
3	on	off	pinc
4	on	on	greenish blue

3.3 Viewing angle dependence of displayed colors

As described above, the spectral characteristics of the rotation angle have one to one correspondence to spectral transmittance of the cell. Then the viewing angle dependence of displayed colors can be understood by measuring the viewing angle dependence of the rotation angle. The results obtained are shown in Figure 13. The feature that the viewing angle is wider than that in the DAP-type color display device,[4–8] can be seen in this figure, because no remarkable change of the characteristics is observable at the angle of inclination of the CN cell up to 20 ~ 30°.

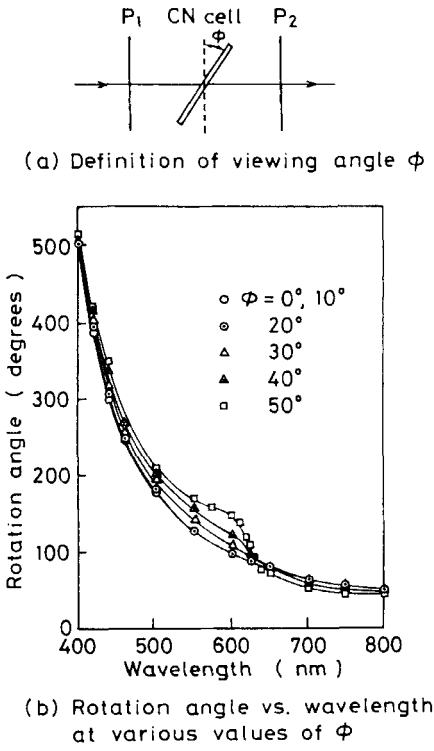

FIGURE 13 The effect of viewing angle to rotation angle.

3.4 Temperature dependence of the rotation angle

The temperature dependences of rotation angle are shown in Figure 14. In the figure (b), the arrow expresses the liquid crystalline–isotropic phase transition temperature T_{L-I}. The remarkable changes can be seen as the temperature is near T_{L-I}. Therefore, less temperature dependence of displayed colors at about room temperature can be obtained by using a mixture of liquid crystals with high T_{L-I}.

3.5 Response and recovery characteristics

Figure 15 shows the response and recovery characteristics, in which the applied voltage is 50 V and square wave of 50 Hz.

In the recovery characteristic shown in Figure 15(b), transmittance decreased just after removing the applied voltage, but the deformed striped texture is observable after several seconds, which has high transmittance and

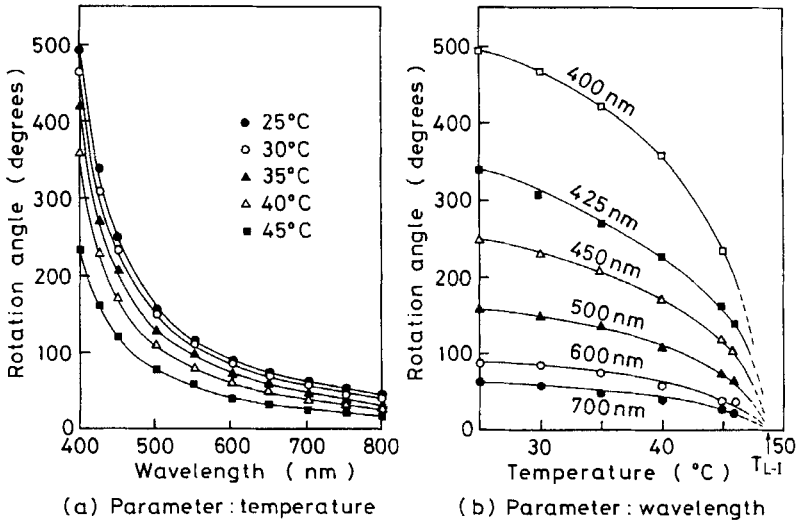

FIGURE 14 Effect of temperature to rotation angle.

is shown in Figure 3-(4).[2] This is because the opaque state of the focal-conic texture appears just after removing the applied voltage.

When the proper composition of the mixed liquid crystals with less cholesteric liquid crystal, that is,

p-methoxybenzylidene-*p'*-*n*-butylaniline	77.6 wt%
p-hexyloxybenzylidene-*p'*-aminobenzonitrile	19.4 wt%
cholesteryl propionate	3.0 wt%

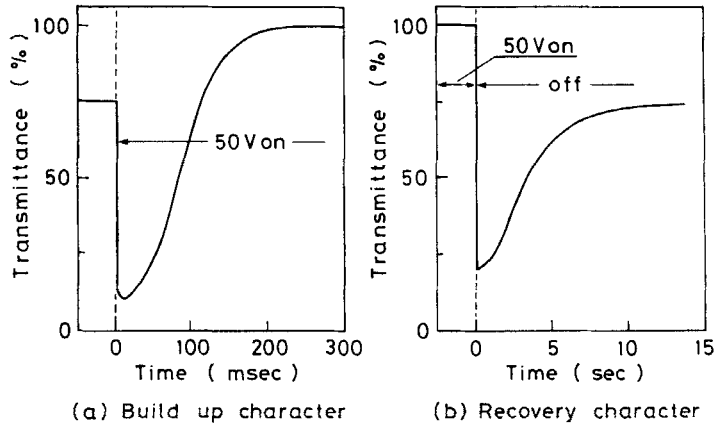

FIGURE 15 Response characters of CN cell.

is used in the cell with the surface treatment by using stearyltrichlorosilane[9] the threshold voltage of the phase transition is about 9 volts and the response and the recovery characteristics are shown in Figure 16. This figure shows considerably fast recovery. But the deformed striped texture in this cell has a little transmittance. Further studies shall be reported in detail on this subject in the near future.

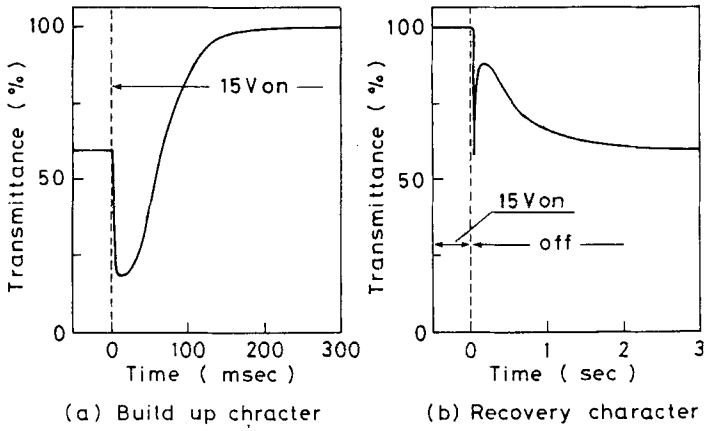

FIGURE 16 Response characters of the sample with less concentration of the cholesteric material.

4 CONCLUSION

A new color display device was suggested by using optical activity in a liquid crystal cell with cholesteric–nematic phase transition, which was surface-treated for homeotropic alignment.

This cell has the following features compared with a DAP cell.

1) Viewing angle is wide.

2. Surface treatment is easily compared with the DAP cell using a Nn-type nematic liquid crystal,[4–6] in which voltage induced molecular alignment must not be random parallel.[10]

3) Black display is possible, different from the DAP cell with a Np-type nematic liquid crystal aligned homogeneously.[7,8] Such a DAP cell is difficult to display real black, because retardation does not reduce to zero, even if considerably high voltage is applied.

A multicolor display device can be made by composing the CN cell and the TN cell. Samples used in our studies have about 30 volts of threshold

voltage and the recovery time is long. These defects can be removed to some extent by using a mixture of liquid crystals with less cholesteric liquid crystal and by surface-treating the electrode surface with silane. The spectral characteristics of optical activity depends upon the thickness of the liquid crystal layer, the kind of mixed liquid crystals and their content ratio. Displayed colors can be selected by controlling these parameters.

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