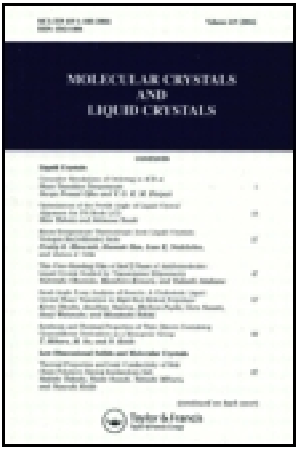

Molecular Crystals and Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl18

Current Status of Dichroic Liquid Crystal Displays

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Version of record first published: 24 Sep 2006.

To cite this article: B. Bahadur (1991): Current Status of Dichroic Liquid Crystal Displays, Molecular Crystals and Liquid Crystals, 209:1, 39-61

To link to this article: http://dx.doi.org/10.1080/00268949108036178

Mol. Cryst. Liq. Cryst., 1991, Vol. 209, pp. 39–61
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Printed in the United States of America

Current Status of Dichroic Liquid Crystal Displays†

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(Received September 3, 1990)

This paper reviews the operational principle, construction and electro-optical performance of various types of dichroic liquid crystal displays such as Heilmeier, phase change, dye doped TN and polymer dispersed dichroic. It also discusses the double layer and positive mode dichroic LCDs. The impact of material properties such as birefringence, dielectric anisotropy, viscosity, elastic constant and cell construction such as alignment, cell gap, etc., on the electro-optical performance of these displays has been mentioned. The contrast ratio, viewing angle, switching speed, etc., of Heilmeier, phase change and dye doped TN have been discussed. The data indicate dye doped TN to be a display with very high contrast (>100:1) and a much wider viewing angle compared to TN display. The colour shift with viewing angle is also found to be much less for dye doped TN than for normal TN liquid crystal displays. Some of the applications of current dichroic displays are shown, and potential future applications are suggested.

1. INTRODUCTION

Dichroic liquid crystal displays,[1,2] though discovered earlier than TN displays,[3] did not get the same market response or applications as TN displays.[4] The reasons for this are problems associated with dichroic dyes and limited or almost no intrinsic multiplexing capability of most of the prominent dichroic LCDs, making them unsuitable for low cost high information content displays.[4] Thus they are basically limited to direct driven low information content applications. Recently the phase-change type dichroic LCDs have received acceptance for applications in military and avionics due to their much wider viewing angle and capability of exhibiting white characters on a black background. The present market for dichroic LCDs including drive electronics in some cases, is estimated to be 30 million US dollars at present. The growth rate is expected to be > 15% per annum. The major market sectors for dichroic LCDs constitute avionic and military. They are also being used in some consumer and industrial applications.

If a small amount of elongated dye is mixed in liquid crystal, the dye molecules

† Paper presented at the 13th International Conference on Liquid Crystals, held at Vancouver, Canada, July 23–27, 1990.

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get aligned in the liquid crystal matrix and hence can be oriented from one position to another along with the liquid crystal molecules on application of electric field. The phenomena of aligning the impurity or guest molecules is called guest-host interaction.[1,2] A small amount of these dichroic dyes are dissolved in a liquid crystal mixture to form a dichroic mixture, which absorbs the light.[5] With proper surface treatment in one state (quiescent or activated) the dichroic mixture does not absorb light while in the other state it does (Figure 1). The application of electric field results in a clear state if quiescent state is absorbing or in an absorbing state if the

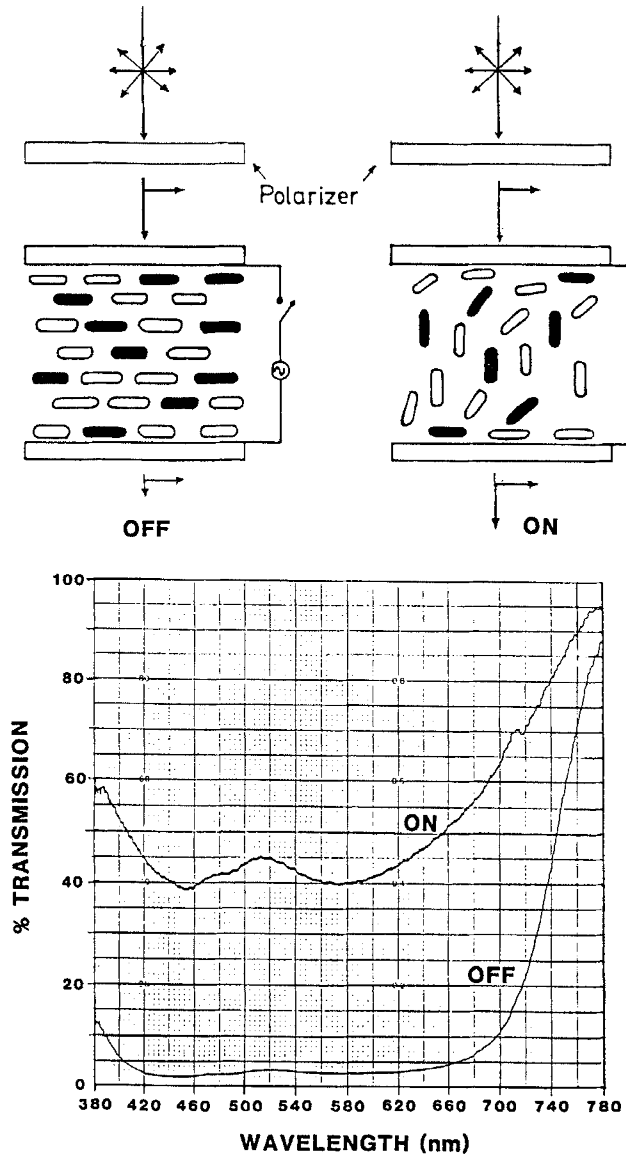


FIGURE 1 Operational principle of Heilmeier LCDs.

quiescent state is clear. This is the basis of all dichroic displays.[5-8] The absorption is usually increased with the help of the polarizer or by the addition of a suitable amount of chiral dopant in nematic host.[8] The most popular dichroic displays are dichroic phase change effect[8] (also called White-Taylor mode)[8] displays and Heilmeier type dichroic LCD.[1,2,6] Besides these, quarter wave plate dichroic,[9-11] double cell guest-host dichroic,[12-15] dye doped TN,[16,17] supertwisted dye effect,[18,19] dichroic ferroelectric,[20-22] and polymer dispersed dichroic[23,24] may be also regarded as dichroic LCDs.

2. DICHROIC DYES

Dichroic dyes usually have cylindrical symmetry. Normally the transition moment of dyes have their major component along the long molecular axis (pleochroic) or short molecular axis (negative dichroic). Pleochroic (or positive dichroic) dyes absorb the E vector of light which is along the long molecular axis of the dye while negative dichroic dyes absorb the E vector of light which is perpendicular to the long molecular axis.[7,25] Usually these dyes have a narrow absorption spectrum, the maximum absorption wavelengths designated as λ_{max}. The colour seen is basically the light which is not absorbed by the dye or the complimentary colour. To make a black mixture one has to use several dyes having different λ_{max}.[46-50] The dyes used in cloth and other industries normally cannot be used in LCDs as we need non-ionic dyes to avoid electrochemical degradation and reduce the current consumption. Moreover, the dyes have to be chemically and photochemically stable and elongated in shape. The usefulness of dichroic dyes in guest-host dichroic displays are determined by the following properties[5,6,25-42]:

i) Chemical and photochemical stability of the dye.[7,30,43-45]
ii) Colour or hue
iii) Spectral width (measured as half width)
iv) Absorbability
v) Dichroic ratio
vi) Order parameter of the dye
vii) Solubility of the dye in host
viii) Influence of the dye on the viscosity of the host
ix) Nonionic nature

These parameters have been discussed in detail by the author and several other workers.[5,6,25-45] In general it has been found that dye order parameter increases with increase in length of the dye while it decreases with increase in breadth of the dye. The dye order parameter is heavily dependent on the host. Usually it increases with increase and decreases with decrease in host order parameter. Elongated dyes are found to have higher order parameter while shorter dyes have lower order parameter than the host. Elongated dyes are also found to withstand thermal fluctuations better at higher temperature and hence show less variation in order parameter compared to the host, with increase in temperature.[25] The solubility of dyes differ in different hosts. The viscosity of host increases with increase in dye doping. The dielectric anisotropy, elastic constants and refractive indices of dichroic mixtures are basically those of the host.

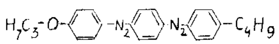
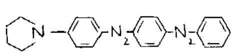
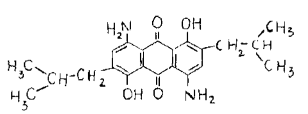
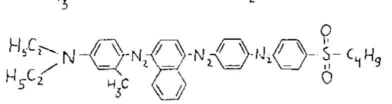
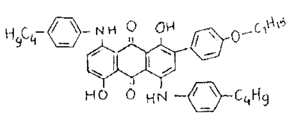
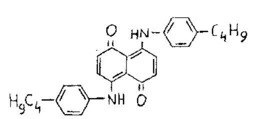
The most widely used dichroic dyes in LCDs fall basically into two classes (Table I) from a chemical structure point of view—first, azo dyes and second anthraquinone dyes.[25,27,51] Anthraquinone dyes, in general, have much higher chemical and photochemical stability but have lower order parameter and solubility compared to azo dyes. There has been significant improvements in these areas recently.[5] Besides these naphthaquinone, merocyanine, tetrazine, etc dyes have also been investigated.[27,52,53] Most of the dyes used are pleochroic dyes as they exhibit higher dichroic ratio and order parameter. Attempts have also been made to synthesize liquid crystalline dyes which exhibit liquid crystalline as well as dichroic dye properties.[51–53]

3. HEILMEIER DISPLAYS

The Heilmeier display was the first discovered of all the dichroic displays and can be made in transmissive, reflective and transflective forms by proper choice of the reflector. Its contrast ratio is heavily dependent on the polarization efficiency of

TABLE I

Structure and parameter of some dichroic dyes.

	λmax (nm)	Order Parameter by height	by area	from lit.	Intensity @ 1%	Half Width (nm)	% Solubility
	391	0.79	0.83	0.75	2.16	68	>3
	492	0.73	0.73	0.72	2.67	128	>1
	541	0.60	0.45		0.62	95	>1
	593	0.75	0.75	0.74	2.11	169	<1.5
	669	0.72	0.63	0.71	1.27	118	>3
	705	0.71	0.69		0.43	108	>0.5

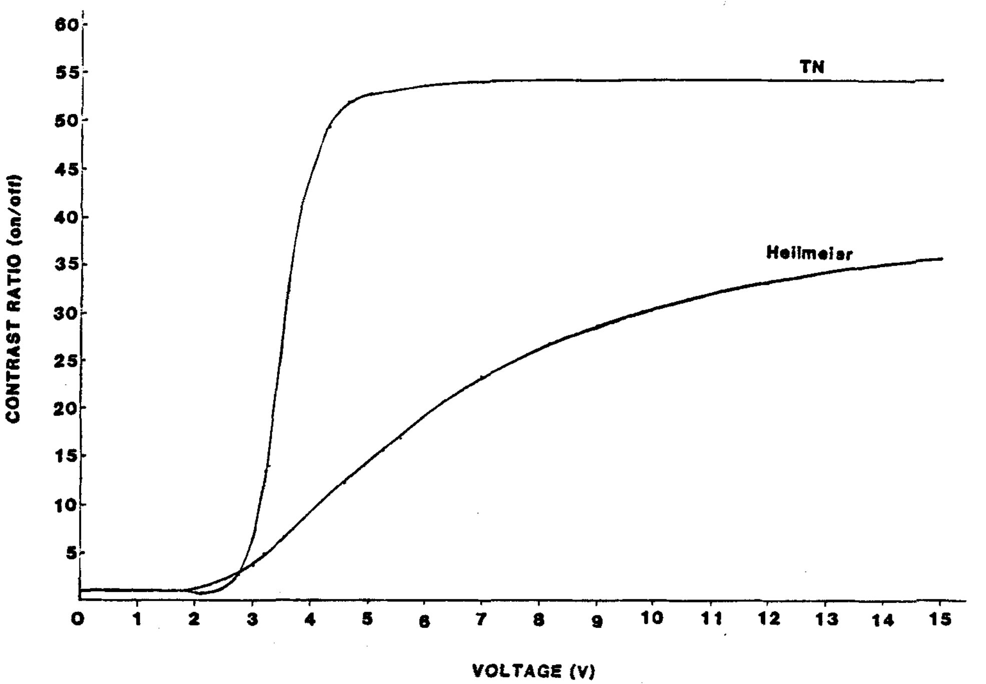


FIGURE 2 Threshold characteristics of a Heilmeier and TN displays.

the polarizer, hence high efficiency polarizers with good transmission should be used. Heilmeier displays use unidirectional homogeneous alignment and can be fabricated with 0 or 90° twist.[6,17] The host liquid crystal has a positive dielectric anisotropy and dyes are pleochroic. This display requires only one polarizer mounted with its polarization axis along the long molecular axis of the dyes in l.c. mixture. The polarizer can be mounted on the front or back of the display. The light after passing through the polarizer gets polarized with its E vector along the long molecular axis of the dye and hence gets absorbed. The cell looks dark coloured or black depending on dyes used. When the electric field is applied, liquid crystal molecules along with the dyes get aligned in the direction of the field. In this mode the E vector of the light is perpendicular to the long molecular axis of the pleochroic dye and light is not absorbed. The operational principle of Heilmeier displays is shown in Figure 1. Some papers on theoretical analysis of Heilmeier displays have appeared recently.[54–56] Although doping of cholesteric is not necessary, occasionally (especially for 90° twist geometry) it is done.

3.1 Threshold Characteristic

The threshold characteristic of a Heilmeier display along with that of a TN display are plotted in Figure 2. Figure 2 shows that TN displays get saturated and achieve maximum contrast at lower voltage, and the threshold characteristic is steeper.[17] In the case of TN displays contrast ratio remains flat after saturation. In the case of Heilmeier displays the contrast ratio continues increasing with increasing voltage

TABLE II

Contrast ratio of Heilmeier, dye doped TN and TN display.

	HEILMEIER		DYE DOPED TN		TN	
VIEW. ANGLE (°)	TRANSMISSION (%)	CONTRAST RATIO ON/OFF	TRANSMISSION (%)	CONTRAST RATIO ON/OFF	TRANSMISSION (%)	CONTRAST RATIO ON/OFF
0	18.5	35.1	30.2	94.2	34.5	81.6
10	17.8	36.3	29.3	92.2	28.6	75.4
20	17.6	39.1	28.7	92.1	28.7	63.2
30	16.8	43.2	26.3	84.7	27.9	43.2
40	15.2	44.2	23.7	61.9	23.3	25.3
50	12.6	41.8	23.3	40.5	20.8	14.3
60	10.3	38.0	20.2	26.1	20.3	8.5
-10	18.2	35.0	31.8	101.5	34.7	82.7
-20	17.7	36.9	27.5	122.9	29.5	72.4
-30	16.5	38.9	24.4	129.4	29.1	48.0
-40	13.5	39.1	19.6	92.8	24.7	26.2
-50	10.1	35.8	17.9	51.5	22. 4	15.7
-60	7.7	34.9	15.7	29.3	21.8	9.7

after becoming almost saturated. The reason for this may be the fact that TN is based on the capability of rotating plane polarized light and once the central layer is aligned with the field, it is unable to rotate the plane of polarization of light and TN has full contrast, while the contrast in Heilmeier display is based on the alignment of more and more dichroic layers in the direction of the field. The central layer gets aligned quickly after the threshold voltage, but layers in the vicinity of the glass plates get more and more aligned only with increasing field.

Figure 2 (and Table II also) shows that for optimized cell thickness with present dyes, both the contrast ratio and brightness are lower in Heilmeier displays than in TN displays. One can always match the contrast of Heilmeier displays to that of TN displays by increasing the amount of dyes in the mixture, but the transmission goes down drastically. If transmission is matched, then the contrast ratio of Heilmeier displays goes down.[5] With increasing viewing angle, we find both the contrast and transmission go down drastically in TN displays while these are affected little in Heilmeier displays (Table II). Hence, Heilmeier displays have a much wider viewing angle than TN displays.

3.2 Effects of Dye Concentration on Electro-optical Parameters of Heilmeier Displays

With increase in dye concentration, the contrast ratio of the Heilmeier display increases while its transmission goes down.[17] The switching time of the display also increases a little due to the increase in viscosity of the liquid crystal. This increase in switching time becomes more significant at lower temperature and very often restricts the lower operating temperature of the display. The threshold voltage does not seem to be affected significantly with increase in dye concentration. Figure 3 shows the dependence of the electro-optical parameter of Heilmeier display on the dye concentration. From the figure one can see that contrast ratio increases exponentially with increase in dye concentration while transmission shows more or less a linear decrease. This means that with small increase in dye concentration one can get a high contrast without heavy loss in transmission.

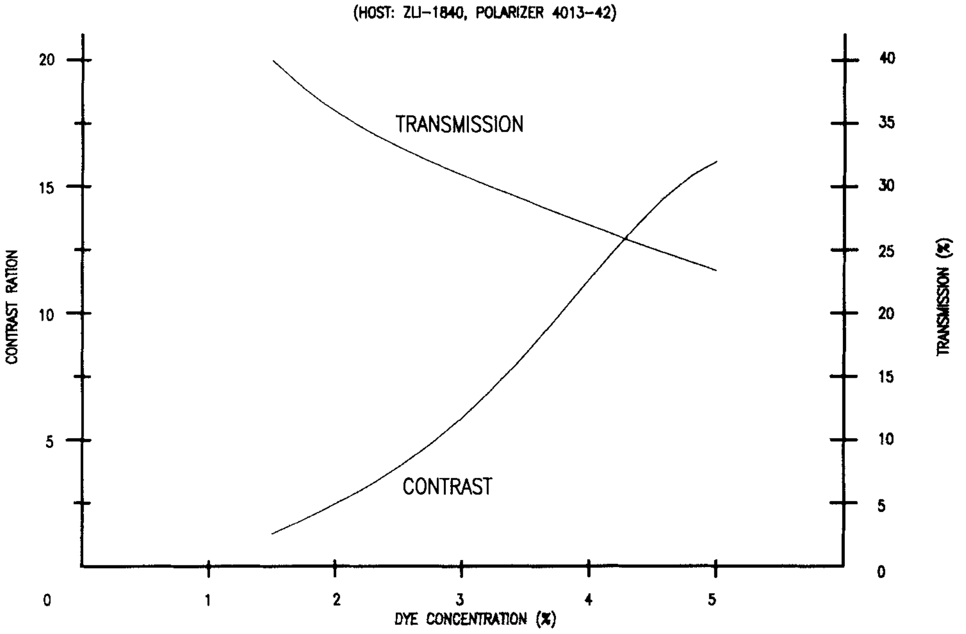


FIGURE 3 Dependence of contrast ratio and transmission of Heilmeier display on dye concentration.

3.3 Effect of Alignment

The 90° aligned cells are found to have sharper threshold characteristic compared to that of a 180° cell. However, 180° twist cells produce slightly higher contrast ratio. 180° twist cells seem to have better threshold characteristic from grey scale application point of view.

3.4 Effect of Thickness

Figure 4 exhibits the effect of cell thickness on threshold characteristic. Cells with smaller cell gap have lower threshold and operating voltages. It has also been found that for an increase in cell thickness from 5- to 8-μm a significant gain in contrast ratio (~2.5 times) is achieved with a small loss in transmission (5% overall and 20% of the initial transmission).

As mentioned earlier, the molecules near the surface do not get aligned with the field due to strong surface anchoring. So even in excited state, this layer would absorb and would therefore reduce the overall contrast of the display. The ratio of this inactive layer vs. the active central layer, which can be aligned by the field, should be kept small. The increased dye concentration, with increase in cell thickness, increases the contrast ratio tremendously. However it reduces the % transmission and increases the switching time.

3.5 Impact of Order Parameter

As predicted from theory, the order parameter has a dramatic impact on the contrast ratio.[5,17,54–56] The order parameter of the dye is the only parameter which increases both the contrast ratio and transmission drastically.[5,17,54–56]

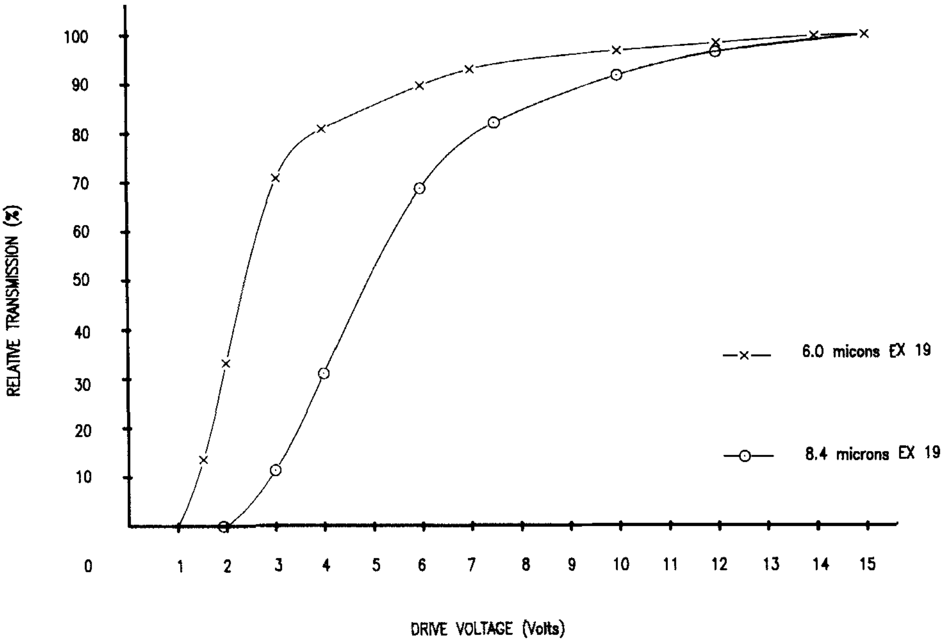


FIGURE 4 Effect of cell thickness on threshold characteristic of Heilmeier display.

3.6 Impact of the Host

As discussed in the dye section, the birefringence, dielectric anisotropy, elastic constant and transition temperature of dichroic mixtures are more or less those of the host. The viscosity of the mixture and order parameter of the dyes are also drastically dependent on host. In choosing the host, one has to select a host with low viscosity, high dielectric anisotropy, wide operating temperature range, low K_{11}, etc.

3.7 Multiplexing of Heilmeier Displays

Heilmeier displays can be multiplexed for low level as threshold characteristic is not sharp enough for high leveling multiplexing. Heilmeier displays also do not show unwanted memory effect. With active matrix displays they can show better grey scale than that of TN displays.

4. QUARTER WAVE PLATE DICHROIC DISPLAY[9–11]

The operational principle of a quarter wave plate dichroic display is shown in Figures 5 and 6. Recently our group has been able to improve the performance of quarter wave plate display dramatically.[10] We have also been able to develop a transflective mode quarter wave plate recently.[11] Quarter wave plate displays are bright and have sufficient contrast. However, their viewing angle is narrow. The

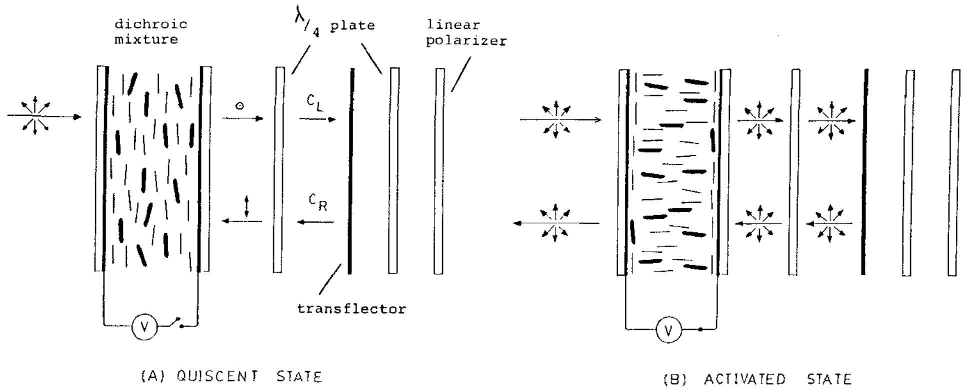


FIGURE 5 Operational principle of a reflective mode quarter wave plate display.

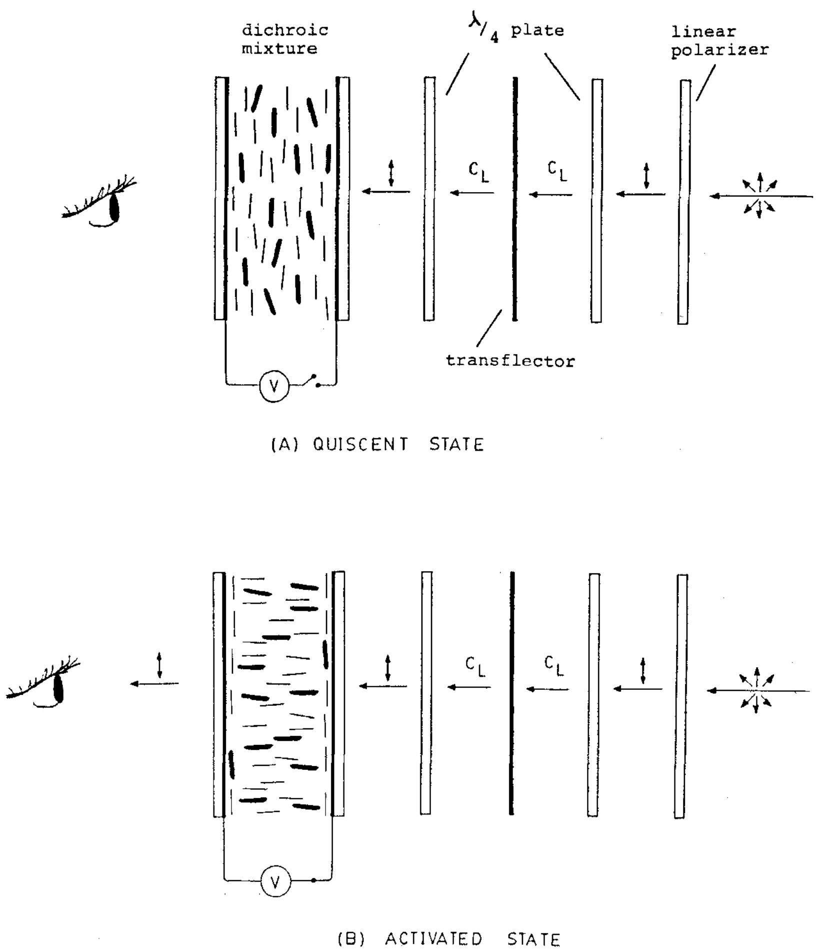


FIGURE 6 Operational principle of a transmissive mode quarter wave plate display.

electro-optical performance of quarter wave plate display is found to be dependent on order parameter and absorption of the dyes. A thicker cell is found to enhance the contrast ratio. However, with increase in thickness, % transmission goes down. Both the contrast and brightness increase with increase in order parameter of the dye.

The quarter wave plate should be kept as thin as possible to increase contrast and reduce shadow effect. Commercially available quarter plate can be made thinner by dissolving the protective polymeric layer in methyl ethyl ketone.[10] The polarizer used should have very high efficiency with good transmission. The metallic reflector or transflector has a great impact on the performance of the cell. Care must be taken in selecting the reflector or transflector so it should not depolarize the light to any significant extent otherwise it will reduce the contrast. Evaporated aluminum coating on the back of quarter wave plate yields good results as reflector of transflector. The contrast ratio of a transflective mode quarter wave display has been found >10:1 in transmissive mode and over 9:1 in reflective mode, which opens its possibly for many applications.[11]

5. DYE DOPED TN DISPLAYS

Dye doped TN has the same cell geometry as TN except for the fact that the liquid crystal fluid is doped with a small amount of dye.[16,17] The addition of dye increases both the contrast ratio and viewing angle. There has been only a few studies reported in the literature about dye doped TN LCDs.[16,17] Most of the results reported here are based on our own studies.[17]

5.1 Threshold Characteristic, Contrast Ratio and Switching Speed

The threshold characteristic of dye doped TN is very similar to that of TN displays (Figure 7). The threshold and operating voltage also increase with increase in thickness. The contrast ratio shows similar effect to Gooch Tarry curve in TN displays.[16,17] The contrast ratio has been found to maximize at first and second Gooch Tarry minima.[16,17] It has been found that the incorporation of dyes broadens the Gooch Tarry minima and also increases the contrast ratio.[16,17] With increase in dye concentration, V_{th} (threshold voltage) does not shift appreciably but V_{op} (operating voltage) does. V_{op} is found to increase with dye concentration. The contrast ratio is found to increase in dye doped TN as compared to TN. Figure 8 shows the viewing angle dependence of dye doped TN compared to TN and Heilmeier i.e., it is better than TN but inferior to Heilmeier at obtuse angles. The contrast of dye doped TN is much higher than both TN and Heilmeier. Table II shows the % transmission and contrast ratio of dye doped TN, TN and Heilmeier displays. From the table it is clear that the incorporation of dye reduces the % transmission slightly, but it improves the contrast tremendously at obtuse angles. This is because of the fact that TN operates on birefringence only while dye doped TN operates on absorption too. It is worth mentioning here, that addition of dye beyond a reasonable limit (~0.5–1%) reduces the contrast ratio of the display.

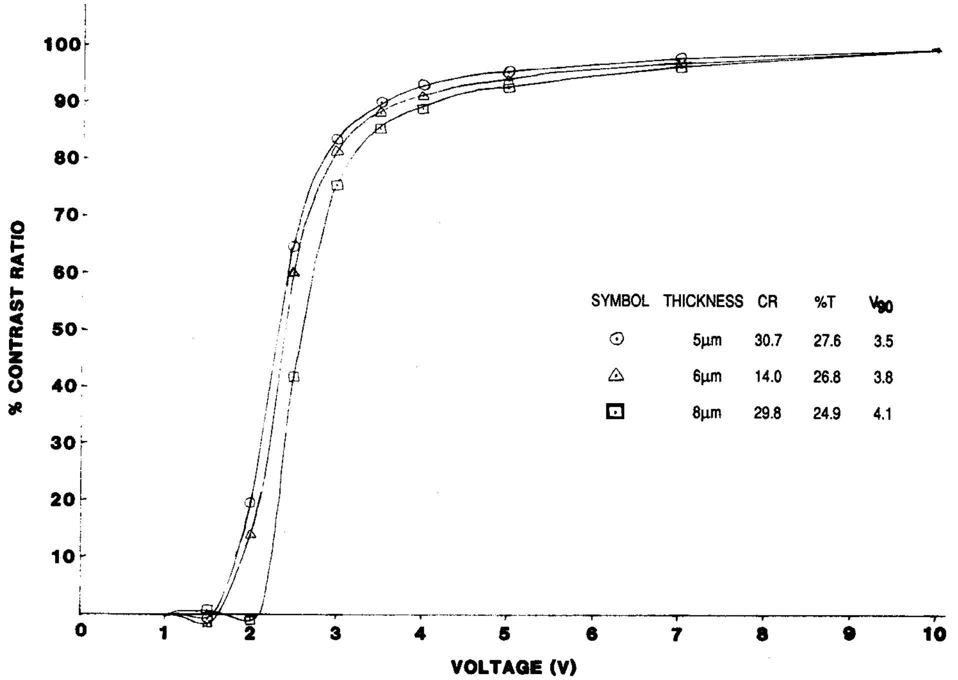


FIGURE 7 Threshold characteristic of a dye doped TN display.

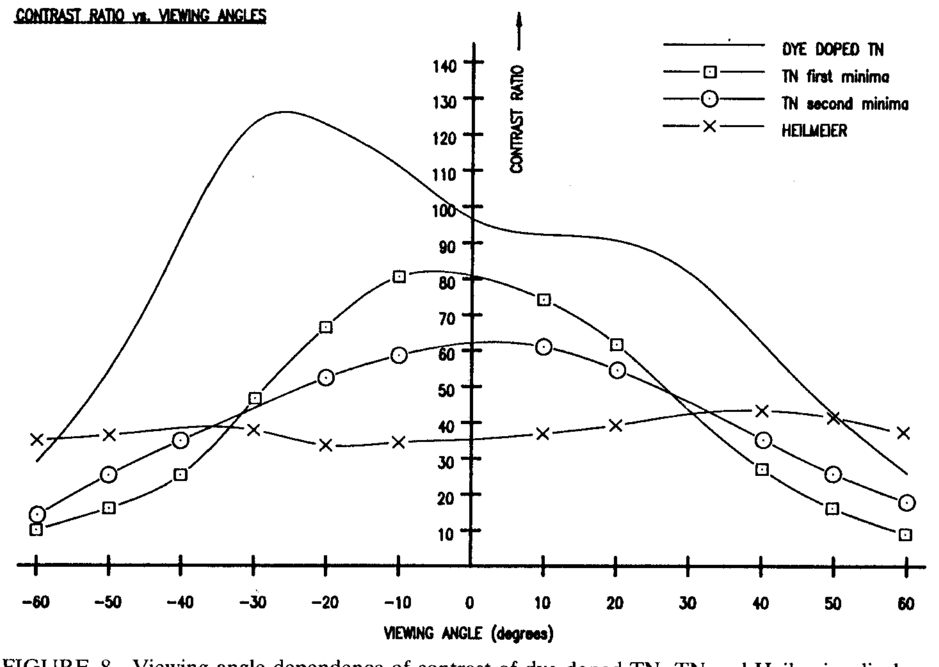


FIGURE 8 Viewing angle dependence of contrast of dye doped TN, TN and Heilmeier displays.

TABLE III

Switching speed of TN, dye doped TN and Heilmeier display.

DISPLAY		Tdelay in on (ms)	Trise (ms)	T_{on} (ms)	Tdelay in off (ms)	Tdecay (ms)	T_{off} (ms)	T_{on} & T_{off} (ms)
Heilmeier Display	0°	15.	25	40	3	63	66	106
(10.38μm)	45°	14.5	24.5	39	3	54	57	96
Dye doped TN	0°	10	26	36	12	29	41	77
(5.00μm)	45°	6	23	29	7	28	35	64
TN	0°	14	23	37	14	28	42	79
(5.00μm)	45°	15	24	39	9	25	34	73

The switching speed of dye doped TN display is also slightly (Table III) more than that of TN, but there is no appreciable difference. However, this difference is found to increase more at lower temperature. To get the best results out of dye doped TN displays the liquid crystal fluid must have low viscosity, appropriate dielectric anisotropy and birefringence. Dyes must have all the advantages already discussed in the Heilmeier display section.

6. PHASE CHANGE EFFECT DICHROIC LCDs

These displays are based on field induced cholesteric-nematic phase transition. The liquid crystal mixture is a long pitch (~2–5 μm) cholesteric material with an appropriate amount (~2–6%) of dichroic dyes. The unpolarized light entering a liquid crystal medium is propagated in polarized modes. For propagation of these modes in a cholesteric liquid crystal, we can have three cases of λ vs p.[6,57–63]

Case I $p \gg \lambda$

In this case the polarized modes follow the twist, and nematic liquid crystal simply behaves as a waveguide.[57,61] In a perfectly ordered system, the dichroic dye dissolved in a long pitch host absorbs only a single component of E vector. In simple terms the initially unpolarized light entering into a dichroic mixture may be divided into two components with the E vector parallel and perpendicular to the long molecular axis of dyes. The parallel component continues to be absorbed while following the liquid crystal rotation, while the perpendicular component basically remains unaltered. The absorption of unpolarized light is only 50% of maximum, limiting the contrast ratio to only 2:1.

Case II $p \simeq \lambda/n$

This case gives rise to iridescent colours due to Bragg reflection.[62,63]

Case III $p \lesssim \lambda/n_e$

This forms the theoretical basis for phase change type dichroic displays. In this case both the normal modes of elliptically polarized light have a component parallel to the local liquid crystal director and the long axis of the dichroic dye. Hence, the unpolarized light can be absorbed more than 50%. The absorption depends on the pitch of the cholesteric, which along with the principal refractive indices $n_{\parallel}$ and $n_{\perp}$, determines the eccentricity of the polarized modes. The other important parameters are the order parameter of the dye, its absorbency, cell thickness (d), etc. The cells are usually prepared with either homogeneous or homeotropic alignment, with cell thickness usually more than 4–5 times the pitch of the dichroic mixture (~2–5 μm). Sometimes hybrid alignment (homeotropic on one plate and homogeneous on the other) is given.

6.1 Threshold Characteristic, V_{th} and Operating Voltage

The threshold characteristic of a phase change dichroic display is shown in Figure 9. With slow increase in voltage, the cell seems to go from Grandjean to a scattering focal conic and from there to nematic texture. Upon reducing the voltage, the same effect is observed in a reverse order. The threshold characteristic shows a noticeable hysteresis. The first threshold is usually for the transition from planar or Grandjean to finger point or focal conic texture and the second threshold is for focal conic to nematic texture. The second threshold is regarded as the threshold for phase transition displays. In homogeneous texture, the molecules are aligned parallel to the glass plates with different layers having different twist depending on their distance from the glass plates. The helix axis is perpendicular to the glass plates and hence is parallel to the applied electric field and light incidents for normal angle. The focal conic texture has helix axes distributed randomly.

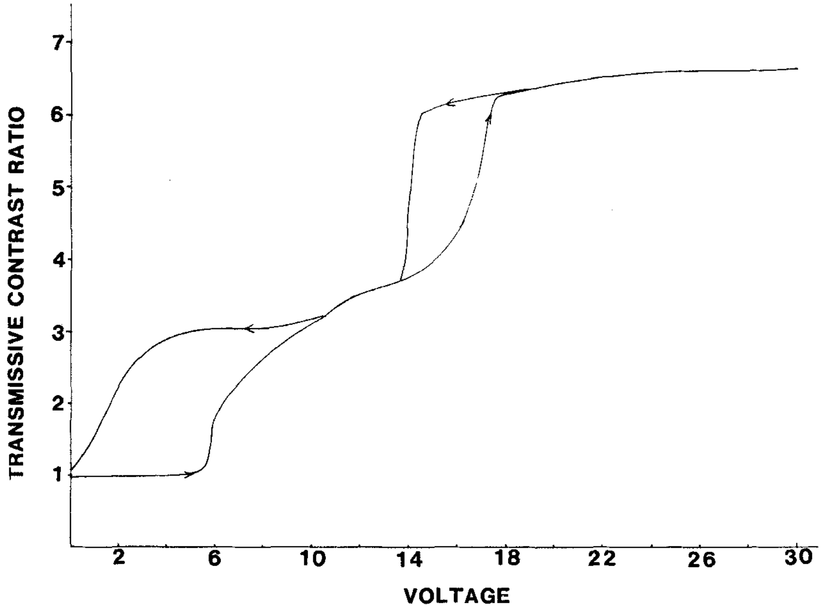


FIGURE 9 Threshold characteristic of a dye phase change (White-Taylor mode) display.

The threshold voltage V_{th} can be calculated from the formulae:

$$V_{th} = \frac{\pi^2 d}{p}\left(\frac{K_{22}}{\Delta\varepsilon}\right)^{1/2} \tag{1}$$

where p is the pitch, d is the cell gap, K_{22} is the twist elastic constant and $\Delta\varepsilon$ is the dielectric anisotropy. The operating voltage is usually 2–3 times that of the threshold voltage. With homeotropic alignment the threshold characteristic shifts towards the lower voltage. Homeotropic alignment generates lower threshold and operating voltage. The equation also shows that threshold and operating voltages are directly proportional to the cell gap and inversely proportional to pitch of the mixture. It is also inversely proportional to the square root of $\Delta\varepsilon$. So to reduce the operating voltage one should reduce the cell thickness and increase the pitch and $\Delta\varepsilon$. However, increasing the pitch reduces the contrast. To get the appropriate contrast and operating voltage d/p is kept ~4–6.

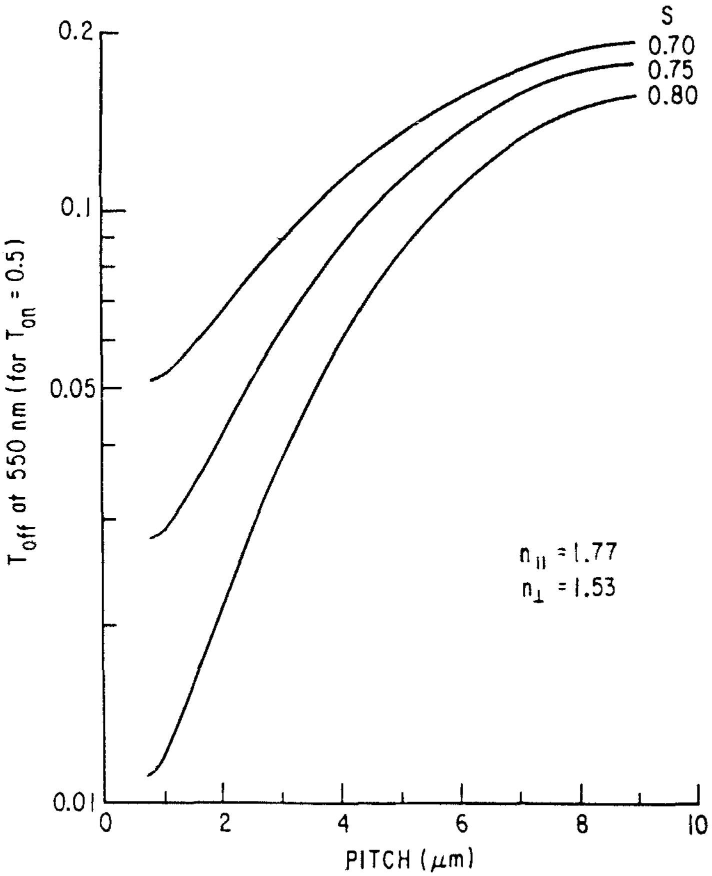


FIGURE 10 Impact of order parameter and pitch on T_{off} of White-Taylor mode display (after Cole and Aftergut[60]).

6.2 Contrast Ratio, Transmission and Brightness[5,6,8,31,60,64–66]

The impact of order parameter and pitch on off state transmission, T_{off}, are shown in Figure 10, which shows that T_{off} is less for higher ordered dyes and this difference becomes very significant when we go to smaller pitch.[6] For a very large pitch the elliptical waves are converted into linear ones, thereby reducing the absorption of the wave and consequently the contrast. When pitch is smaller, the dyes seem to absorb more, yielding a higher contrast. When p becomes equal to λ/n_e, the value of absorption coefficients (α_1 and α_2) become equal and light propagates in circularly polarized mode. However, this increases the operating voltage drastically. So, one has to make a compromise between contrast and operating voltage. In fact in normal White-Taylor mode displays the light is significantly elliptically polarized as p is usually kept moderately large (i.e. more than λ/n_e) to reduce the operating voltage and memory.

The impact of birefringence on the contrast ratio can be seen in Figure 11. It also shows the impact of the number of turns of pitch on the contrast ratio.[6] The curve shows that low birefringence material attains saturation of the contrast ratio with less turns or with smaller amount of cholesteric doping. Hence a lower value of Δn would be preferable from an operating voltage point of view too. The figure also shows that contrast ratio increases with increase in number of turns of cholesteric for fixed cell thickness. The contrast ratio of a dichroic display can be increased by adding more and more dye to the mixture. However, it decreases the brightness of the display and it looks dull.

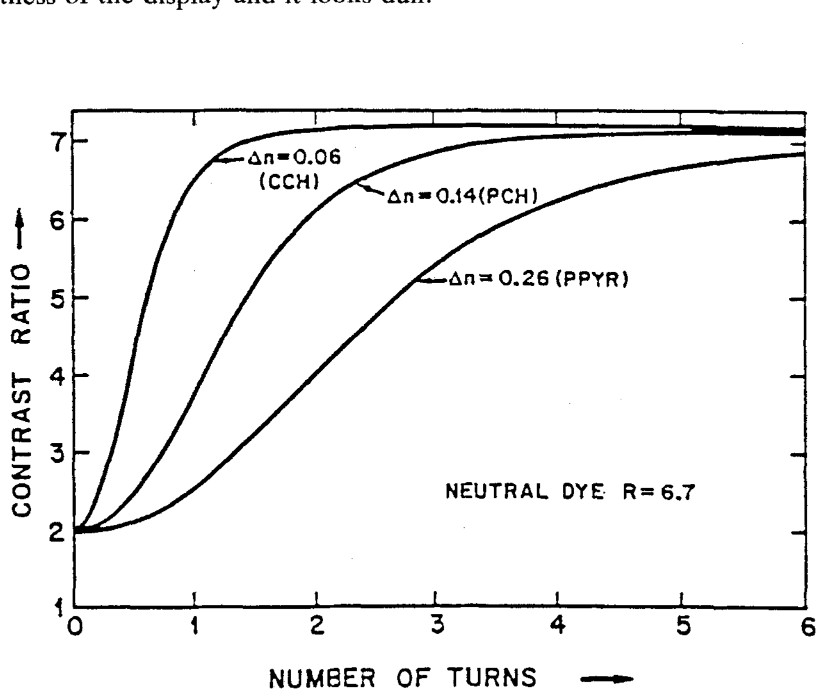


FIGURE 11 Impact of birefringence on the contrast ratio of White-Taylor mode display (after Scheffer and Nehring[6]).

Scheffer and Nehring[6] proposed a useful index, f_1, for selecting a host material giving lower operating voltage by combining the relationship of contrast vs. pΔn and the threshold voltage relationship with material parameters.

$$f_1 = \frac{1}{\Delta n}\left[\frac{\varepsilon_0 \Delta\varepsilon}{K_{22}}\right]^{1/2} \tag{2}$$

where K_{22} is the twist elastic constant and ε_0 is the permittivity of the free space ($=8.85 \times 10^{-12}$ MKS)

As it does not include the impact of order parameter (S) and viscosity (η) of the host on the performance of the dichroic display, we define another parameter: f_2,

$$f_2 = \frac{S}{\eta \Delta n} \tag{3}$$

A higher value of f_1 and f_2 would be advantageous. Usually liquid crystals having lower Δn also have lower η. Sometimes, in very simplistic terms S can be replaced by T_c as nematic materials of the same family having higher T_c have higher S, and order parameter of dye follows the order parameter of the host.

The brightness of the display is found to be dependent on the reflector too. A diffuse $BaSO_4$ reflector or Melinex® plastic film is found to be a good Lambertian reflector. It has been found that bonding these reflectors on the rear of the display reduces the brightness a bit. Sometimes it is preferable to put $BaSO_4$ on another glass plate and keep it separate from the LCD.

6.3 Memory

As mentioned earlier, a phase change display on application of voltage, goes from planar or Grandjean texture to finger print cholesteric and then to homeotropic nematic. The voltage is applied quickly and hence the transition from planar cholesteric to homeotropic nematic is very fast and no unwanted electro-optical effects are observed. However, when the voltage is removed, the nematic texture quickly goes to finger print cholesteric which is scattering in nature. From finger print texture it finally relaxes to Grandjean or planar texture because of surface alignment. Usually it takes a long time to relax from finger print to planar cholesteric texture and hence shows the unwanted memory effect. If the scattering state is really bad, it still looks excited a long time after the voltage is turned off.

White Taylor type dichroic displays[8] are being made either with a homogeneous or a homeotropic alignment treatment on the glass. Both these alignments have their own advantages and disadvantages. With homogeneous treatment, the cholesteric material adopts a twisted planar structure with helix axis perpendicular to the glass and molecules are parallel to the glass. Some people find that parallel boundary application is unsuitable[6] for display applications because with Grandjean texture in deactivated regions of the display, it is full of metastable disclination lines. These disclination lines strongly scatter the incident light and give the display an objectionable "after image" which persists from several seconds to several minutes after the segment is deactivated. The cholesteric texture obtained with perpendicular boundary condition is not a uniform texture.[6] Under the microscope the entire fields of view is filled with right and left handed spirals. This cholesteric texture is termed scroll texture[67] and appears very much like an end view of a bundle of rolled up scrolls. The helix axis in this texture is still predominantly perpendicular to the plane of the layer. An exact analysis of this texture was found to be difficult. It is noteworthy from an application point of view that the scroll texture is adopted without disclinations immediately after a display element is turned off and this structure, essentially a non-scattering scroll texture is quite different from the highly scattering cholesteric focal conic texture which occurs at intermediate voltages. In the focal conic texture, the helix axis is essentially parallel to the glass. The focal conic texture does not occur with homeotropically aligned cells under the fully turned on or off condition of the cell. However, it has been found that homogeneous alignment generates higher contrast ratio and is also more durable. With proper adjustment of the cell thickness, pitch, birefringence and viscosity, one can make a very good cell with low memory using homogeneous alignment.

Phase change type dichroic LCDs are used mainly in direct driven applications.[68] Some attempts have been made to develop low level multiplexed WT mode LCDs by reducing the pitch.[31,69–71] However, these efforts did not yield in very fruitful results due to the reduction in contrast.

7. DOUBLE CELL DICHROIC LCDs

A single cell guest host nematic (with ∞ or very long pitch) dichroic LCD unassisted by polarizer or quarter wave plate can have maximum contrast ratio of 2:1 as it absorbs only the E vector of unpolarized light parallel to the long molecular axis of the dye.[5,6,60] Even in the case of phase change transflective dichroic LCD with reasonable reflective brightness (15–18% at 45° angle) the transmissive contrast ratio (typically ~5–6:1) falls short of the requirements for many applications.[68] To increase the contrast ratio without sacrificing the brightness much, double cell geometry has been used. Basically there are three categories of double cell dichroic LCDs: (i) double cell nematic dichroic LCDs,[13] (ii) double cell one pitch cholesteric dichroic LCDs[14] and (iii) double cell phase change mode dichroic LCDs.[5,68]

7.1 Double Cell Nematic Dichroic LCD

The geometry of a double cell nematic dichroic LCD is shown in Figure 12. The liquid crystal mixture generally used is composed of pleochroic dyes and nematic host of positive dielectric anisotropy. The first cell has a unidirectional homogeneous alignment in one direction while the second cell has the unidirectional homogeneous alignment perpendicular to the first cell. Instead of joining two independently fabricated cells together one can also make a double cell by keeping the middle plate common and using only three pieces of glass. This reduces the thickness of the glass in the middle and consequently the parallax. For direct driven or low multiplexed alphanumeric displays, usually the two outer plates have common electrodes while the middle one has the segmented electrode patterns on the both

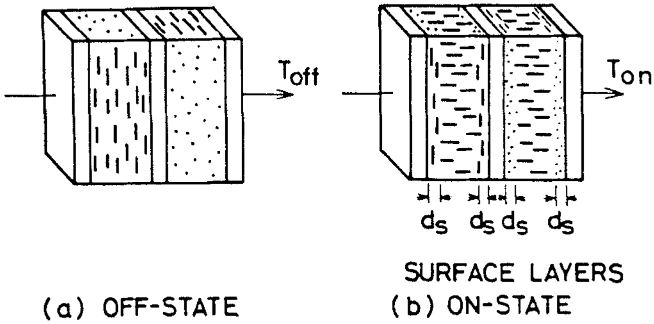


FIGURE 12 Geometry of double cell nematic dichroic LCD (after Seki, Uchida and Shibata[13]).

sides of the glass. The connections are made either using double sided contact pins or double sided notched zebras.

The E vector of the unpolarized light parallel to the pleochroic dyes in the first cell is absorbed by the first cell while the remaining E vector of the light perpendicular to the pleochroic dyes in the first cell gets absorbed by the second cell. Thus double cell absorbs the unpolarized light very effectively in its quiescent state. On application of the voltage the dye molecules get aligned in the direction of the field along with liquid crystal and hence the light is not absorbed. Due to the very effective absorption of both components of unpolarized light (both components being linearly polarized due to ∞ or extremely long pitch) by the double cell in its quiescent mode, double cell has a very high contrast ratio and wide viewing angle.

The liquid crystal mixture may by either pure nematic (∞ pitch) or slightly doped nematic with very high pitch ($p >> 4d$). The cell geometries could be made either unidirectional homogeneous or twisted nematic. In TN geometry the alignment on the first surface of the second cell should be perpendicular to the alignment on the second surface of the first cell. The double cell has a high contrast ratio (>20:1) with extremely good brightness and viewing angle. The drawbacks are complex fabrication, slow speed and shadowing effect.

7.2 Double Cell One Pitch Cholesteric LCD

The geometry is very similar to that of double cell nematic dichroic LCD with each cell having one pitch cholesteric dichroic mixture.[14]

7.3 Double Cell Phase Change Dichroic LCD

In this double cell geometry, two identical cells are put together with a transflector in the middle. In reflected light or daylight mode, the cell behaves as the normal reflective cell as mentioned in the earlier section. The reflectors used usually reflect ~90–95% and transmit only ~5%, so most of the light reaching to the reflector is reflected back. In daylight mode, generally the first cell is excited while in transmissive mode; both the cells are excited together. The background in quiescent transmissive mode looks much darker as the light is absorbed by the two layers of the dichroic mixture. When the field is applied the pixels become transmissive due to the alignment of pleochroic dyes in field direction. The light is not absorbed in this situation. The transmissive contrast in double cell mode is very high (>15:1), which is good enough for almost all the applications.

8. POSITIVE MODE DICHROIC LCDs

Most of the LCDs discussed in earlier section are negative mode LCDs i.e. displays exhibit colourless or white digits on coloured or black background. In many applications people prefer coloured or black digits on colourless background.

8.1 Positive Mode Heilmeier Cells[5,72]

The geometry of Heilmeier cell is already discussed in earlier section. By filling a liquid crystal mixture of negative dielectric anisotropy mixed with pleochroic dye in initially homeotropic geometry, we can make a positive mode display. In quiescent condition the cell would look clear as the long axis of pleochroic dye is in the direction of the propagation of light and hence perpendicular to the E vector of the light. On the application of the field the liquid crystal molecules will stand perpendicular to the electric field due to their negative dielectric anisotropy and consequently dyes are now parallel to the E vector of the light. Hence the light is absorbed and we get coloured or black information on colourless background. Earlier this approach was requiring high voltage driving as the materials were having small $-\Delta\varepsilon$ (~ -0.5). However, recent synthesis of materials of higher negative dielectric anisotropy (~ -4.5), such as ZLI 2806, has solved this problem. To get the best results, homeotropic alignment is obtained on top of the unidirectional homogeneous aligning surface. This can be done by having oblique SiO coatings first and then having long chain organosilane coating later on.

In another approach one can mix a dichroic dye of negative dichroism in liquid crystal mixture of positive dielectric anisotropy and fill in a Heilmeier cell having unidirectional homogeneous alignment. The cell does not absorb in quiescent state as the transition moment of the dye is perpendicular to the E vector of the light. On application of the electric field the transition moment of the dye becomes parallel to the E vector of light. In this case light is absorbed.

8.2 Positive Mode Dichroic LCDs Using λ/4 Plate

In quarter wave display we do not need any polarizer. One can get positive mode quarter wave displays using the homeotropic alignment and dichroic mixture of $-\Delta\varepsilon$ as already discussed in previous section.

8.3 Positive Mode Double Cell Dichroic LCD

The same geometry and materials can be used as discussed in single cell positive mode LCDs.

8.4 Positive Mode Dichroic LCDs Using Special Electrode Patterns

A positive mode dichroic LCD can be demonstrated by using special electrode patterns even in case of pleochroic dyes embedded in a liquid crystal of positive dielectric anisotropy.[73] In this case the voltage is applied on the whole visible area and is removed only from the desired segmented areas.

8.5 Positive Mode Phase Change Dichroic LCDs

The molecular structure of a long pitch cholesteric mixture is determined both by the cell gap and the type of the alignment. If the cell gap is sufficiently large, the structure is always helicoidal in bulk of the layer irrespective of the homeotropic or homogeneous alignment on the surface. If the cell gap is below a critical thickness d_c, where $d_c = p\ K_{33}/2K_{22}$, the helix is unwounded in presence of a homeotropic alignment and the whole structure is homeotropic nematic.[74] Two versions of the cells using this property has been proposed using pleochroic dichroic mixture of positive dielectric anisotropy.[75] The operational principle of both type of cells is that the area surrounding the picture element has homeotropic alignment and cell gap $< d_c$ resulting in homeotropic nematic structure of the molecules. The pixel area has the helicoidal arrangement. Thus the pixels appear coloured (helicoidal structure) on a clear background (homeotropic structure) in absence of an electric field. With application of electric field, the helicoidal structure is destroyed and the liquid crystal molecules adopt a homeotropic structure with the result that only the non-activated pixels remain dark. The control logic for this display is inverted with respect to that required for White-Taylor type with negative contrast.

In first geometry the areas surrounding the pixels are given homeotropic treatment while the pixels areas are given homogeneous alignment. The cell gap is less than d_c. Thus pixel area have helicoidal arrangement of the molecules while the remaining area have homeotropic. In second geometry the alignment on the whole cell is homeotropic but the cell gap is adjusted in such a way that pixel areas have cell gap more than d_c while the remaining area has it less than d_c resulting in helicoidal structure in pixel area and homeotropic in remaining area.

Another way of obtaining positive mode phase change type display is to use a pleochroic cholesteric mixture of negative dielectric anisotropy.[76,77] The surface treatment is homeotropic and cell thickness d is chosen less than d_c. In quiescent mode the cell is in homeotropically aligned nematic state and hence pleochroic dyes do not absorb the light. On applications of the voltage molecules become parallel to the glass plates and also adopt the helicoidal structure. In this situation the light is absorbed by the dyes. A display of this type has advantages of positive contrast, brightness, wider viewing angle, lower operating voltage and multiplexing capability. It has been found experimentally that electro-optical characteristics are optimized for the value of d/p close to 0.7 for both multiplexed and non-multiplexed displays.

9. SUPERTWISTED DICHROIC DISPLAYS

The $3\pi/2$ twist imparts a very steep slope in the threshold characteristic of the cell hence it can handle higher level of multiplexing. However, the threshold characteristic of $3\pi/2$ displays unaided by dye or interference of ordinary and extraordinary ray has low contrast. The dyes absorb the leakage and enhance the viewing angle and contrast. Two types of SDEs can be made; one by using Heilmeier geometry or by using single polarizer and the second is by using phase change or White Taylor mode. However, SDE's did not become popular due to their lower contrast, brightness and slower speed compared to those of other supertwist displays.

10. FERROELECTRIC DICHROIC LCDs[20–22]

Ferroelectric LCDs show bistability i.e., Θ and $-\Theta$ both positions are equally stable. If the molecules lie in $+\Theta$ position in quiescent state, on application of the field they go to $-\Theta$ position where they can remain for a very long time even absence of the field. For ferroelectric dichroic mixture with $\Theta = 45°$, alignment is given such that in quiescent state molecules are parallel to the polarizer giving rise to the high absorption by the dyes. When the cell is activated, due to rotation of the molecules by 2Θ i.e., 90° with respect to initial geometry, the dye molecules will be perpendicular to the polarizer and hence will not be absorbed. This geometry gives a colourless digit on coloured background. In complimentary geometry coloured (or black) digit on colourless background can be achieved by putting the polarizer perpendicular to the molecules in the quiescent state. The FLC display working on this principle has much less thickness limitations imposed by FLC based on birefringence effect. Therefore avoiding splay would be a more decisive factor. A cell of 5 μm cell gap is feasible by this technique. The cell can be operated in reflective as well as in transmissive geometry.

A ferroelectric liquid crystal with $\Theta = 22.5$ and high pleochroic content can be used entirely without polarizer by using $\lambda/4$ plate and a reflector. In off state the incoming light is selectively absorbed along the homogeneous alignment in the cell. A quarter wave plate is placed along or perpendicular to the director, **n**. The non-absorbed radiations (~50%) in the ideal case vibrates perpendicular to the direct **n** and is reflected back unaffected. In on state **n** has been turned at 45° to the axis of $\lambda/4$ plate and the non-absorbed orthogonal vibration is thus split up and components retarded corresponding to double pass $2\lambda/4 = \lambda/2$. The polarization plane is therefore turned by 90° and the radiation is absorbed on its way back to the liquid crystal.

11. POLYMER DISPERSED DICHROIC LCDs[23,24]

These provide good contrast and high transmission as they do not require any polarizer. For polymer dispersed dichroic LCDs, Fergason's process is found to be slightly better than Doane's process. One excellent article by Prof. Doane appeared recently in this areas,[24] so we are not discussing this topic in detail here.

Acknowledgment

Thanks are due to S. Bahadur, Joy Tunnoch, Dr. L. Krzymien, Claude Dupont and Kam Wan for their help in preparing this paper. We are also thankful to IRAP (NRC) for providing the financial assistance during the course of this work. Thanks are also due to John Wright for his interest and encouragements.

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