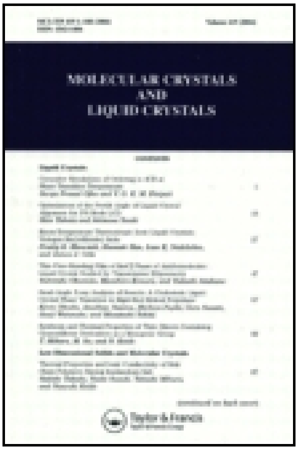

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Order Parameter and the Performance of Nematic Guest-Host Displays

A. C. Lowe [a] & R. J. Cox [a]
[a] IBM Research Laboratory, San Jose, California, 95193, U.S.A.

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Order Parameter and the Performance of Nematic Guest-Host Displays

A. C. LOWE† and R. J. COX
IBM Research Laboratory, San Jose, California 95193, U.S.A.

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A simple model of a nematic guest-host display is presented in which the limiting "on" and "off" states are considered to be uniform arrays of molecules oriented perpendicular and parallel (or at a small tilt angle), respectively, to the plane of the display. Calculated contrast ratio and brightness curves are presented for several angles of view and for all planes of view as functions of dye order parameter, pretilt and polarizer efficiency. The effects of host refractive index and front surface reflectivity are discussed.

INTRODUCTION

The nematic guest-host effect[1,2] is well suited for application to integrated liquid crystal displays.[3] As part of a program to develop and to evaluate new dyes for such applications, a simple model of a nematic guest-host display in its limiting "on" and "off" sites has been derived.[4] In this communication, we show how the limiting contrast ratio of reflective nematic guest-host displays varies with angle of view and plane of view as functions of dye order parameter, alignment pretilt and polarizer efficiency. The effects of front surface reflectivity and refractive index of the nematic host are explicitly included.

THE MODEL

The dichroic properties of a dye dissolved in an oriented nematic phase were

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† Present address: IBM United Kingdom Laboratories Ltd, Advanced Display Technology Group, Hursley Park, Winchester, Hampshire SO21 2JN, England.

first described by Cehelnik *et al.*[5] More recently, Zbinden's description of the infrared dichroism of polymers[6] has been extended to nematic guest-host displays by Schadt.[7] Both treatments yield identical expressions for the absorbance parallel and perpendicular to the mean axial alignment direction of the dye molecules, if the appropriate definition of the distribution function, $f(\gamma)$, is used, i.e.,

$$S = \frac{1}{2}\left[3\int_0^{\pi/2} \cos^2 \gamma f(\gamma)\, d\gamma - 1\right]$$

where S is an order parameter[8] and γ is the angle between the geometric axis of the dye molecule and the mean alignment direction of the nematic host.

We present expressions for the absorbance of a nematic guest-host display which differ from those of Schadt.[9] The expressions presented here are symmetrical about the normal to the plane of the display, which should be the case for reflective displays. Expressions for the brightness and contrast ratio of nematic guest-host displays at normal incidence have previously been given by Scheffer.[10]

Consider a nematic guest-host display with alignment pretilt δ, viewed at angle of incidence ϕ in a plane making an angle ψ with the component of the nematic director in the plane of the display, i.e., the u' axis of Figure 1. The liquid crystal has a mean refractive index n_{LC}, so the propagation direction of light through the cell is $\phi_r = \sin^{-1}(\sin \phi/n_{LC})$. The dye has an absorbtivity $A_0 = \varepsilon.c.d.$ (where ε, c, d are the extinction coefficient of the dye measured in isotropic solution, concentration and the cell thickness, respectively).

The absorbance of the dye parallel and perpendicular to the plane of

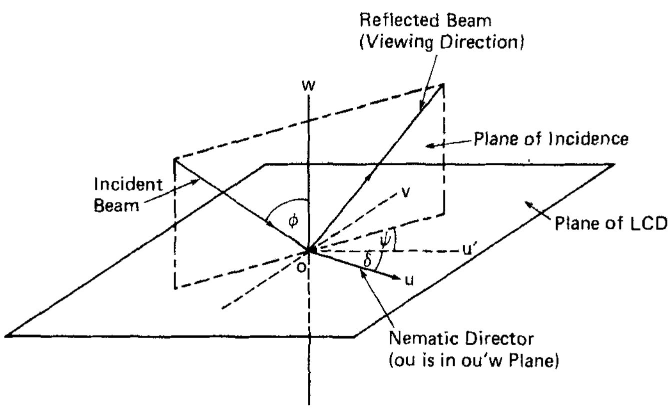

FIGURE 1 Pretilt, plane of incidence and viewing angle of a nematic guest-host display.

incidence is given by[4]

$$A_p = (A_0/\cos\phi_r)[A^2(S(3\cos^2\theta - 1) + 1) + 1/2(B^2 + C^2)(S(1 - 3\cos^2\theta) + 2)]$$

and

$$A_s = (A_0/\cos\phi_r)[E^2(S(3\cos^2\theta - 1) + 1) + 1/2(F^2 + G^2)(S(1 - 3\cos^2\theta) + 2)]$$

where θ is the angle between the transition moment of the dye and the molecular axis (θ is set to zero in the following discussion), and A through F are the direction cosines of the components of the transition moment of the dye molecule in the *uvw* coordinate system (Figure 1) transformed into the *pst* coordinate system (t is the propagation direction of the light beam). A through F are functions of δ, ψ, ϕ.

To describe the contrast ratio of a nematic guest-host display, we must determine the azimuth of the ellipse described by the intersection of the *ps* plane and the absorption indicatrix of the dye molecules (Figure 2). This

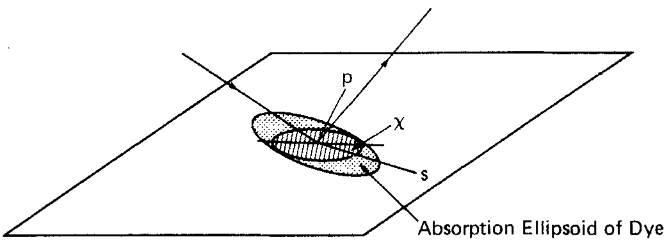

FIGURE 2 The absorption ellipse and its azimuth χ formed by the intersection of the ps plane with the ellipsoidal absorption indicatrix of the dye.

is done by rotating by χ about the t axis and determining the value of χ for $dA_\chi/d\chi = 0$. (For the purposes of modelling the display it matters not whether a minimum or a maximum is identified.) We can now describe the liquid crystal by the maximum and minimum absorbance, and the aximuth χ

$$A_{\max} = A_p \sin^2\chi + A_s \cos^2\chi$$

$$A_{\min} = A_p \sin^2\chi + A_s \cos^2\chi.$$

The same method can be used to describe the polarizer. In this case, the expressions for A through F are simplified since $\delta = 0$, and parameters A_{pol} and S_{pol}, equivalent for A_0 and S, are used.

Each element of the display is now described by an appropriate Mueller matrix[11] to a dichroic polarizer. For $\sigma \neq 0, \pi/2$, the matrices for the incident and reflected passes through the liquid crystal layer are not equivalent. The display is illuminated with unit intensity unpolarized light, described by the Stokes' vector [1, 0, 0, 0], which is multiplied into each matrix in turn. The reflected intensity is given by the first element of the resultant Stokes' vector. The limiting "on" intensity is calculated by setting $\delta = \pi/2$. The effects of host birefringence are not considered.

RESULTS AND DISCUSSION

Representative contrast ratio and brightness curves are shown in Figure 3. More extensive results for the limiting cases $\psi = 0$, $\pi/2$ are included in Table I, and properties of the polarizers used in the calculations are given in Table II.

The variation of contrast ratio with ψ and ϕ is strikingly different from that observed for twisted nematic displays.[12] Instead of four lobes, only two, at $\psi = \pi/2$, $3\pi/2$, are seen. The decrease in contrast ratio with increasing angle of view at $\psi = 0$ is due both to a decrease in off-state and to an increase in on-state absorbance. The component transmitted by the polarizer along the u' axis decreases as $\cos \phi_r$ whereas that along the w axis (the direction for maximum absorbance in the on-state) increases as $\sin^2 \phi_r/\cos \phi_r$.

For $\psi = \pi/2$, the increase in on-state absorbance is attributable predominantly to increased path length through the polarizer and liquid crystal. However, the increase in off-state absorbance from the same cause is greater, and the contrast ratio increases with increasing viewing angle.

From Table I, some general conclusions may be drawn concerning the consequences of changing the extinction ratio and absorbance of the polarizer and the order parameter of the dye:

– At any angle of incidence, for $\psi = 0$, contrast ratio is determined mainly by the order parameter of the dye.

– At oblique incidence, for $\psi = \pi/2$, the extinction ratio of the polarizer significantly influences the contrast ratio, providing $A_{pol} > A_0$, which is the case for neutral dyes yielding contrast ratios of the order of 10:1. For $A_0 = 1$, which is typical for measurements at the extinction maximum, increasing S_{pol} from 0.82 to 0.95 changes the contrast ratio by only 3%.

– Display brightness is influenced more by S_{pol} than by S for $A_{pol} > A_0$.

The data in Figure 3 and Table 1 are for zero pretilt. Increasing the pretilt will always degrade the contrast ratio of a nematic guest-host display. The extent of the degradation may be seen from Figure 4. The influence of pretilt decreases with increasing ϕ for $\psi = 0$, $\pi/4$, but increases for $\psi = \pi/2$.

TABLE I

Brightness (B) and contrast ratio (CR) as functions of dye order parameter and polarizer order parameter and absorbance

S	A_0	S_{pol}	A_{pol}	B			CR		
				$\phi = 0$	$\phi = 67.5$		$\phi = 0$	$\phi = 67.5$	
					$\psi = 0$	$\psi = 90$		$\psi = 0$	$\psi = 90$
0.66	0.25	0.85	0.5	0.24	0.06	0.20	9.5	1.98	15.4
0.66	0.25	0.95	0.5	0.30	0.08	0.26	9.6	1.97	16.4
0.66	0.25	0.95	1.0	0.27	0.08	0.23	10.0	1.98	18.6
0.80	0.25	0.85	0.5	0.28	0.06	0.24	15.2	2.24	25.2
0.80	0.25	0.95	0.5	0.35	0.09	0.32	15.4	2.23	28.2
0.80	0.25	0.95	1.0	0.32	0.07	0.28	16.1	2.42	35.5

TABLE II

Polarizer properties (at normal incidence)

Polarizer	S_{pol}	A_{pol}	Transmittance In Polarizing Plane, $T_{\parallel}$	Transmittance Normal to Polarizing Plane, $T_{\perp}$	Overall Transmittance $(T_{\parallel}+T_{\perp})/2$	Extinction Ratio $\rho=T_{\perp}/T_{\parallel}$
P1	0.85	0.5	0.84	0.044	0.44	0.052
P2	0.95	0.5	0.94	0.035	0.48	0.037
P3	0.95	1.0	0.89	0.0012	0.45	0.001

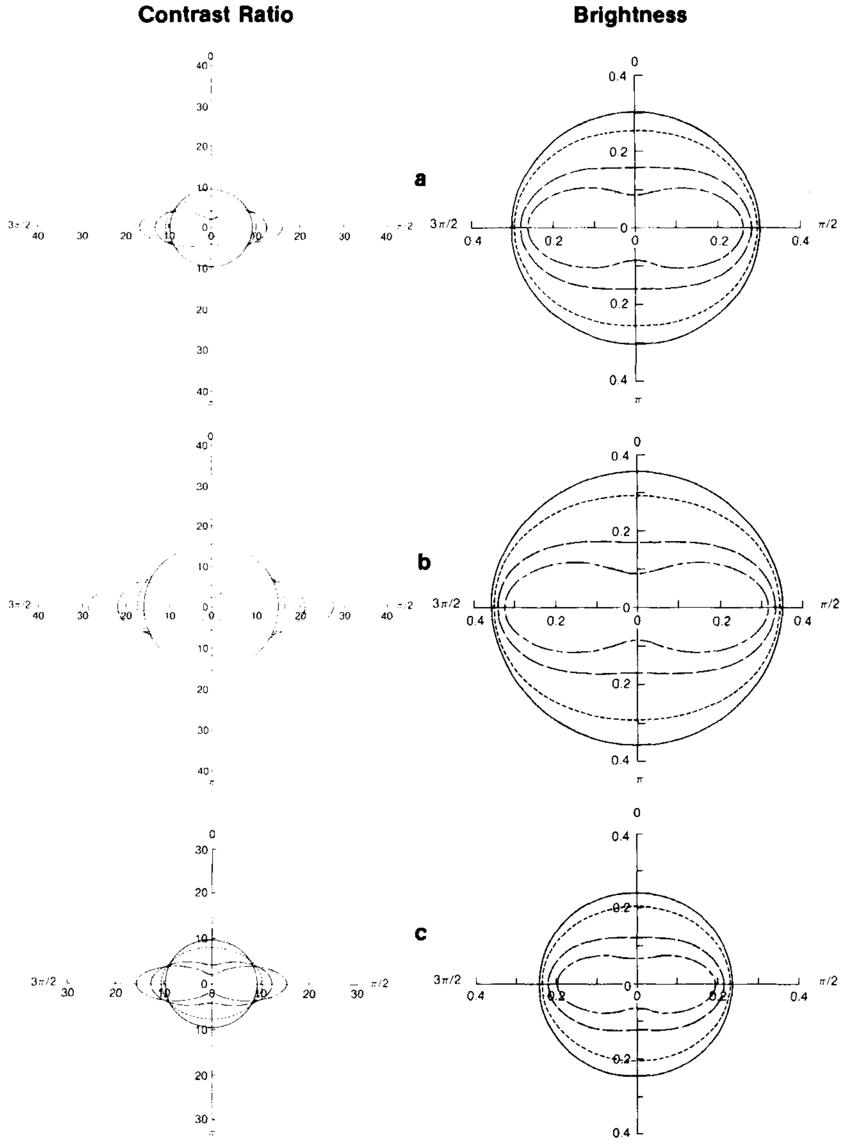

FIGURE 3 Contrast ratio and brightness for all planes of incidence as a function of the order parameters of the dye (S) and the polarizer (S_{pol}) at four viewing angles (——— 0 deg; ----- 22.5 deg; —— 45 deg; ——— 67.5 deg). $A_0 = 0.25$ and $A_{pol} = 0.5$ throughout. (a) $S = 0.66$, $S_{pol} = 0.95$, (b) $S = 0.80$, $S_{pol} = 0.95$, (c) $S = 0.66$, $S_{pol} = 0.85$.

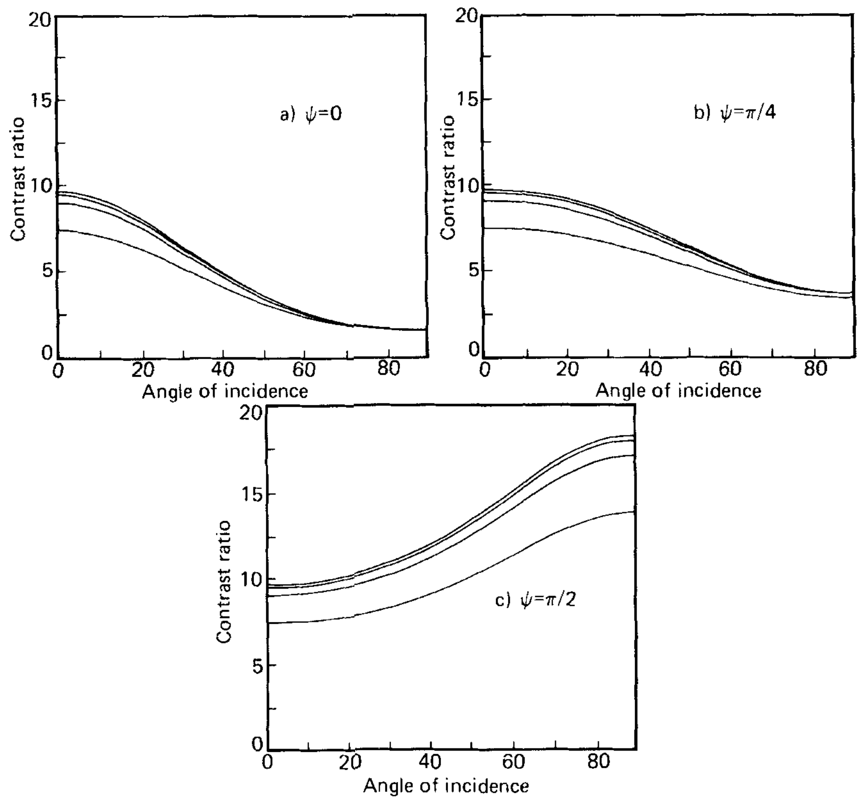

FIGURE 4 Contrast ratio as a function of viewing angle and pretilt at three different planes of incidence. $A_0 = 0.25$, $A_{pol} = 0.5$, $S = 0.66$, $S_{pol} = 0.95$. From the upper to the lower curves, $\delta = 0$, 5, 10 and 20 deg, respectively.

The degradation of contrast due to front surface reflectivity is now considered. If no antireflection coatings are applied to the front surfaces of the display, the changes in refractive index in going through air/polarizer/glass/ITO/liquid crystal interfaces are about 0.6, −0.1, 0.5, −0.5, respectively. The ITO thickness can be controlled to minimize the net reflectivity from the glass/ITO and ITO/liquid crystal interfaces. Even so, net reflectivity of 0.06 from the front surfaces is not unreasonable. We have assumed that this can be reduced to 0.02 and have calculated the reduction in contrast ratio (Figure 5). At normal incidence, this corresponds to a 35% drop from 9.6:1 to 6.3:1. At $\phi = 67.5°$, $\psi = \pi/2$, the decrease is 52% from 16.3:1 to 7.8:1, so in terms of overall display contrast ratio, there is as much to be gained by developing

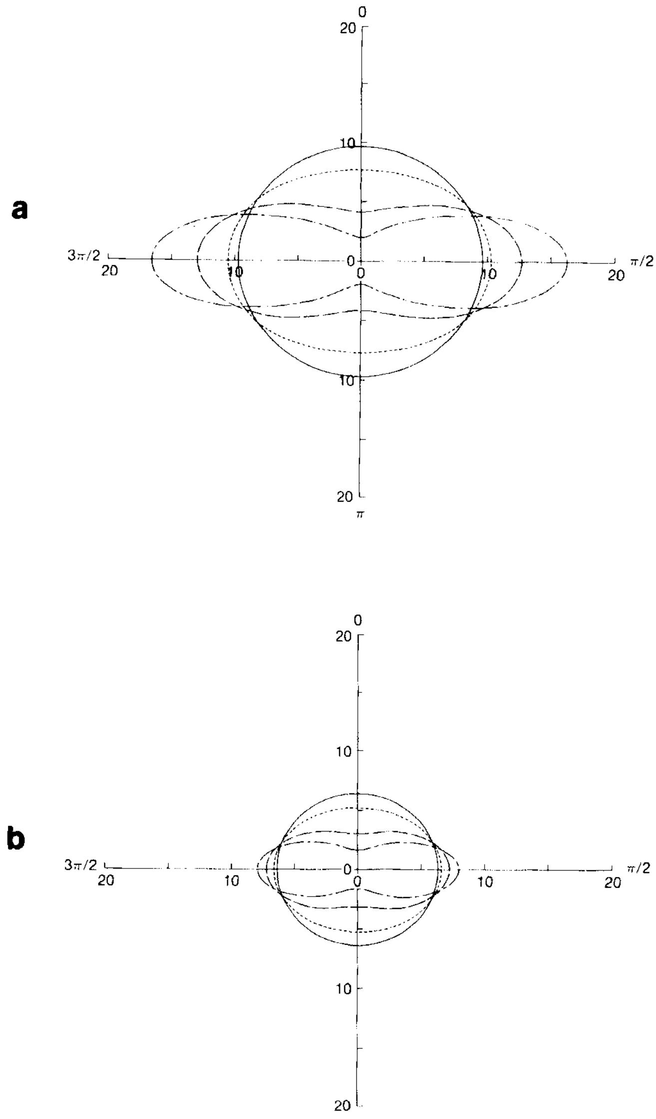

FIGURE 5 The effect of front surface reflectivity on contrast ratio (a) zero front surface reflectivity, (b) 2% front surface reflectivity. Other data and line definitions as for Figure 3(a).

efficient antireflection coatings for the polarizer/front window of the display as by increasing S from 0.66 to 0.80. Finally, the calculations shown here have used the relatively low value of $n_{LC} = 1.5$, which corresponds to a limiting value of $\phi_r = 42°$. Increasing n_{LC} will decrease $\phi_r \leqslant 36°$ for $n_{LC} = 1.7$, and will improve the contrast ratio at oblique incidence.

CONCLUSIONS

The limiting contrast ratio and brightness of nematic guest-host displays have been calculated over a wide range of viewing angles for all planes of view as functions of dye order parameter and polarizer efficiency. The effects of alignment pretilt and front surface reflectivity have been discussed. In general, displays exhibit good contrast for all angles of view for $\psi \simeq 90 \pm 20°$, although brightness decreases with increasing viewing angle for all cases. The off-normal contrast ratio for $\psi = 0$ is degraded by 50% at an angle of view of 45°, probably restricting the range of viewing angles to $\pm 45°$ in this plane.

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