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Frederic J. Kahn [a]
[a] Hewlett-Packard Laboratories, Palo Alto, CA, 94304
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Capacitive Analysis of Twisted Nematic Liquid Crystal Displays

FREDERIC J. KAHN

Hewlett–Packard Laboratories, Palo Alto, CA 94304

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Magnetocapacitive null (MCN) and capacitance versus voltage (C–V) measurements are valuable tools for analyzing electro-optical properties of twisted nematic LCDs. The C–V technique is particularly useful when results are presented in the form of reduced capacitance $C_R(V) = [C(V) - C_\perp]/(C_\parallel - C_\perp) = \sin^2 \alpha_e$, where $\alpha_e(V)$ is an effective molecular tilt. Thus, the effective voltage induced distortion of the LC is determined by monitoring C_R–V.

Data showing the dependence of C_R–V on initial molecular tilt, α_0, and temperature are presented and related to electro-optical properties. The first observations of temperature dependence of α_0 are reported. Effectiveness of sequential oblique incidence evaporation techniques in controlling α_0 is demonstrated quantitatively.

I INTRODUCTION

Device interest[1] in twisted nematic[2] liquid crystal displays (TN LCDs) has stimulated considerable experimental[3,4] and theoretical effort[5,6] to explain their optical and electro-optical properties. Theoretical models developed by van Doorn[3,5] and Berreman[4,6] have successfully simulated the detailed electro-optical response of TN LCDs by numerical solution of the relevant differential equations. However, these models require extensive knowledge of the LC's material constants and the numerical computation methods require use of large digital computers. Furthermore, the inherent nature of numerical computation tends to obscure the physics of the device.

It is shown in the present work that capacitance versus voltage (C–V) curves[7] when appropriately normalized as reduced capacitance versus voltage (C_R–V) quantitatively represent the effective voltage induced distortion states of a TN cell. Furthermore, when one transmission versus voltage (T_r–V) curve is known for an LC material at a particular temperature (T), initial molecular tilt (α_0), and angle of incidence (θ_i), T_r–V curves for other temperatures and tilts can be determined directly from the relevant C_R–V

curves without numerical computation. The results are not exact, but the semi-quantitative agreement is useful in illuminating the physical origin of TN LCD optical properties.

An effective director model is used here to explain our experimental observation that TN cells with the same LC material and equal reduced capacitances (C_R) have equal transmissions (T_r) for the same angles of incidence. TN cell transmission is determined at a fixed angle of incidence by the angle between the light ray in the liquid and an effective director, $\hat{d}_e(V)$, determined from the reduced capacitance (C_R). We believe this model can be extended to explain angular dependence of transmission as well, provided we account for some additional boundary and polarization dependent terms and the dependence on refraction angle of the effective pitch encountered by the light ray.

Experimental techniques for measuring C_R–V using phase sensitive detection and for determining initial molecular tilt α_0 by a magnetocapacitive null (MCN) measurement[8,9] are described. The MCN method is used to demonstrate that α_0 can be accurately controlled by a sequential oblique incidence evaporation process. Experimental results showing the dependence of C_R–V on α_0 and T are presented and correlated with electro-optical properties. These results include what we believe to be the first observation of temperature dependence of molecular tilt.

II MEASUREMENT TECHNIQUES

Reduced capacitance

Following Metzger[10] and Gruler *et al.*,[11] we analyze our data in terms of a reduced capacitance

$$C_R = \frac{C(V) - C_\perp}{C_\parallel - C_\perp}, \tag{1}$$

where $C_\parallel$ and $C_\perp$ are the respective capacitances for the nematic director uniformly aligned parallel and normal to the applied field. Other previously published studies[7] of capacitance-field relations have generally contained data analyzed in terms of relative capacitance

$$C_r = \frac{C(V) - C(0)}{C(0)}, \tag{2}$$

where $C(0)$ is the capacitance at zero field. We find C_R physically more meaningful and indeed will show below how it relates directly to the optical properties of a TN cell.

Consider the TN LCDs shown schematically in Figure 1. For simplicity the twist has been ignored and all molecules are shown oriented in the Y–Z

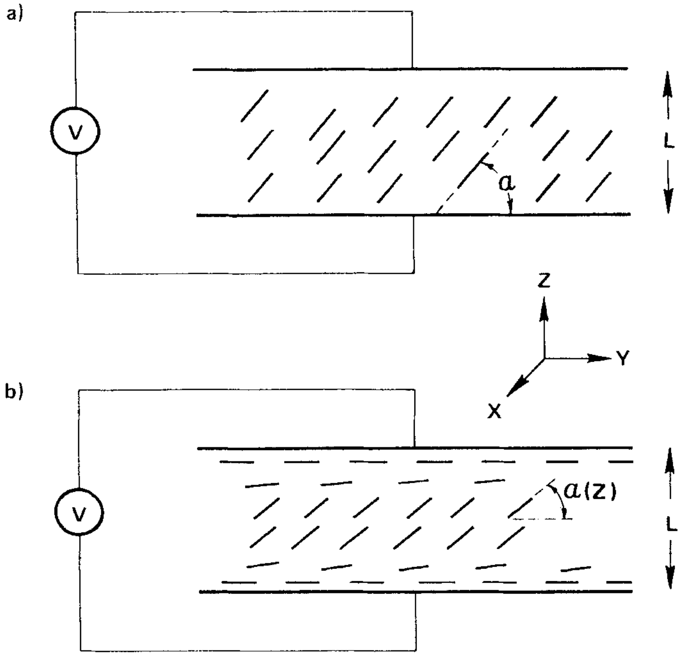

FIGURE 1 Twisted nematic liquid crystal cells. For simplicity, both cells have been untwisted and all molecules are shown oriented in the Y–Z plane. (a) Uniformly oriented LC, and (b) nonuniformly oriented LC. Director orientation is a function of position (Z).

plane. This simplification does not affect our discussion which is nevertheless applicable to twist cells.

The local dielectric tensor of the nematic liquid crystal is given by

$$\boldsymbol{\varepsilon} = \begin{pmatrix} \varepsilon_\perp & 0 & 0 \\ 0 & \varepsilon_\perp & 0 \\ 0 & 0 & \varepsilon_\parallel \end{pmatrix}, \tag{3}$$

where the principal axes have been taken to be normal and parallel to the nematic director. Transformation through angle α to the X-Y-Z coordinate system of Figure 1 then gives

$$\varepsilon_{zz}(z) = \varepsilon_\perp \cos^2 \alpha + \varepsilon_\parallel \sin^2 \alpha \tag{4}$$

from which we obtain by definition

$$\varepsilon_R(z) = \frac{\varepsilon_{zz}(z) - \varepsilon_\perp}{\varepsilon_\parallel - \varepsilon_\perp} = \sin^2 \alpha. \tag{5}$$

Thus, for the uniformly oriented cell of Figure 1(a),

$$C_R = \varepsilon_R = \sin^2 \alpha. \tag{6}$$

For the nonuniformly oriented cell of Figure 1(b), we find

$$C_R = \frac{\varepsilon_{zz}(z) - \varepsilon_\perp}{\varepsilon_\parallel - \varepsilon_\perp} = \sin^2 \alpha, \tag{7}$$

where, following Gruler,[12]

$$\varepsilon_{zz}(z) = \left(\frac{1}{L}\int_0^L \frac{dz}{\varepsilon_{zz}(z)}\right)^{-1} \tag{8}$$

Finally, we define an effective orientation angle, α_e, such that

$$C_R = \sin^2 \alpha_e \tag{9}$$

for the nonuniformly oriented cell. The physical significance of α_e is that the director of a uniformly oriented cell with the same C_R will be given by

$$\hat{d}_e = \hat{y}\cos\alpha_e + \hat{z}\sin\alpha_e. \tag{10}$$

We will see that TN cells with the same LC material and the same $\hat{d}_e(C_R)$ have approximately the same transmission at the same angles of incidence.

Capacitance versus voltage (*C–V*) measurements

Capacitance versus voltage measurements were made by using a phase sensitive detection technique.[7] This is superior to a bridge measurement because it permits greater freedom of voltage and frequency as well as higher speed and simplicity of obtaining analog readout for an X-Y recorder.

The apparatus used to measure and plot C–V characteristics for the LC cells is shown in Figure 2. An amplitude swept sine wave at about 950 Hz is used for the cell bias. It is desirable for this bias to be at relatively high frequency ($\sim$1 kHz) in order to prevent the liquid crystal orientation from being modulated at the second harmonic of the applied field, especially for low viscosity LCs measured at high temperatures.

A low amplitude sine wave (100 mV at 126 Hz) was used as the measurement signal. The measurement frequency was chosen to be sufficiently high for good sensitivity and fast response, and sufficiently low to avoid any dielectric relaxation effects intrinsic to the LC. The LC capacitance is proportional to the quadrature component of current at 126 Hz and the apparatus is readily calibrated by substituting standard capacitors for the LC cell.

By setting the zero of the recorder ordinate to $C_\perp$ and the maximum ordinate (1.00) to $C_\parallel$, C_R versus V may be plotted directly. $C_\parallel$ was determined by using a 20 Vrms bias across the TN LCD. This corresponds to $V/V_e \gtrsim 20$ for the biphenyl LCs reported on here, where V_e is the threshold for LC reorientation by the field. $C_\perp$ was determined by measurement with zero bias for low tilt cells ($\alpha_0 \leq 5°$) or by computation using the MCN determined

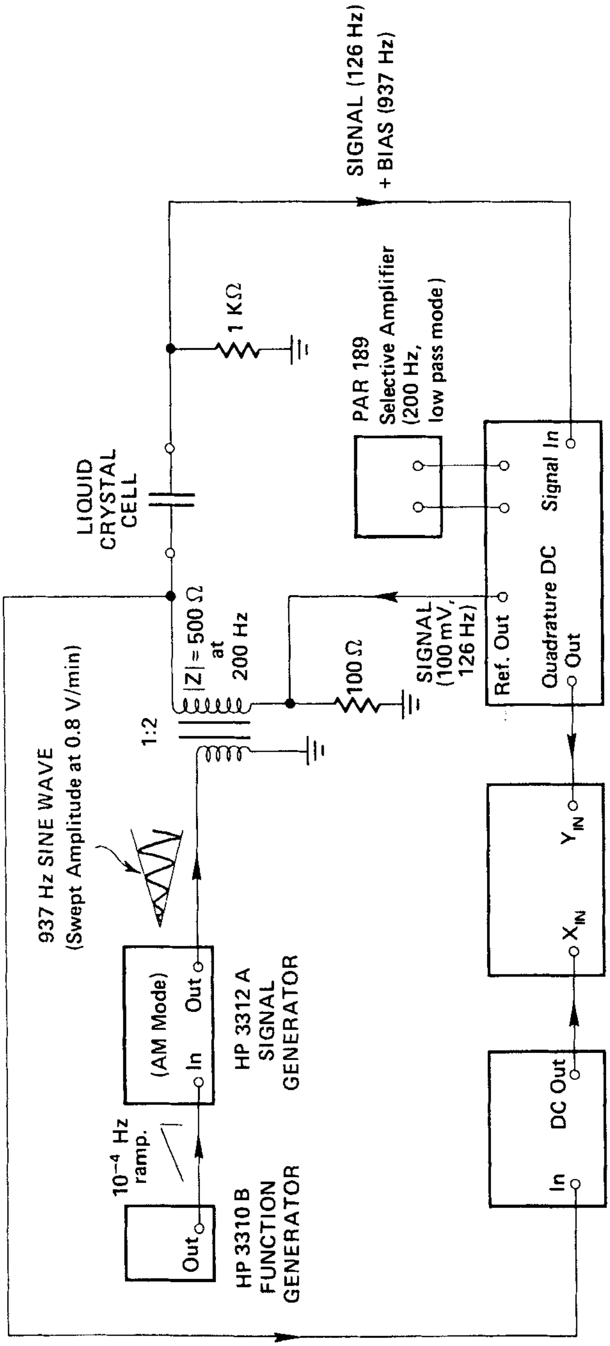

FIGURE 2 Apparatus for measurement and plotting of capacitance versus voltage characteristics of liquid crystal cells.

value of molecular tilt (α_0) for $\alpha_0 > 5°$. These procedures enable measurement of C_R with an absolute error conservatively estimated to be less than 2%.

Magnetocapacitive null measurement (MCN)

In the magnetocapacitive measurement technique of Toriyama,[8] the capacitance of the TN LCD is measured first at zero field and then as a function of cell orientation in a high magnetic field (9 kOe). Because the LC molecules tend to align parallel to an applied magnetic field,

$$C(H) = C(0) \tag{11}$$

only when H is parallel to the average molecular orientation at zero field. This orientation of magnetic field corresponds to the initial molecular tilt angle (α_0). There are, in general, two different magnetic field angles, α_H, for which Eq. (11) is satisfied. However, only the one in which H is parallel to $\hat{d}_e$ corresponds to the zero field state and will give a capacitance which does not change when the field is cycled on and off.[8,9]

In the MCN measurement of the present work, the cell is rotated in an external magnetic field ($H = 12$ kOe) until Eq. (11) is satisfied. However, sensitivity of the measurement is increased and measurement time reduced by using a GR 1615 capacitance bridge with a tuned amplifier detector as shown in Figure 3. The bridge is first balanced at $H = 0$, and then the cell is rotated starting with H in the plane of the LC layer until the detector nulls again, at which point $\alpha_H = \alpha_0$. Typical reproducibility of this measurement is $\pm 0.5°$ for $\alpha_0 \lesssim 1°$ and $\pm 0.25°$ for $\alpha_0 > 1°$.

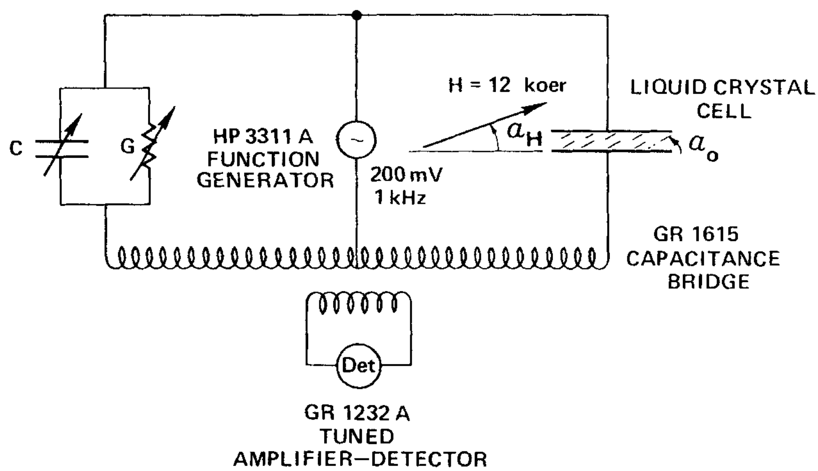

FIGURE 3 Magnetocapacitive null measurement (MCN) of molecular tilt angle.

Although tilt is independent of Z for parallel oriented cells as illustrated in Figure 1(a), tilt is a function of Z for twist cells. For measurements of the highest accuracy, tilt should be measured on parallel cells. However, for tilts less than $\sim 5°$, the variation of tilt with Z in 90° twist cells is small (less than $\sim 10\%$) and measurements can be made on twist cells with little loss in accuracy. For all values of tilt, qualitatively useful results can be obtained from measurements on twist cells. All measurements described in this paper were performed on 90° twist cells. The $\underline{H}$ field was rotated in a plane containing the sample normal and at 45° azimuth to the oblique incidence evaporation plane (see below).

General

All results described in the present work are for BDH E-7 biphenyl liquid crystal (nematic range: $-10°C$ to $+59°C$) physically oriented on SiO_x layers deposited by oblique incidence evaporation.[13] For cells with $\alpha_0 \leq 7°$, 1% by weight of the optically active biphenyl MBCP[14] (BDH C-15) was added to eliminate reverse twist. LC layer thicknesses were nominally 10 μm.

Optical measurements were made using crossed HN22 polarizers, a Photo Research Model 1980 Pritchard photometer with photopic response, and a tungsten light source with $\sim 2700°K$ color temperature. LCD temperatures were controlled thermoelectrically. All LC cells had 90° twist and polarizer axes were parallel to the directions of LC alignment at the substrates.

III MEASUREMENT RESULTS

Initial molecular tilt

Display substrates with well-defined initial molecular tilts (α_0) can be generated by oblique incidence evaporation of various materials, such as SiO_x.[13,15] The tilt can be controlled to within $\pm 1°$ for $0 \leq \alpha_0 \leq 25°$ by sequential evaporation of high and low tilt producing layers. The high tilt producing layer can be obtained by using a relatively high incidence angle of evaporation ($> 80°$) and the low tilt producing layer by using a relatively low incidence angle (40–70°).[15] Since the LC molecules tend to align parallel to the plane of incidence of the high tilt evaporation and normal to the plane of incidence of the low tilt evaporation,[15] the planes of incidence for these evaporations are chosen to be mutually orthogonal. Tilt is a function of the thickness of the "variable" layer if the thickness of one layer is held constant. Experimental results showing dependence of α_0, as determined by MCN measurement, versus "variable" layer thickness are given in Figure 4. Similar techniques have been developed independently by Meyerhoffer[16] and Johnson.[17] Raynes, Rowell, and Shanks[18] have shown that the high and low tilt coatings can be deposited simultaneously.

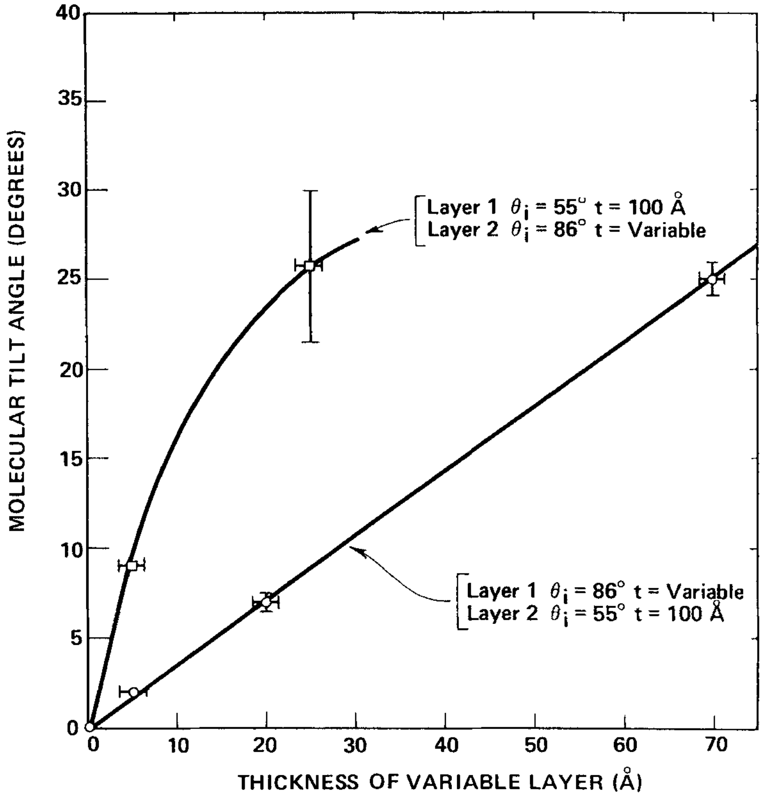

FIGURE 4 Control of initial molecular tilt (α_0) by sequential oblique incidence evaporation method. Dependence of α_0 on thickness of "variable" layer is shown.

Figure 4 shows that by itself the SiO_x evaporated at 85° would result in a high tilt cell ($\alpha_0 > 25°$). Similarly, the 55° evaporated layer would produce very low tilt ($\alpha_0 < 0.5°$). For sequentially evaporated cells, tilt increases monotonically with increasing thickness of the high-tilt producing, 86° evaporated layer. Tilt is highest when the 86° layer is evaporated over the 55° layer. The error bars include sample-to-sample variations as well as errors inherent in the MCN measurement and in monitoring the spatially averaged SiO_x film thickness. Thus Figure 4 demonstrates simultaneously the effectiveness of the sequential evaporation process and of the MCN measurement technique.

Reduced capacitance

Reduced capacitance versus voltage (C_R–V) at 23°C for TN LCDs with initial molecular tilt angles (α_0) equal to 0.5°, 3.5°, 7.2° and 21.5° are shown in Figure 5. Also indicated in Figure 5 is the correlation between optical

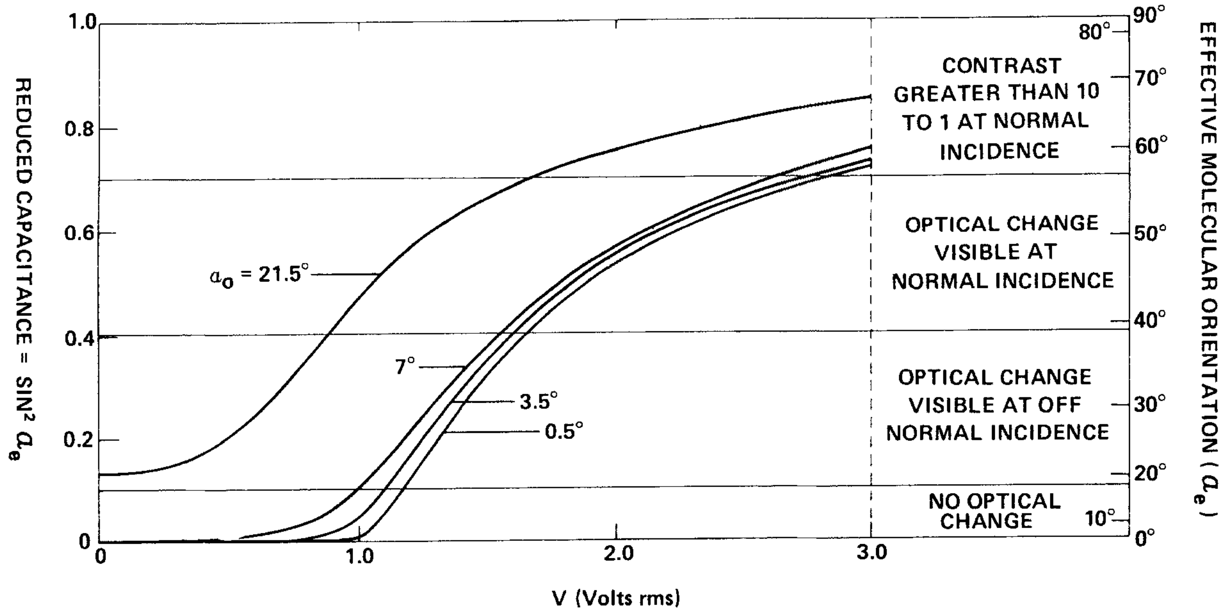

FIGURE 5 Reduced capacitance versus applied voltage with initial molecular tilt (α_0) as a parameter. Qualitative correlation between optical properties and reduced capacitance is indicated. For details see text.

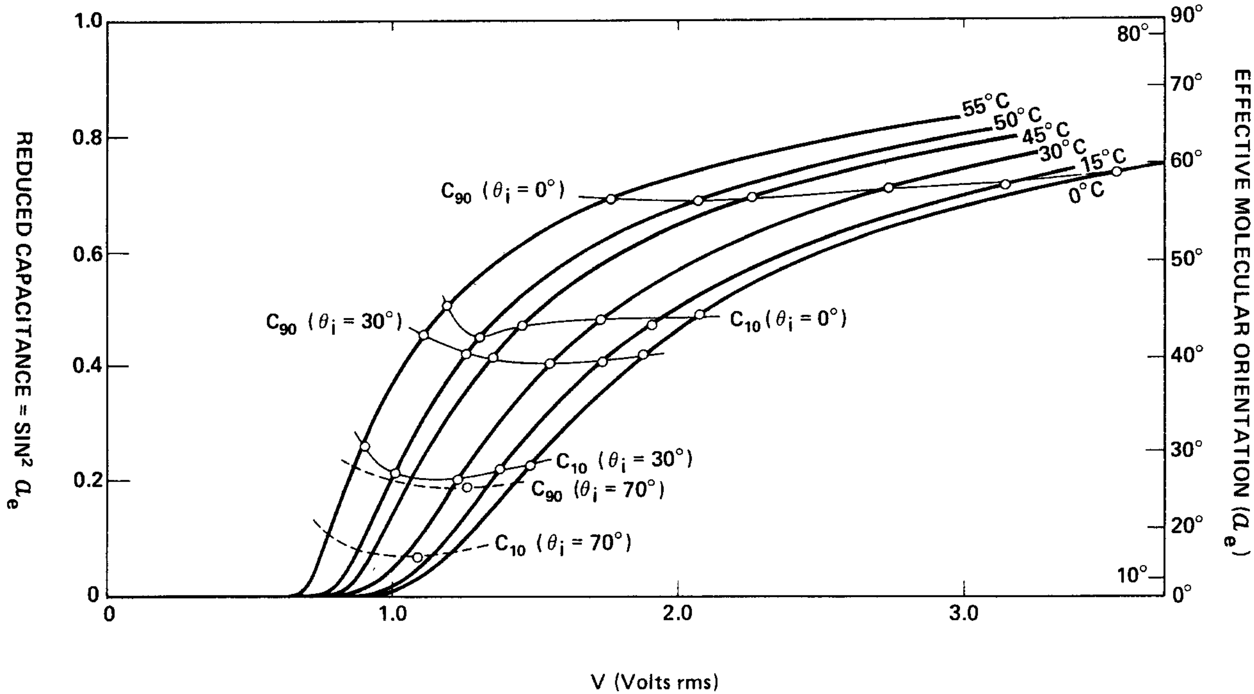

FIGURE 6 Dependence of reduced capacitance on temperature and relation to optical thresholds at various angles of incidence θ_i . $C_x(\theta_i)$ = reduced capacitance for which transmitted light intensity is reduced $x\%$ below zero voltage value for angle of incidence θ_i in principal viewing quadrant.

properties and reduced capacitance. Note that the reduced capacitances for constant transmission are relatively independent of α_0. It is seen that optical changes first become visible at large off-normal incidence angles (in the principal viewing quadrant defined by the direction of average initial tilt α_0) when $C_R \simeq 0.1$. Optical changes are not visible at normal incidence until $C_R \gtrsim 0.4$, and contrast ratios greater than 10 at normal incidence require $C_R \gtrsim 0.7$. It is readily apparent that the various optical thresholds are significantly higher than the capacitance thresholds.[19] The relatively sharp thresholds of low tilt cells and relatively low operating voltages of high tilt cells are also seen in Figure 5.

The dependence of reduced capacitance on temperature is shown in the C_R–V curves of Figure 6 for a low tilt cell ($\alpha_0 = 2°$ at 30°C). Optical thresholds for various angles of incidence, θ_i (in the principal viewing quadrant), are also shown. The contours C_{90} (θ_i) and C_{10} (θ_i) are respectively the C_R values for which cell transmission is 90% and 10% below its zero voltage value for

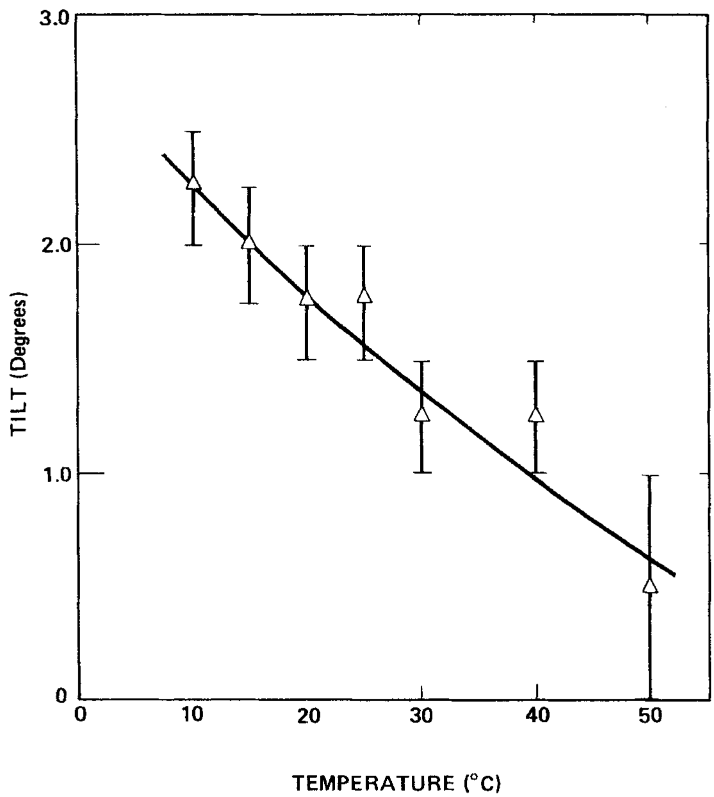

FIGURE 7 Initial molecular tilt (α_0) versus temperature. Same LC cell as in Figure 5.

angle of incidence θ_i. Of particular interest is the relative temperature independence of these contours.

Figure 5 shows that the C_R–V thresholds are very sharp for $\alpha_0 \simeq 0°$ and soften with increasing α_0. Figure 6 shows that the C_R–V thresholds for that particular sample soften with decreasing temperature. We conclude from comparison of Figures 5 and 6 that $\alpha_0 \simeq 0°$ at 55°C and decreases to $\simeq 3°$ at 0°C. This is confirmed by direct MCN determination of α_0 versus T as shown in Figure 7, where we see that α_0 decreases at about 0.04°/°C.

We have found for very low tilt samples ($\alpha_0 \sim 1°$) that the temperature dependence of α_0 can vary $2X$ or more from sample to sample. We believe these sample-to-sample differences originate in small variations in chemical composition of the orienting surface or of the LC itself.

IV EFFECTIVE DIRECTOR MODEL FOR ELECTRO-OPTICAL PROPERTIES

Description of effective director model

Relative capacitance and optical thresholds for twisted nematic cells are shown in Figures 5 and 6. A striking result, immediately evident from these figures, is that the C_R values corresponding to a given level of cell transmission (between crossed polarizers) for a particular angle of incidence, i.e., C_R (θ_i = constant, T_r = constant), is relatively independent of temperature (T) and initial molecular tilt (α_0).

As shown in Section II above, C_R gives a quantitative measure of the reorientation of an LC in response to an applied field. In particular, from Eqs. (9) and (10), an effective director,

$$\hat{d}_e = \hat{y}(1 - C_R)^{1/2} + \hat{z}C_R^{1/2}, \tag{12}$$

represents the orientation of a uniformly aligned cell with the same reduced capacitance, C_R. The results of Figures 5 and 6 indicate that, for a given angle of incidence and LC material, the cell transmission is largely determined by

$$\theta_{rd} = \cos^{-1}(\hat{k}_r \cdot \hat{d}_e), \tag{13}$$

i.e., the angle between the propagation vector $\hat{k}_r$ of the refracted light ray in the liquid crystal and the effective director $\hat{d}_e$. Although this effective director model oversimplifies the electro-optical properties of twisted nematic structures, it provides a useful physical insight into these properties particularly with respect to dependences on α_0 and T.

Physical basis for model

The propagation of light in a twisted nematic cell is controlled by a parameter[3]

$$f = \lambda/p\Delta n, \tag{14}$$

where

$$\Delta n = n_e - n_0, \tag{15}$$

$$n_e = [(\sin^2 \theta_{rd}/n_{\parallel}^2) + (\cos^2 \theta_{rd}/n_{\perp}^2)]^{-1/2}, \tag{16}$$

$$n_0 = n_{\perp}, \tag{17}$$

and λ is the wavelength of light in vacuum, p is the local effective pitch of the nematic twist, and $n_{\parallel}$ and $n_{\perp}$ are the respective indices for light polarized parallel and normal to a uniformly aligned nematic director. Note that p will be a function of θ_i. It can be shown that when $f \ll 1$, the electric field vector of light polarized parallel or normal to a plane containing $\hat{k}_i$ and $\hat{d}$ will lock-in to the twist and be rotated 90°. Application of a field causes the LC molecules to reorient such that a nonuniform pitch results. Both p and Δn decrease with increasing field. For $f > 1$ the polarization vector no longer locks-in to the twist and the cell transmission decreases (between crossed polarizers). If f could be measured directly and birefringence effects are negligible or could be separately accounted for, it would be possible to draw a single valued T_r versus f curve. The effective director model essentially provides a method for determining when the same values for f and hence T_r apply to light transmitted through TN cells characterized by different values of α_0, θ_i, T and V. As a zeroth order approximation, constant C_R implies both constant p and, for a fixed angle of incidence, constant $(\hat{k}_r \cdot \hat{d}_e)$. The latter implies constant Δn, provided $n_{\parallel}$ and $n_{\perp}$ are not strongly temperature dependent. Hence, equal values for C_R imply equal values for transmission for a given value of θ_i. This explains why C_R for constant transmission is relatively independent of α_0, as shown in Figure 5, and temperature, as shown in Figure 6.

V DISCUSSION

$C_R(\theta_i = \text{const}, T_r = \text{const})$ is relatively independent of α_0 and T as shown in Figures 5 and 6. This independence leads to the effective director concept described above and provides the basis for using reduced capacitance as a tool in analyzing optical properties of TN LCDs.

The residual temperature dependence of the $C_x(\theta_i)$ contours in Figure 6 is attributed to temperature dependence of $n_{\parallel}$ and $n_{\perp}$, particularly as T approaches $T_{NI} = 59°C$, and to variations in p due to temperature dependence of the ratios between the Frank elastic constants. The increase in initial slope of C_R versus V with increasing temperature is attributed to an increase of K_{11}/K_{33} with temperature.[20] This T dependence of K_{11}/K_{33} is attributed to formation of cybotactic groups and tendencies to form smectic phases at low temperatures.[20,21] A more detailed discussion of the origin of temperature dependence of V_e has been presented elsewhere.[20]

The dependence of α_0 on temperature shown in Figure 7 can be explained by an extension of the alignment model proposed by Crossland *et al.*[22] They postulate that the aromatic part of the alkyl and alkoxybiphenyl molecules, of which *E*-7 is composed, is strongly attracted to the substrate; but the aliphatic chains may have less affinity for the substrate than for themselves and therefore have a tendency to bend away from the surface, thereby resulting in a net molecular tilt α_0 due to the alignment of subsequent molecular layers. We propose that as a consequence of increased thermal motion and reduced order parameter with increasing temperature, the effect of aliphatic chains or other surface disturbances in producing tilt will be reduced with increasing T, features relating to the specific chemical structure of the LC molecules and the surface being averaged out by the thermal fluctuations. Hence, tilt α_0 decreases with increasing T as observed.

VI CONCLUSION

We have demonstrated that reduced capacitance and magnetocapacitive null measurements are effective tools for analyzing orientation and electro-optical properties of TN LCDs. MCN measurements show that tilt can be accurately controlled by sequential oblique incidence evaporation. Reduced capacitance can be used to determine optical transmission of TN cells as a function of temperature or initial tilt, provided a reference transmission value is available at the same angle of incidence. Data have been presented showing dependence of C_R–V on molecular tilt and temperature. The first observation, to our knowledge, of T-dependence of initial tilt has been reported and a tentative explanation proposed.

Acknowledgments

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