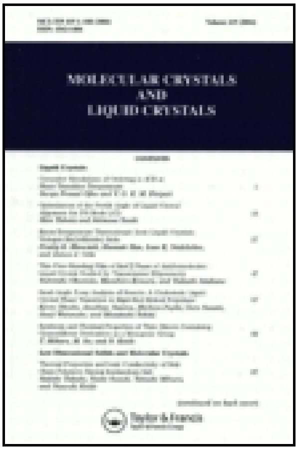

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Interpretation and Nomenclature for the Transmittance vs. Voltage Curves for LCDs

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Interpretation and Nomenclature for the Transmittance vs. Voltage Curves for LCDs

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Like other fields that rapidly change from academic to commercial interest, there is a need for standardization of nomenclature in liquid crystal technology. A case in point involves the interpretative features of the transmittance vs. voltage curves for 90° twisted field effect LCDs. It will be shown that a semi-logarithmic plot is far superior to the linear plot. Considerations must be given to the pronounced interferences that are introduced by internal reflection at the electrode–liquid crystal interfaces when using monochromatic light. Measurements should be made with polars both crossed and parallel.

The features of these plots that have offered varying definitions and measurement details are: (1) zero field transmittance, (2) threshold or critical voltage, (3) interference fringes, (4) 90% turn-on voltage, and (5) saturation voltage. The usual practice of attributing threshold voltage solely to elastic constants and dielectric anisotropy overlooks the dominating factor of surface director tilt. Logarithmic plots quickly reveal the fallacy of the saturation voltage parameter. Transmittance can be shown to continuously change at voltage greater than 4 times the 90% turn-on voltage.

The transmittance versus voltage plot for a liquid crystal display (LCD) provides information of considerable interest for both theoretical and practical purposes. Figure 1 shows such a plot for an experimental 90° twist, field effect, LCD filled with an ester blend liquid crystal (LC) mixture. There are six attributes of this plot that have been singled out in the LC literature and identified in Figure 1. Some of these attributes have little or misinterpreted significance, and this becomes apparent when examining numerous LCD's with the data replotted in log transmittance versus voltage coordinates with polars in both crossed and parallel orientations.

It should be noted that this paper is concerned only with measurements made at normal incidence with transmitting cells. The instrumentation used is a modification of an apparatus designed for light scattering measurements.[1] The important elements of the apparatus are identified in Figure 2. The light

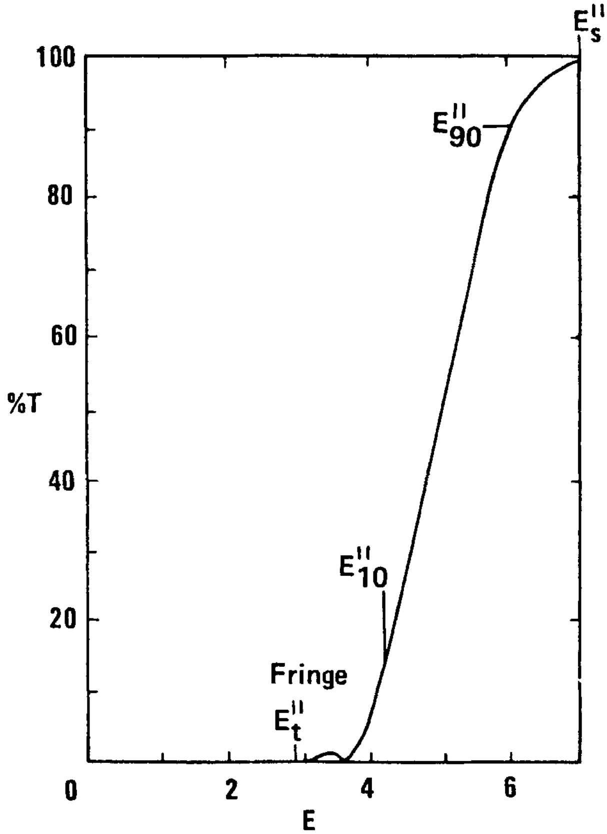

FIGURE 1 Transmittance vs. voltage for a 90° twist cell, ester blend LC, $\frac{1}{4}$ mil spacers, normal incidence, parallel polars, $\psi = 90°$, surface director parallel to the cell plates.

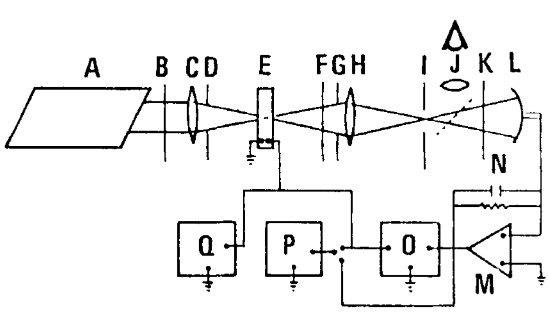

FIGURE 2 Simplified diagram of the instrumentation (see test for identification of components).

source *A* is a helium neon laser providing monochromatic polarized radiation of 632.8 nm wavelength. B is a 25 % neutral density strain-free filter that serves to minimize optical feedback to the laser from samples oriented precisely normal to the beam. C is a 10 cm focal length lens which focuses the beam to a diameter of approximately 70 μm at the LCD sample at position E. Three mm diameter apertures at D and G minimize the detection of stray rays. The polaroid analyzer at F is mounted in a rotating stage. The relay lens H images the sample onto the Field Stop I with unity magnification. The field stop usually had a diameter of three to five times the nominal beam diameter at the sample. A telescope J permitted viewing the sample at sixty times magnification and facilitated alignment of the sample. This telescope was moved out of the beam when using the detector. Additional neutral density filters at K attenuated the light beam to a suitable level for the polarization insensitive detector at L. Not shown is the mount for the sample. It allowed a translation about two axes and a rotation about two axes. A square wave function generator Q powered the LCD, and a digital voltmeter P precisely monitored this voltage. A high speed galvanometer recorder O, as well as the DVM, served as readout of the optical signal. Scale expansion was facilitated by removal of one or more attenuators. In the absence of a sample, the ratio (extinction) of optical signals with the analyzer in parallel and crossed positions exceeded 10^5.

In the preparation of plots such as Figure 1, it is first necessary to orient the cell normal to the beam, then orient the surface director (on the side of the cell facing the source) perpendicular to the plane of polarization of the incident light. Instrument gain is then adjusted to normalize the response when a high voltage (± 16 v) is applied to the sample with the polars parallel. The instrument is zeroed with the beam blocked.

Soon after using the above instrument with LCD's it became obvious that interference between reflected beams within the cell introduced significant errors if not properly taken into consideration. In particular, the sum of the transmittances with polars parallel and perpendicular did not equal 1. The interfering reflections were found to arise at the LC–electrode InO_2–SnO_2 interfaces. This is to be expected because the InO_2–SnO_2 has a refractive index of about 2. The amplitude of the interference may exceed 20 % of the total optical signal. The interference varies with the optical path between the reflecting interfaces, and this optical path is the product of refractive index and LC thickness. LCD's are not made with a thickness control better than a few light wavelengths, hence interference varies within and between LCD's. Of more concern, the refractive index may vary with LC molecular orientation, hence with voltage applied to the cell. When a zero twist cell is studied, the refractive index varies with voltage if the molecular director is parallel to the plane of polarization. It does not do so when the director is perpendicular to this plane. In a 90° twist cell, it is not possible to orient the cell for zero interference at all voltages.

However, the effect is minimized when the front surface director is perpendicular to the incident plane of polarization (POP). This effect is seen in Figure 3. The upper portion of this figure shows the 45 Hz electrical signal applied to the cell while the lower portion reveals the light intensity. The analyzer was removed when making this recording so the detector did not respond to retardation. Interference exists when the front surface director is perpendicular to the incident POP, because there is an incomplete rotation of the POP within the cell at intermediate voltages. The E vector of the light beam then encounters a finite component of the molecular axis. This interference introduces an unavoidable error in transmittance versus voltage

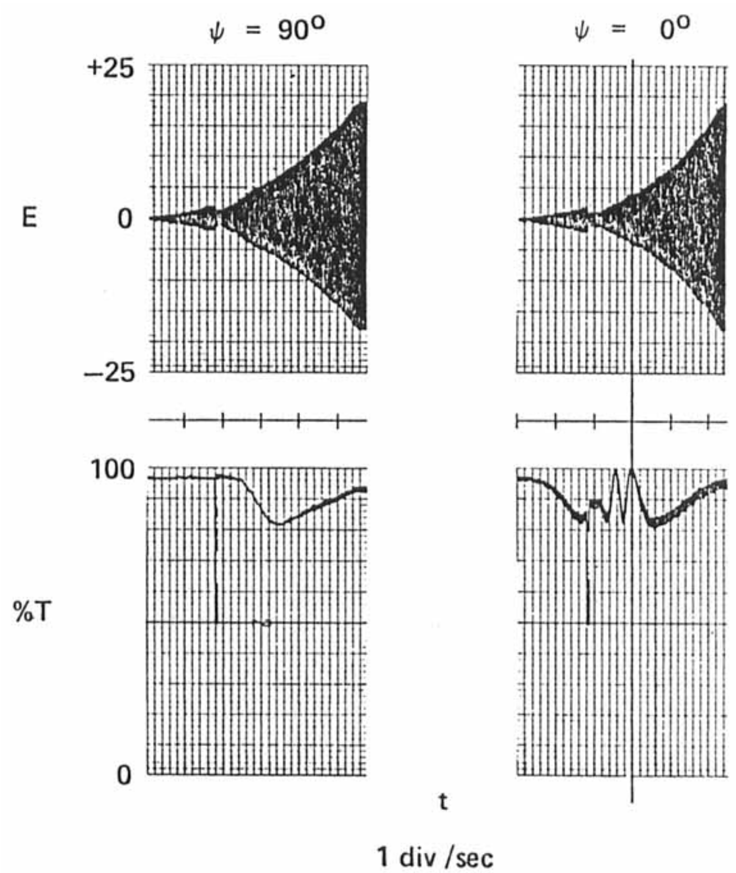

FIGURE 3 Voltage envelope (upper) and transmittance (lower) versus time for a ramped 45 Hz signal. ψ is the angle between the incident POP and the front surface director.

curves when using monochromatic light. However, the error expressed as a fraction of the detected signal is small at low transmittance levels. Careful measurements with properly oriented samples with and without the analyzer have shown that the sum of the transmittances with parallel and crossed polars does indeed equal 1. By making measurements with the analyzer in both orientations, the full range of reading can be obtained while the observed transmittance never need exceed 50%. Low transmittance readings can be expanded by simply removing the attenuators from the beam without sacrificing the signal to noise ratio. The expansion limit is set by the extinction ratio of the analyzer. In the above instrument, it is possible to make transmittance readings down to 0.001%. Much of the useful information in the T versus E curves is found in the region of low transmittance. It now becomes obvious that a linear plot is inappropriate.

The log transmittance versus voltage curves for three different types of experimental cells are included here to illustrate the different features of these curves. The cell plates were separated by plastic strips and held together with clamps. Essentially the same ester type liquid crystal mixture was used in all three cells. They differ in thickness, twist and surface director tilt. This tilt was controlled either by the angle at which the oxide layer was deposited,[2] or by rubbing.

ZERO FIELD TRANSMITTANCE, $T_0^{\parallel}$

The transmittance of an LCD with parallel polars can significantly affect contrast ratios, hence may be of practical importance. Theoretically, it has been shown that the $T_0^{\parallel}$ can range anywhere from 0–12% (of the maximum transmittançe after correcting for reflection and absorption losses), depending upon LC birefringence, thickness, and wavelength.[2] The wavelength dependence of T_0 is reponsible for the slight color (crossed or parallel polars) seen in LCD's at normal incidence. Commerical LCD's are usually of a thickness that $T_0^{\parallel}$ cannot reach 12%, but does oscillate between 0 and 4% within normal production tolerances on thickness. With polychromatic light, the wavelength integrated transmittance has a smaller amplitude and never reaches zero.

THRESHOLD VOLTAGE, E_t

Figure 4 shows a pronounced threshold voltage below which there is no change in transmittance. The LC literature assigns this threshold voltage to a function of elastic constants and dielectric anisotropy with no reference to the

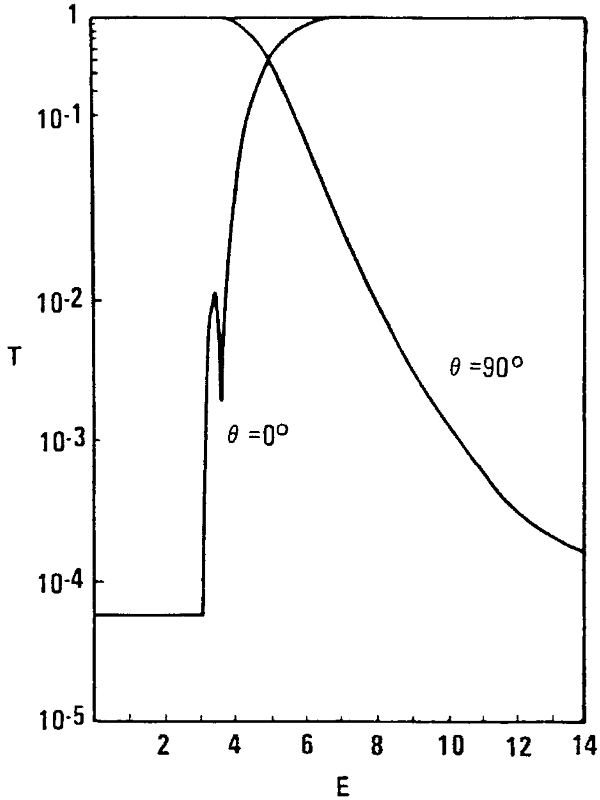

FIGURE 4 Log transmittance vs. voltage, same cell as Figure 1, parallel ($\theta = 0°$) and crossed ($\theta = 90°$) polars.

dominating influence of surface director (SD) tilt. In Figure 5 E_t approaches zero. There is little difference in composition of the LC, hence, in the elastic constants and dielectric anisotropy of these two cells. The difference is in the angle at which the oxide layer was deposited, hence the SD tilts are different.[2] When the SD tilt is nearly zero, the field-induced torque on the LC molecule is nearly zero, irrespective of molecular parameters. Of course, thermal motion prevents the LC molecules from remaining exactly normal to the field lines, hence, torque is then affected by molecular parameters.

It is impractical to make LCD's with zero SD tilt, because the cells break up into regions of reverse tilt, and scatter light badly. The threshold voltage can be used as a sensitive measure of SD tilt, but only in cells having a very small tilt angle. The threshold voltage for the rubbed cell (Figure 6) was 1.8 v and the surface director tilt for a similar rubbed cell has been shown to be 2.9°.[3]

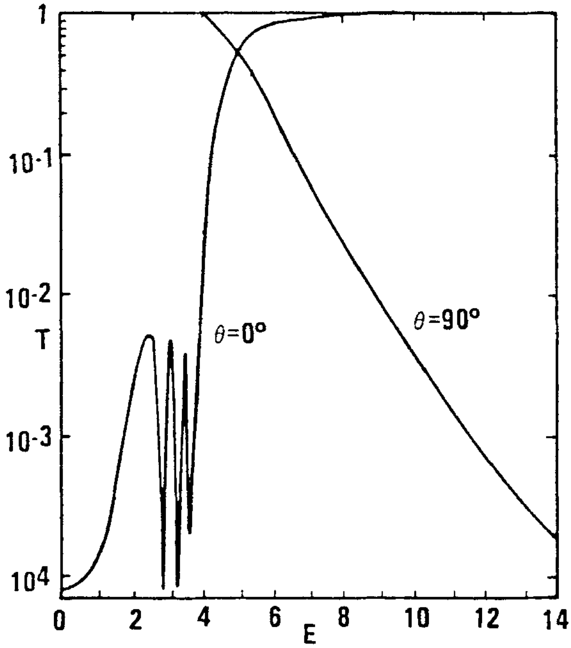

FIGURE 5 Log transmittance vs. voltage for a 90° twist cell, ester blend LD, normal incidence, $\psi = 90°$. Surface director tilted approximately 25°. $d = \frac{3}{4}$ mil.

FRINGE COUNT

A 90° twisted LCD does not perfectly rotate the POP by 90°. Theoretical studies have shown that a component of wavelength and thickness dependent retardation remains.[4] This retardation component introduces cyclic oscillations in the T versus E curve with maxima and minima occurring at almost the same voltages as would occur in untwisted cells oriented with the optic axis 45° to the POP although with much reduced amplitude. The fringes are easily seen in the log T vs. E curves. They are influenced by wavelength, cell thickness, and liquid crystal birefringence. Usually a count on the number of fringes will indicate cell thickness and this is verified on comparing figures 4 and 5. However, the redistribution of twist accompanying a slow change in voltage often results in a loss of fringe detail. As discussed elsewhere,[5] it is better to measure the fringes on the leading edge on an abruptly applied voltage pulse when inferring cell thickness. In order to differentiate these fringes from those arising from interference between reflected rays, I have found it convenient to call them residual retardation (RR) fringes.

TEN PERCENT VOLTAGE $E^{\parallel}_{10}$

The voltage at which the transmittance reaches 10% of "saturation" with parallel polars has been used by some investigators to describe the onset of LC reorientation. Some have called this voltage the threshold voltage. The $E^{\parallel}_{10}$ value always occurs in the vicinity of the RR fringes, hence is sensitive to wavelength and cell thickness. Since the first order RR fringe can have a maximum transmittance of 12%, it is possible to observe three $E^{\parallel}_{10}$ points on a $\log T$ versus E curve. This situation is manifested in Figure 6. I believe use of an $E^{\parallel}_{10}$ designation should be discouraged. If another number is needed to describe the shape of the T versus E curve an E_{50} (voltage for 50% transmittance) would be more definitive.

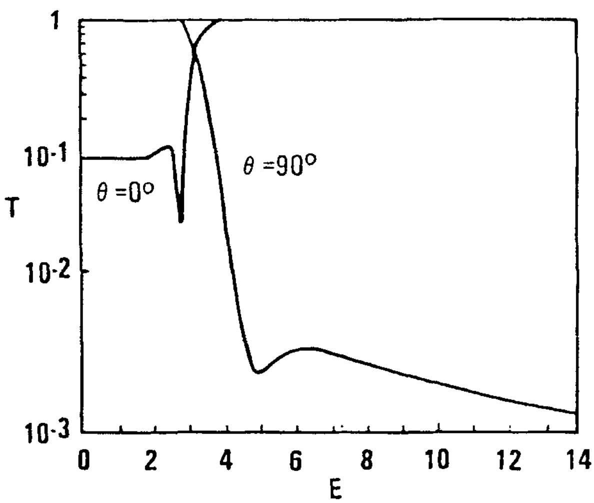

FIGURE 6 Log transmittance vs. voltage for an 88° twist cell, ester blend LC normal incidence, surface director orientation determined by rubbing. $d = \frac{1}{4}$ mil.

NINETY PERCENT VOLTAGE $E^{\parallel}_{90}$

The voltage at which transmittance reaches 90% of saturation with parallel polars is probably the single most significant point on the T versus E curve as far as display purposes are concerned. Properly measured, it is unambiguous and nicely describes the minimum operating voltage for most display purposes. The $E^{\parallel}_{90}$ should be measured using crossed polars and calculated from the equation $E^{\parallel}_{90} = 1 - E^{\perp}_{10}$. For reasons discussed above the direct measurement of $E^{\parallel}_{90}$ with parallel polars is subject to large errors caused by interference.

SATURATION VOLTAGE $E_s^{\parallel}$

The voltage above which there is no appreciable increase in transmittance in T versus E plots has been called the saturation voltage, $E_s^{\parallel}$. When E measurements are made at voltages above E_{50} by use of crossed polars and the relationship $E^{\parallel} = 1 - E^{\perp}$, it becomes evident that there is no saturation voltage below the point of dielectric breakdown. The transmittance continues to change at voltages several times $E_{90}^{\parallel}$. This is clearly seen in Figures 4, 5, and 6. There is significant information in the T versus E curves above $E_{90}^{\parallel}$.

The transmittance at three times the $E_{90}^{\parallel}$ is sensitively determined by the twist angle in the cell. Elsewhere, it is shown that twist is retained in the LC cells at voltages considerably above $E_{90}^{\parallel}$.[5] However, the component of molecular birefringence in a plane normal to the beam is so small, the cell rotates the POP very inefficiently. Some retardation does occur, and this influences light transmission. When the twist angle is less than 90°, the transmittance will exhibit a high voltage minimum as seen in Figure 6. The lowest transmittance between crossed polars at voltages more than twice $E_{90}^{\parallel}$ is obtained when the twist is exactly 90°. For these reasons, use of the term "saturation voltage" should be discouraged. In its place the transmittance, $T_{op}^{\perp}$, between crossed polars, at the operating voltage may have value in predicting the ultimate contrast ratio. However, the temptation to quote contrast ratios on the basis of normal incidence laser illuminant measurements should be resisted. There is need for the LCD industry to standardize the illuminating and viewing conditions for such quoted properties as contrast ratio. The above described laser measurements are most informative of the structure of the LCD, but are of limited value in describing the visual appearance of an LCD.

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