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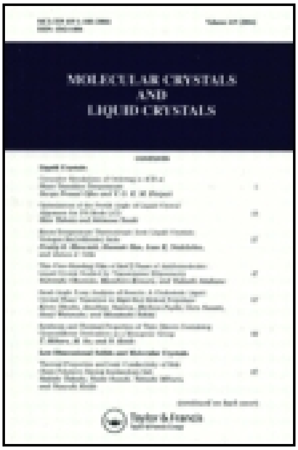

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Optical Properties of 90° Twisted Nematic Liquid Crystal Displays; Estimation by Colorimetry

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Optical Properties of 90° Twisted Nematic Liquid Crystal Displays; Estimation by Colorimetry†

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Colorimetric technique was applied to the estimation of the optical properties of 90° twisted nematic displays. It is possible to explain semi-quantitatively the facts which are well known empirically but interesting and important to us such as the optimum gap thickness, gap allowance and comparison of display performance with parallel polarizers and crossed ones.

INTRODUCTION

Liquid-crystal displays, especially 90° Twisted Nematic (TN) displays are now widely used. However, these devices still have insufficient performances in such as response times, viewing angles and contrast ratio. Response times of liquid crystal devices are dependent on viscosity η, cell gap thickness d, elastic constants K, etc., so that rise time τ_r and decay time τ_d are given as follows:[1]

$$\tau_r = \eta d^2(\epsilon_0 \Delta\epsilon E^2 - K\pi^2)^{-1} \tag{1}$$

$$\tau_d = \eta d^2 / K\pi^2 \tag{2}$$

It is obvious, especially, the response of liquid crystal is proportional to the square of the thickness d; the thinner the cell, the shorter the response time.

†Presented at the Eighth International Liquid Crystal Conference, Kyoto, July 1980.

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Meyerhofer noted that a good display device is obtained by use of thin cells, small values of birefringence and near planar aligned at the surface.[2] However, it is well known empirically that thinner cells give lower contrast and worse color uniformity of appearance of the device.

The purpose of this paper is to explain semi-quantitatively the optimum gap thickness, the gap tolerance Δd and comparison of display performance with parallel polarizers and crossed ones.

TN liquid crystal structure occurs when the molecules on the surfaces align homogeneously (parallel) and molecules form a portion of a herical twist as a function of distance through the layer. Normally, the twist is 90°. To a first approximation, the direction of polarization of light entering the cell normal to the plane of the molecules is rotated 90° by the layer. Actually, it is well known the normal mode are slightly elliptical; thus, in TN device, the birefringence and the optical rotation are combined. For parallel polarizers, Gooch-Tarry and McIntyre gave independently the equation of the transmission of TN cells in normal mode, given by the following equation:[3,4]

$$T = \sin^2 \frac{\pi}{2} \sqrt{1 + u^2}/(1 + u^2) \tag{3}$$

where $u = 2d\Delta n/\lambda$, Δn is the birefringence of the liquid crystal and λ is the wave length of the transmitted light.

EXPERIMENTAL METHOD AND ANALYTICAL APPROACH

Our experiments are divided into three parts; the measurement of birefringence of liquid crystals (LC) used, that of transmission of 90° TN cells with various cell thickness, and the observation of appearance of 90° TN cell constructed in a wedge-type cell. In order to measure birefringence of LC, especially parallel alignment cells (homogeneous cells) were constructed. Molecular alignment of these cells was produced using either the rubbing or 60° oblique evaporation of SiO. Cell thickness was controlled by Mylar spacers and determined by optical interference method. Used LC in our experiments were E-7, E-8, E-18 (BDH), and ZLI-1132 (Merck), by weight containing 0.01–0.05 wt% of cholesteryl nonanoate (CN) to eliminate disclinations in all samples.[5]

Determination of the birefringence was done by measuring retardation of LC, and thickness that is independently obtained; Figure 1 shows the results. Solid lines show the values obtained by the method of least square.

The transmission was measured as a function of wavelength for each cell using a spectrophotometer, taking care to align the polarizers accurately in

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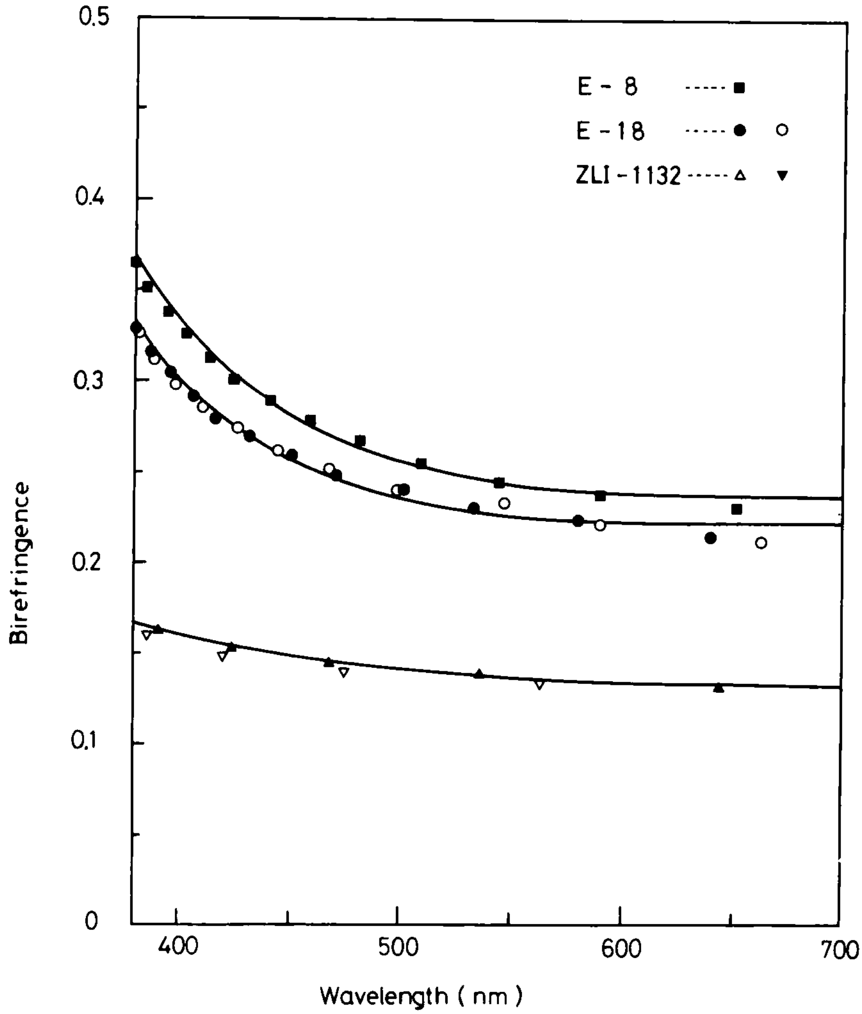

FIGURE 1 Birefringence versus wavelength. Solid lines show the values obtained by the method of least square.

appropriate direction. Polarizers used were LC2-81-18 manufactured by Sanritsu Electric Co., Ltd.

One of the subjects of our experiments is to decide the validity of the Eq. (3) given by Gooch-Tarry and McIntyre. Figure 2 shows several examples of the observed data and the calculated values obtained from Eq. (3). It can be seen that these experimental values are in good agreement with the calculated ones; therefore the validity of the Eq. (3) seems to be adequate, we will use this equation hereafter.

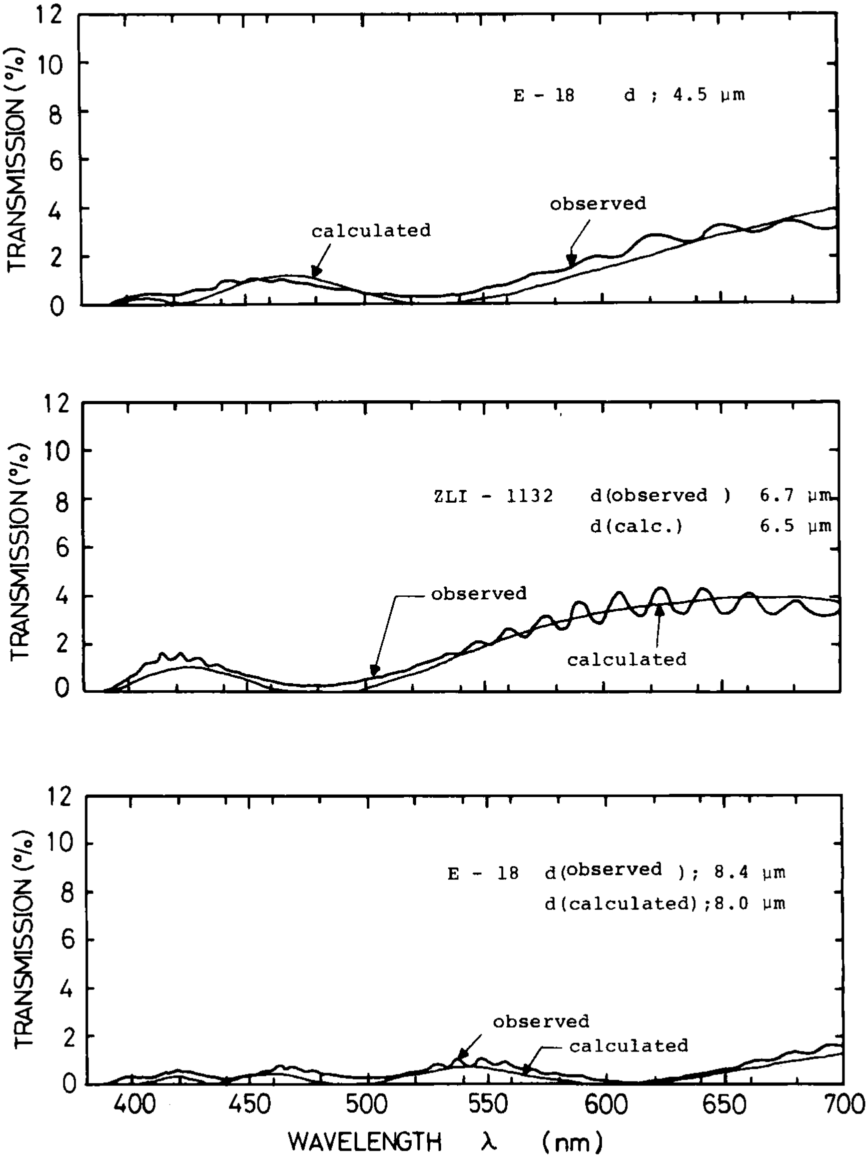

FIGURE 2 Comparison with the observed data and the calculated values obtained from the Eq. (3).

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DISCUSSION

a. Optimum gap thickness

Of more practical interest is the brightness and contrast ratio of a display as it appears to an observer when illuminated with white light. These quantities are calculated by employing standard photometric procedures taking into account the spectral content of the illumination and wavelength sensitivity of the eye. Therefore, we adopt the physical colorimetry to evaluate a 90° TN display device. First, the perceived brightness (lluminous transmittance) is given as

$$Y_0 = \frac{1}{K}\int S(\lambda)T(\lambda)\bar{y}(\lambda)d\lambda \qquad (4)$$

where $S(\lambda)$ is the spectral irradiation of the illumination, $T(\lambda)$ is the transmission of the display, $\bar{y}(\lambda)$ is the standard luminous efficiency function of the eye, and $K = \int S(\lambda)\bar{y}(\lambda)d\lambda$.[6] We calculated the luminous transmittance Y_0 using (3), (4), and the data of birefringence and investigated the dependency of Y_0 on the cell thickness d. Figure 3 shows this result. Y_0 decreases accompanying a periodic oscillation.

Incidently, we also have investigated the dependency of x, y on the cell thickness in the co-ordinate of the C.I.E. 1931 system and u, v in that of the C.I.E. 1960-U.S.C. system. The quantities x, y and u, v change initially very largely and later gradually with the increase of the cell thickness, and become to neutral color ultimately.

For usual TN device, it is the brightness that effects the display performance mostly. For parallel polarizers, the brightness in the off-state should be as low as possible. Therefore, we define the useful minimum cell thickness d_u, such the minimum thickness whose transmission is certainly less than 1% as shown in Figure 3; this definition seems to be acceptable. Figure 4 shows the useful minimum cell thickness d_u as a function of birefringence Δn at 550 nm. Δn approaches to zero, while d_u nears an infinity. In other words, Δn becomes larger, d_u approaches to zero at the same time. Experimentally, the useful minimum thickness is given by

$$d_u = A(\lambda)/\Delta n(\lambda) \quad [\mu\mathrm{m}] \qquad (5)$$

where $A(\lambda)$ is nearly equal to unity at 550 nm. This result coincides with Maughin limit $d = 2\lambda/\Delta n$.[7] For example, d_u is 4–5 μm for E-7, E-18, and is 7–8 μm for ZLI-1132.

To certify this estimation, we have compared this relation with the observed results. Figure 5 shows appearance of 90° TN cells, which are constructed in wedge-type cell. From the top, ZLI-1132, E-8, and E-18, respectively. It is ob-

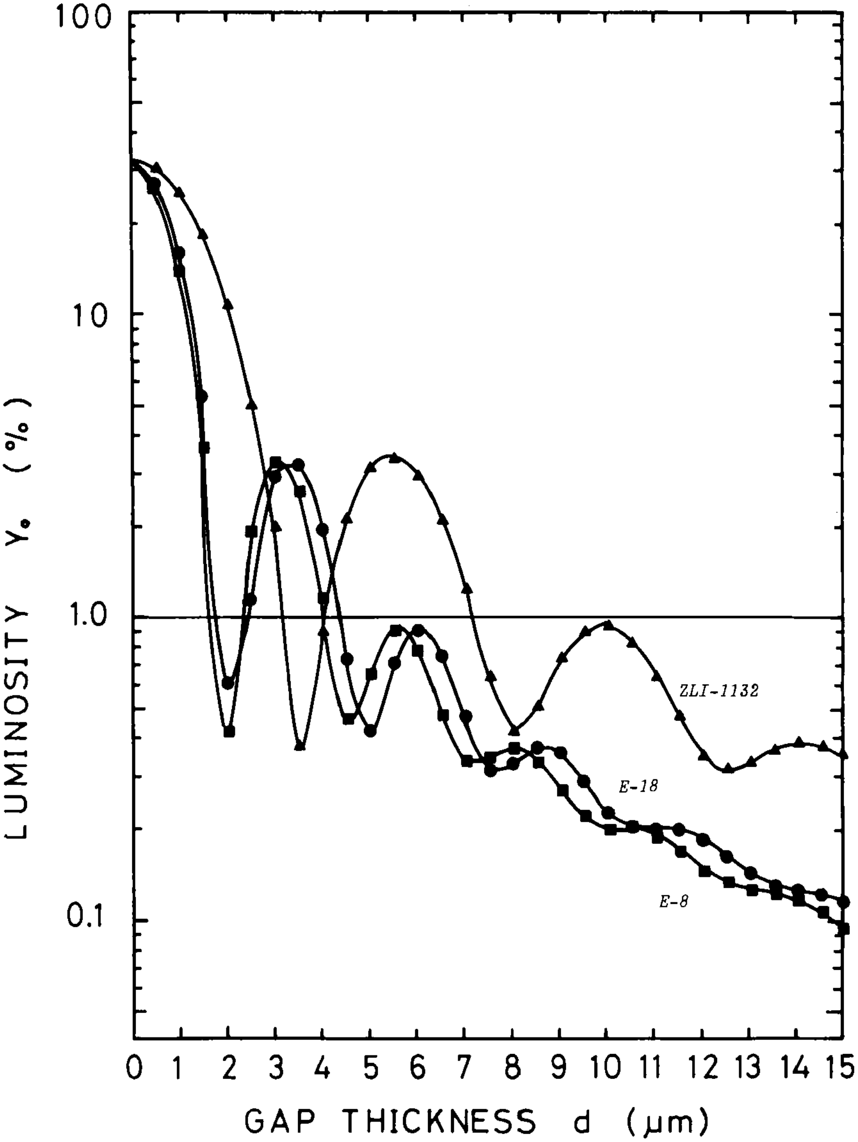

FIGURE 3 Luminous transmittance Y_0 versus gap thickness d; for parallel polarizers.

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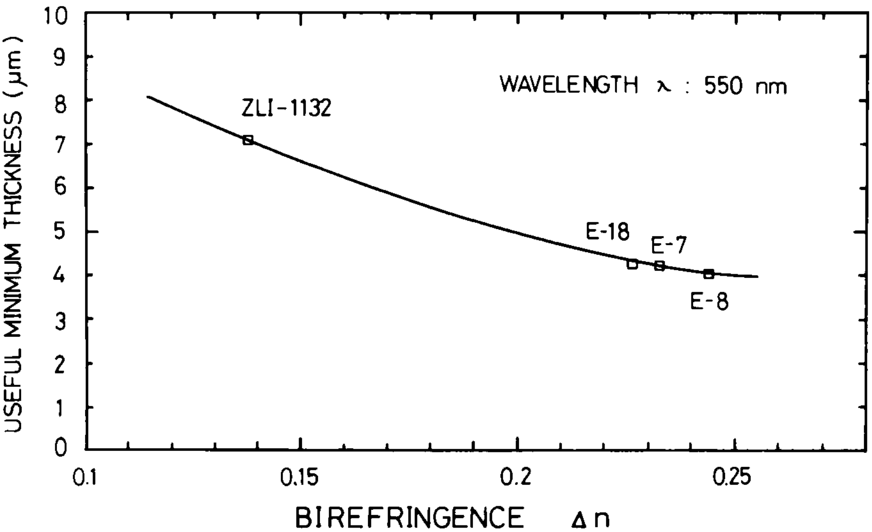

FIGURE 4 Dependency of the useful minimum gap thickness d_u on the birefringence of LC.

vious from this figure, in the devices with the thickness larger than d_u, brightness is low enough.

b. Contrast ratio

If we assume that a device is operated by extremely high voltage, liquid crystal alignment will be quasi-homeotropic state. Therefore, Y_∞ will be equivalent to the luminance of the parallel polarizers used, neglecting the absorption of LC. Contrast ratio CR is defined as $CR = Y_\infty / Y_0$.[8] Figure 6 shows CR versus gap thickness. Contrast ratio also increase with the increase of d, not monotonously. With the increase of gap thickness the curve shows steep rise in the initial stage and after making some rise-and-fall, it finally approaches to a saturated value. CR is dependent on both d and Δn very much. At d_u that we defined earlier, contrast ratio is about 20.

c. Gap allowance

We have employed color difference ΔE as[9]

$$\Delta E = [(\Delta U^*)^2 + (\Delta V^*)^2 + (\Delta W^*)^2]^{1/2} \tag{6}$$

where

$$\begin{aligned} W^* &= 6.6439[\log Y + 4] \\ U^* &= 13\, W^*(u - u_0) \\ V^* &= 19.5\, W^*(v - v_0) \end{aligned} \tag{7}$$

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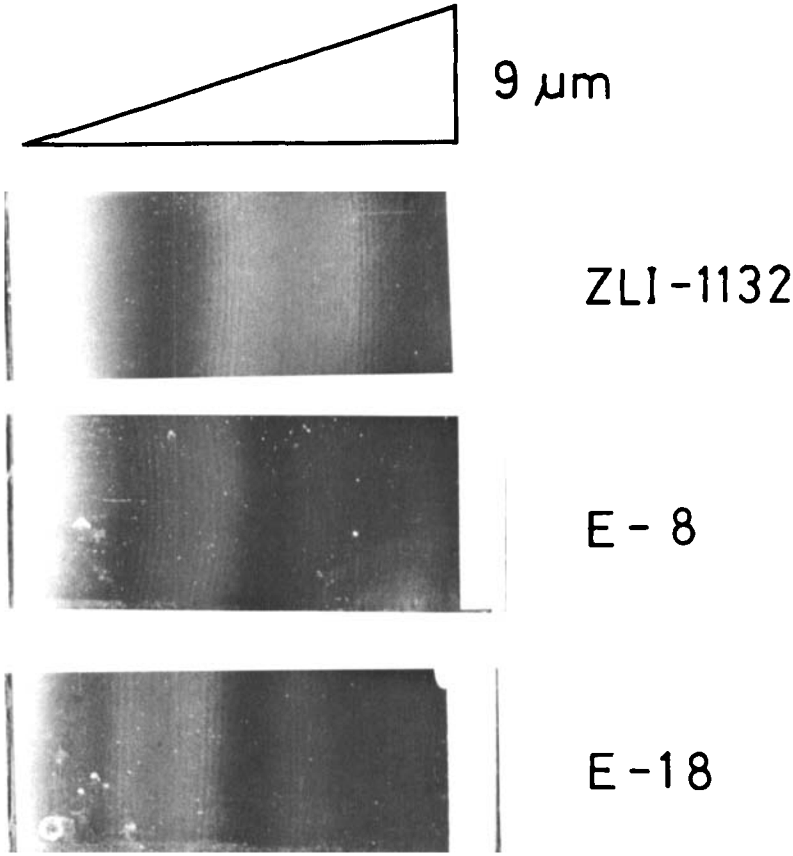

FIGURE 5 Observation of the appearance of 90° TN cells constructed in Wedge-type cell.

where u, v are chromaticity coordinates of the UCS chromaticity diagram, u_0, and v_0 are the chromaticity coordinates of the white point at a given color temperature, and Y is the brightness. The gap allowance Δd is so defined the color difference ΔE due to this allowance should be within 2.0 C.I.E.-unit. That is,

$$\Delta E \lesssim 2.0 \text{ C.I.E.-unit.} \tag{8}$$

Namely, the color uniformity is maintained within Δd. Figure 7 shows gap allowance Δd versus gap thickness d in the case of TN device with parallel polarizers, calculated from the condition (8). Used LC were E-18 and ZLI-1132, respectively. Δd also in this case increases with increase of d, not monotonously but with periodicity.

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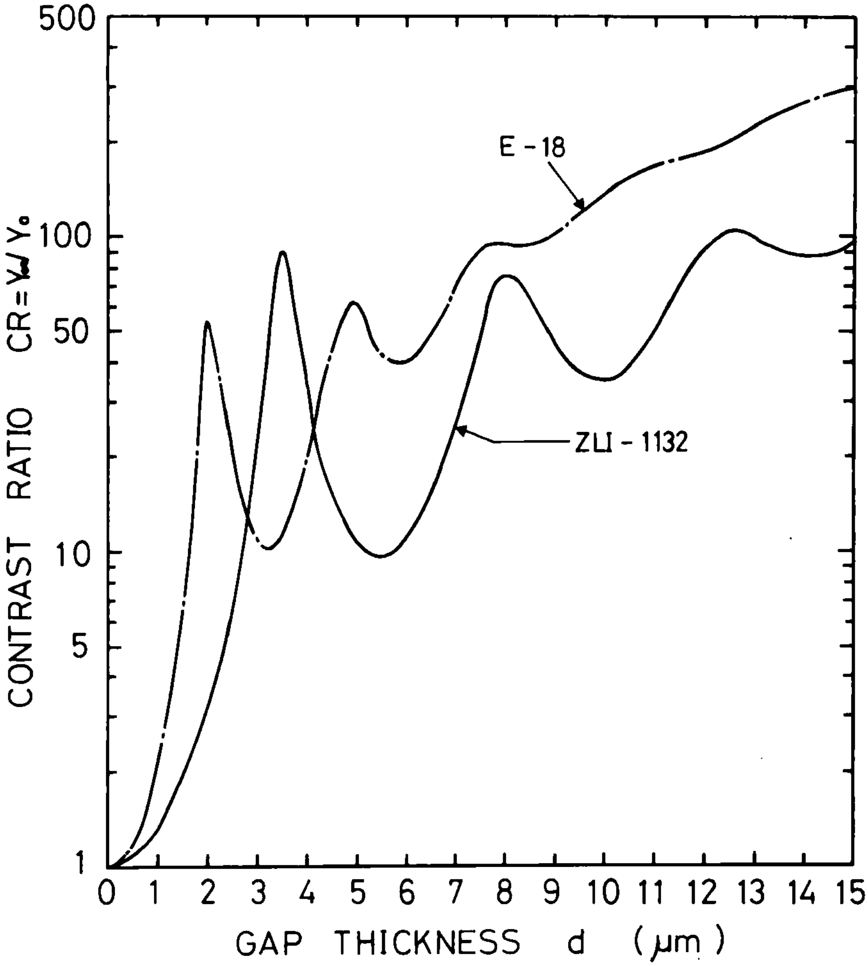

FIGURE 6 Contrast ratio $CR = Y_\infty / Y_0$ versus gap thickness d; for parallel polarizers. (TN device is assumed to be operated by extremely large voltage).

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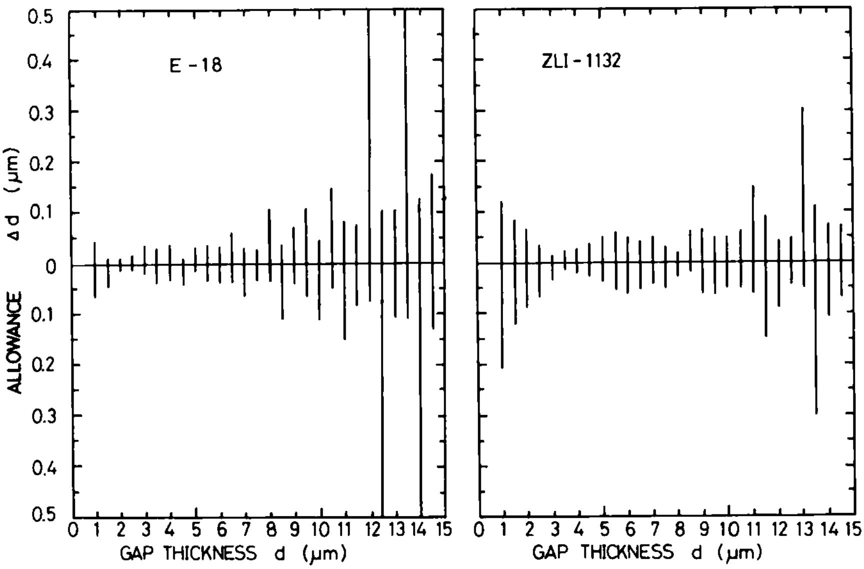

FIGURE 7 Gap allowance Δd versus gap thickness d for parallel polarizers.

d. Comparison of TN display performance with parallel polarizers and crossed ones

Thus far, we have discussed the case of TN devices with parallel polarizers (negative display). We have taken the same consideration into the case of crossed polarizers (positive display). Figures 8, 9 and 10 show the luminous transmittance Y_0 versus gap thickness d, contrast ratio $CR = Y_0/Y_\infty$ against d and gap allowance (torelance) versus d, respectively. It can be seen that Y_0, CR and Δd also increase with increase of gap d. However, by making comparison with negative display, Y_0 and CR of the positive type more quickly reach to a saturated value than negative type. Furthermore, gap allowance Δd of positive type is much larger than that of negative ones.

CONCLUSION

We have evaluated the optical properties of 90° TN devices using physical colorimetry. We have three results.

1) We can determine the useful minimum thickness d_u, where the contrast ratio, response times of TN devices are enough satisfactory.

2) By introducing color difference ΔE, the gap allowance Δd will be estimated.

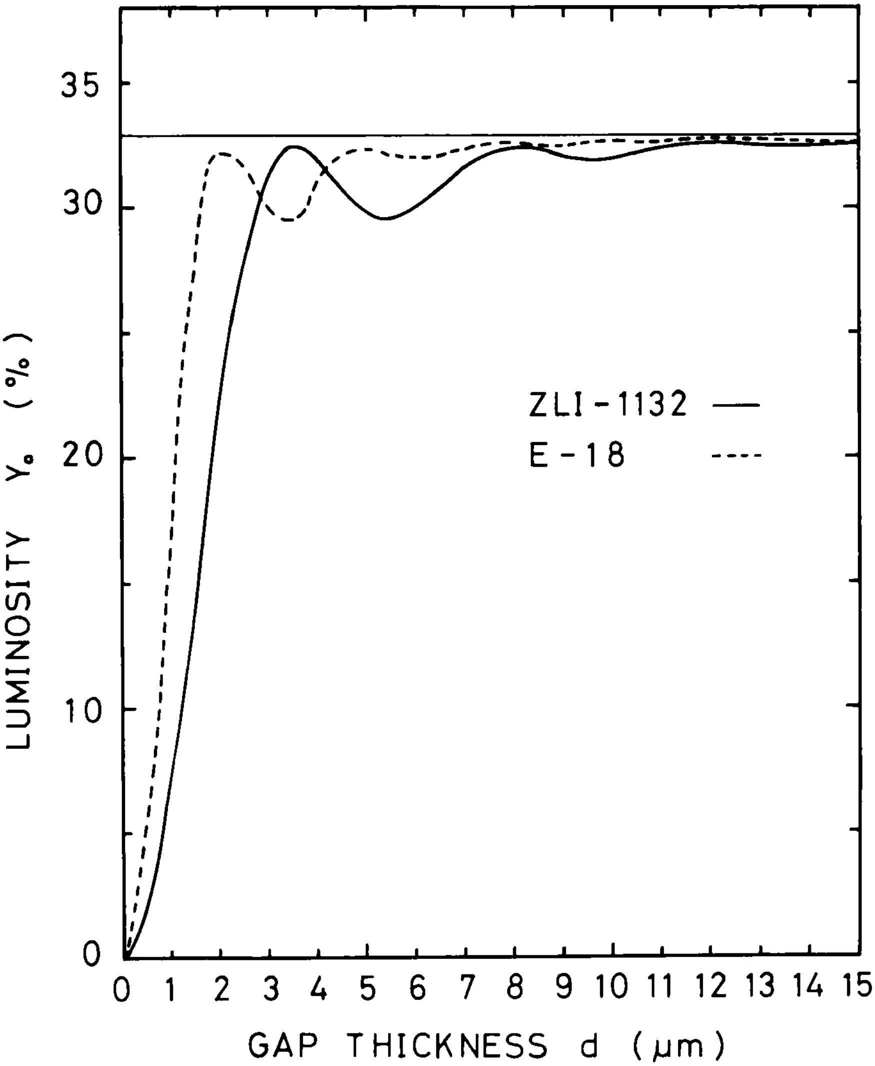

FIGURE 8 Luminous transmittance Y_0 versus gap thickness d for crossed polarizers.

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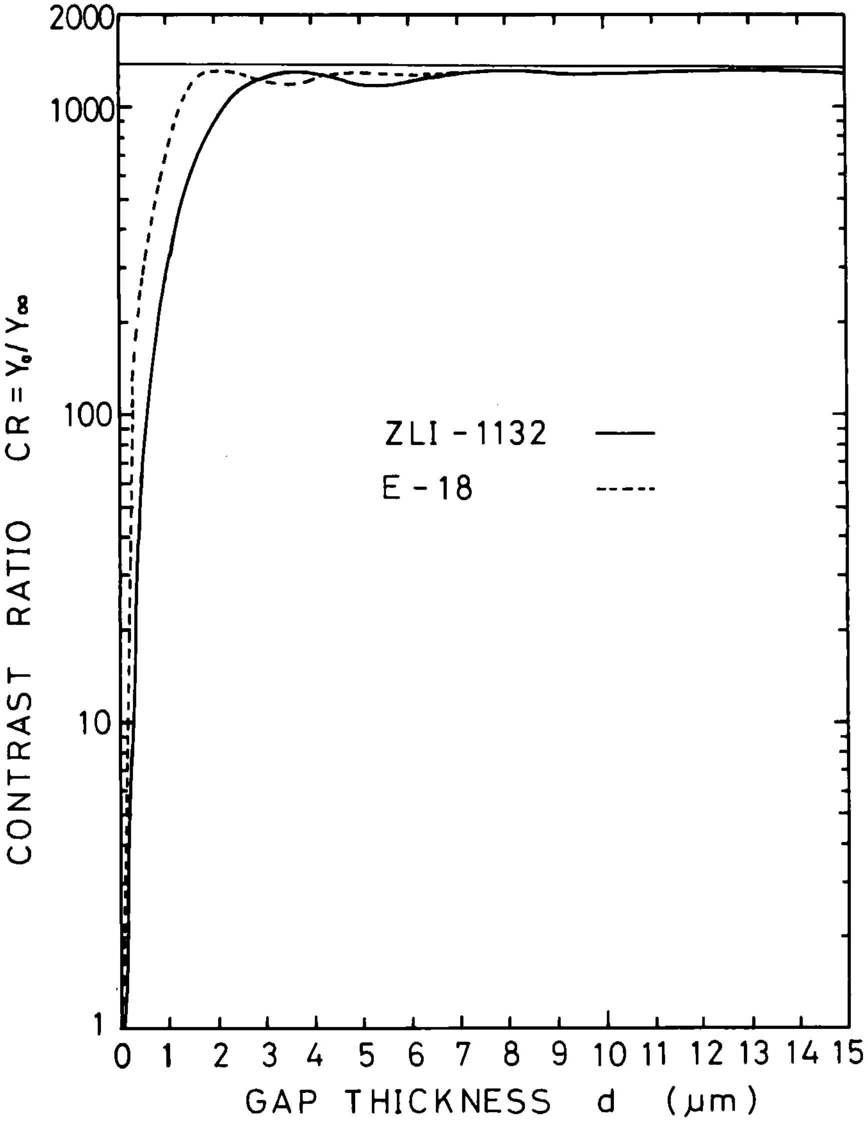

FIGURE 9 Contrast ratio $CR = Y_0/Y_\infty$ versus gap thickness for crossed polarizers. (TN device is assumed to be operated by extremely large voltage).

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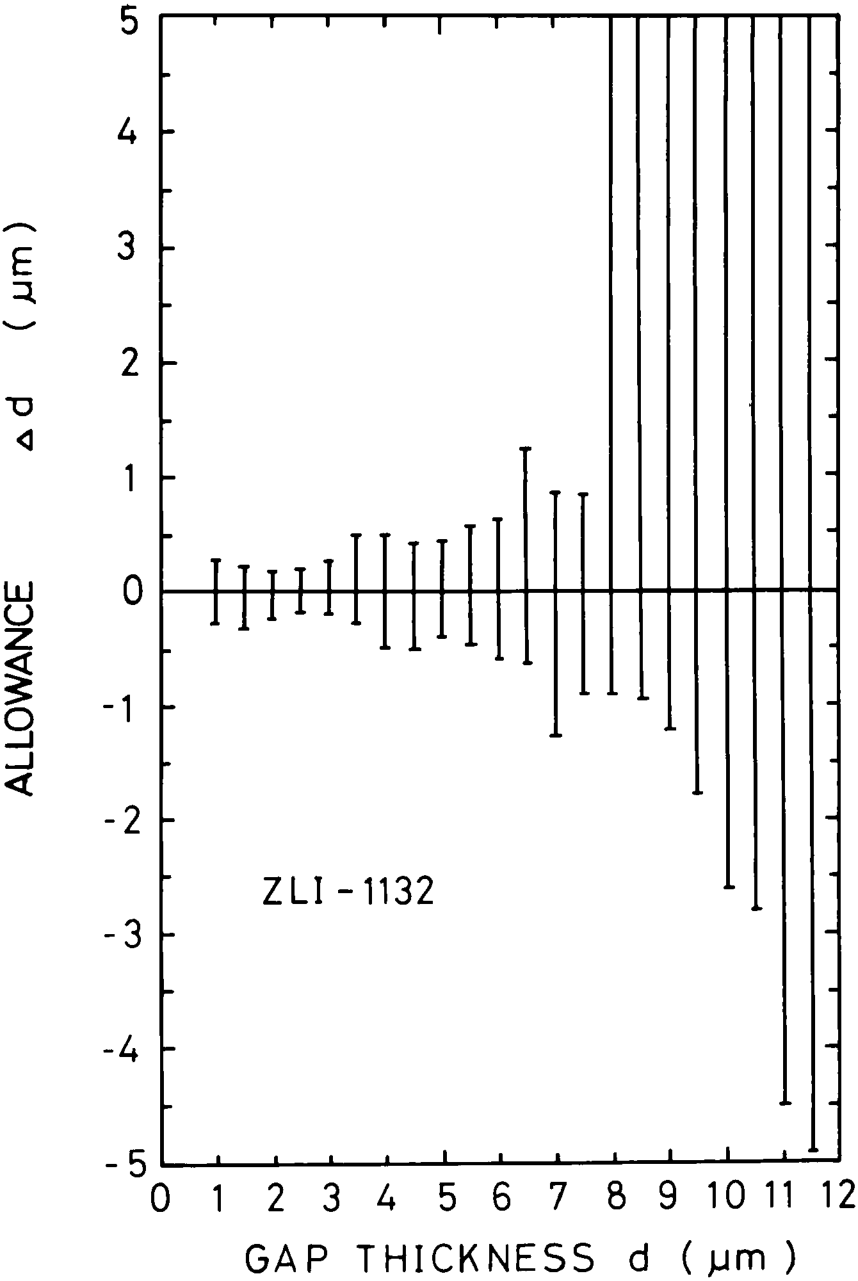

FIGURE 10a Gap allowance Δd versus gap thickness d for crossed polarizers.

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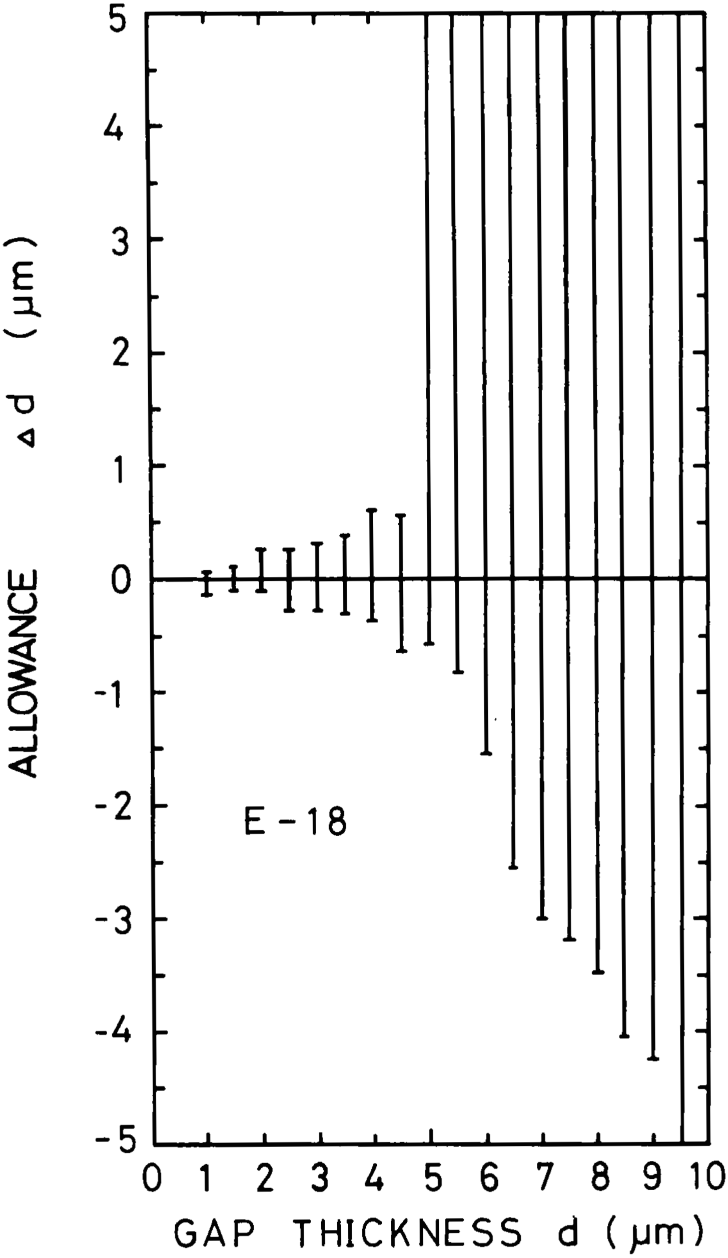

FIGURE 10b Gap allowance Δd versus gap thickness d for crossed polarizers.

3) Making a comparison of TN display performance with positive display and negative display, positive type is better in all the points of view.

In conclusion, as mentioned above, employing colorimetry, we can obtain several useful information on designing Twisted Nematic liquid crystal display devices.

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