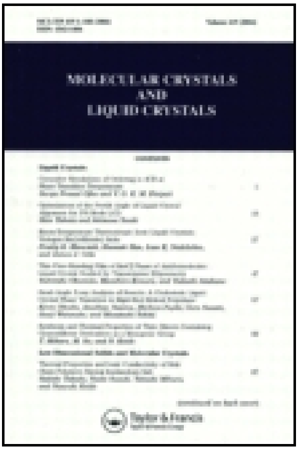

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A Positive Contrast Guest-Host Display Using a Liquid Crystal of Negative Dielectric Anisotropy

F. Gharadjedaghi [a]
[a] ASULAB SA, Physics Group, Neuchátel, Switzerland
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A Positive Contrast Guest-Host Display Using a Liquid Crystal of Negative Dielectric Anisotropy

F. GHARADJEDAGHI

ASULAB SA, Physics Group, Neuchâtel, Switzerland

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Recently we described a novel guest-host cell which exhibits a positive contrast (dark digits on a clear background) employing a mixture of a nematic liquid crystal with negative dielectric anisotropy, a chiral component, and a dichroic dye. In this cell, the cell thickness and the alignment layers are chosen such that in the absence of a field, the mixture shows a uniform homeotropic structure. When a voltage greater than the threshold value is applied, a helicoïdal structure is adopted, which absorbs the incident illumination.

In this work the expression for the threshold voltage is derived and compared with experimental results. Experimental results are also presented which indicate, for a given cell thickness, the influence of the pitch of the mixture on the contrast and the response time.

1 INTRODUCTION

The first liquid crystal cell to employ a dichroic dye (the guest-host effect) was proposed by Heilmeier *et al.*[1,2] More recently White and Taylor[3] have described a different type of guest-host cell based on the cholesteric-nematic phase change effect. The White-Taylor (W—T) cell has an advantage over the Heilmeier cell in that it provides good contrast without the use of a polarizer. Both types of cell employ a liquid crystal mixture having a positive dielectric constant, and have negative contrast, i.e., information is displayed as clear digits on a colored background. For many applications, negative contrast is considered undesirable for physiological reasons.

A display having positive contrast can be obtained by employing a liquid crystal mixture with either a positive[4,5] or a negative[6,7] dielectric anisotropy. A cell has been described recently which employs a mixture of the latter type and a chiral additive.[7] The molecular alignment across the whole of this cell is perpendicular, and the ratio d/*P* (where d is the cell thickness, and *P* is the helicoïdal pitch of the mixture) is chosen to be less than, or equal to, the critical value[8] defined by $k_{33}/2k_{22}$ (k_{22}, k_{33} are two of the elastic constants of the mixture). Under these conditions it has been shown experimentally by the author that in the absence of a field, the mixture adopts a homeotropic structure (transparent state), while application of a field results in a helicoïdal structure whose axis is perpendicular to the substrates (Figure 1). The advantage of this

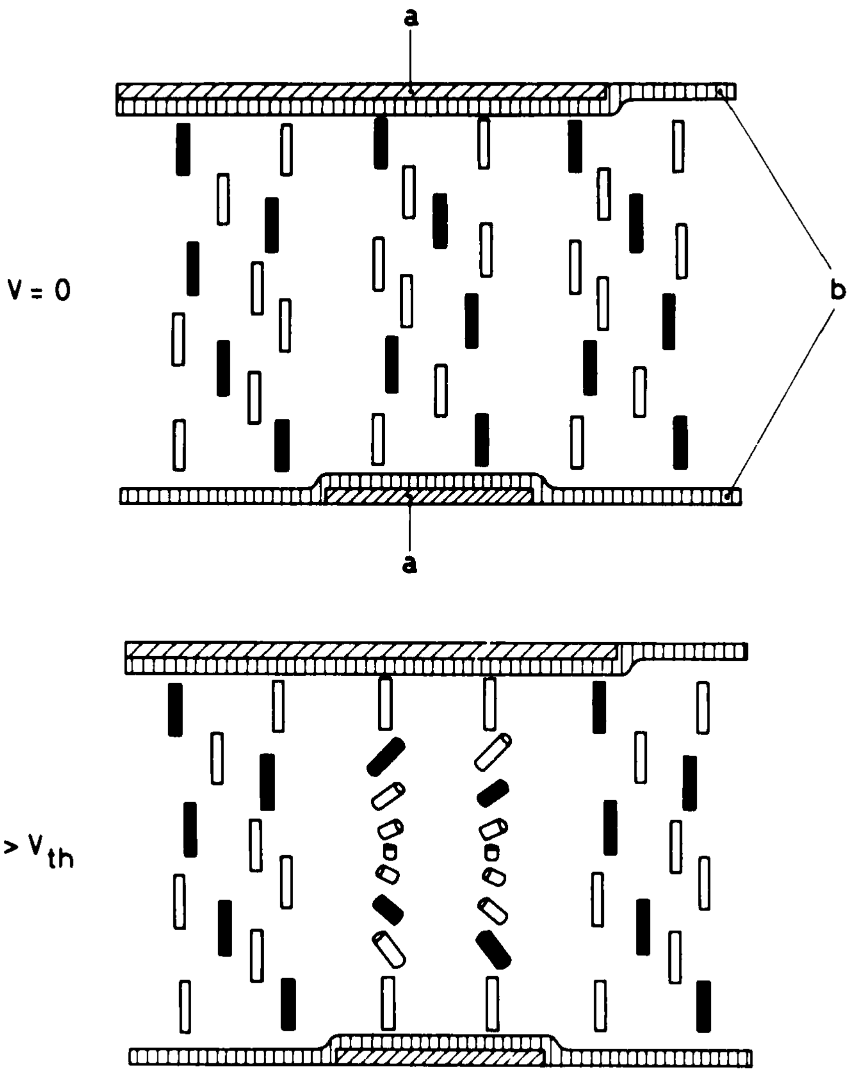

FIGURE 1 Operating principle a) transparent electrode, b) perpendicular alignment layer.

type of cell over positive contrast cells employing positive liquid crystal mixtures ($\Delta\epsilon > 0$) lies in its technological simplicity.

In this paper some theoretical and experimental results relating to the latter type of cell are presented and an expression for the threshold voltage above which the homeotropic structure is destroyed is stated. The values obtained using this expression are compared with the experimentally determined threshold voltages. Experimental results are also presented which indicate for a given cell thickness, the influence of the pitch of the mixture, P, on the contrast and the response times of the cell.

2 CALCULATION OF THE THRESHOLD VOLTAGE

This calculation is based on the equations which describe the distortion of the system. These equations are obtained by minimizing the free energy of the system. Consider a coordinate system Oxyz, such that the axis Oz is perpendicular to the cell's substrates, and the origin is equidistant between them. Assume that at any point in the system the local optical axis is inclined at an angle α to the Oz axis, and that its azimuthal angle to the Oxy plane is φ. The angles α and φ are assumed to be independent of both x and y. In the case of an applied electric field, E, the equation required for the minimization of the energy of the system may be deduced from those given by Leslie,[9] i.e.:

$$g(\alpha)\frac{d\varphi}{dz} - k_{22}\, q \sin^2\alpha = k \tag{1}$$

$$f(\alpha)\left(\frac{d\alpha}{dz}\right)^2 + g(\alpha)\left(\frac{d\varphi}{dz}\right)^2 - \frac{|\Delta\epsilon|}{4\pi}E^2\cos^2\alpha = c \tag{2}$$

where

$$f(\alpha) = k_{11}\sin^2\alpha + k_{33}\cos^2\alpha$$
$$g(\alpha) = (k_{22}\sin^2\alpha + k_{33}\cos^2\alpha)\sin^2\alpha$$

and

$$q = \frac{2\pi}{P}$$

where k_{11}, k_{22}, and k_{33} are three elastic constants, $\Delta\epsilon$ is the dielectric anisotropy, and k and c are two constants.

The term $(\Delta\epsilon/4\pi)E^2\cos^2\alpha$, which describes the contribution of the electric field, is only exact in the case where the field can be considered uniform throughout the system. This corresponds to a situation where the homeotropic structure is either undisturbed or only slightly distorted, or to a system employing a liquid crystal of low dielectric anisotropy. In this calculation, it is only necessary to consider fields which are close to the threshold state, and therefore, the field may be considered to be uniform throughout the system. The conditions for the angle of tilt, α are:

$$\alpha(d/2) = \alpha(-d/2) = 0$$

and

$$\frac{d\alpha}{dz}(z = 0) = 0$$

This second condition expresses the symmetry of the system with respect to the origin. Assume that α_m is the value of α at the center of the cell. From Eq. (1) and (2) the following relation between z, α and α_m can be derived:

$$z = \int_{\alpha}^{\alpha_m} \left[\frac{f(\psi)}{k_{22}^2 q^2 \left(\frac{\sin^4 \alpha_m}{g(\alpha_m)} - \frac{\sin^4 \psi}{g(\psi)} \right) - \frac{|\Delta\epsilon| E^2}{4\pi} (\sin^2\alpha_m - \sin^2\psi)} \right]^{1/2} d\psi \quad (3)$$

For $z = d/2$, α is zero, hence:

$$d/2 = \int_{0}^{\alpha_m} \left[\frac{f(\psi)}{k_{22}^2 q^2 \left(\frac{\sin^4 \alpha_m}{g(\alpha_m)} - \frac{\sin^4 \psi}{g(\psi)} \right) - \frac{|\Delta\epsilon| E^2}{4\pi} (\sin^2\alpha_m - \sin^2\psi)} \right]^{1/2} d\psi \quad (4)$$

The expression for the threshold voltage ($V_{th} = E_{th} \cdot d$), is obtained by evaluating the limit of the above integral as α_m tends to zero. It is found that:

$$V_{th} = 2\pi \left(\pi \frac{k_{33}}{|\Delta\epsilon|} \right)^{1/2} \left[1 - \left(\frac{2k_{22}}{k_{33}} \frac{d}{P} \right)^2 \right]^{1/2} \quad (5)$$

V_{th} $(d/P = 0)$ being the threshold voltage corresponding to a purely nematic system, one can write:

$$V_{th}/V_{th}(d/P = 0) = \left[1 - \left(\frac{2k_{22}}{k_{33}} \frac{d}{P} \right)^2 \right]^{1/2} \quad (6)$$

3 DISCUSSION OF THE EXPERIMENTAL RESULTS

3.1 Experimental conditions

Threshold voltage, contrast and response time measurements were made in transmission on a microscope, and employed completely unpolarized monochromatic light ($\lambda = \lambda$ max, λ max being the wavelength corresponding to the absorption peak of the dye). The same cell, of thickness $d = 8$ μm, was used for all the measurements. Perpendicular alignment was obtained by treating both substrates with lecithin.

The mixtures employed contained a nematic liquid crystal, (EN18—CHISSO), a chiral agent (S1082—MERCK), and a dichroic dye (D2—BDH). The concentration of the chiral agent was varied from mixture to mixture, while that of the dye was held fixed at 0.87% by weight. For D_2, this concentration corresponds to twice the optimum value, from a physiological point of view, for a cell viewed in reflection. The value of the dielectric anisotropy was considered to have been identical for each mixture. This was a valid assumption as the dipole moment of the molecules of the chiral agent chosen was very weak, and the concentrations employed were very low.

The critical value $(d/P)_c = k_{33}/2k_{22}$, defining the limit below which the structure adopts spontaneously a homeotropic structure, was measured using a lens, following the method proposed by M. Brehm *et al.*[10]

3.2 Experimental results

The variation in transmission as function of the applied voltage for four different values of the ratio d/P is shown in Figure 2. As d/P increases, the threshold voltage and the transmission for voltages above this threshold voltage, decrease.

Theoretical and experimental values of the reduced threshold voltage $V_{th}/V_{th}(d/P = 0)$ as functions of the ratio d/P are given in Figure 3. The

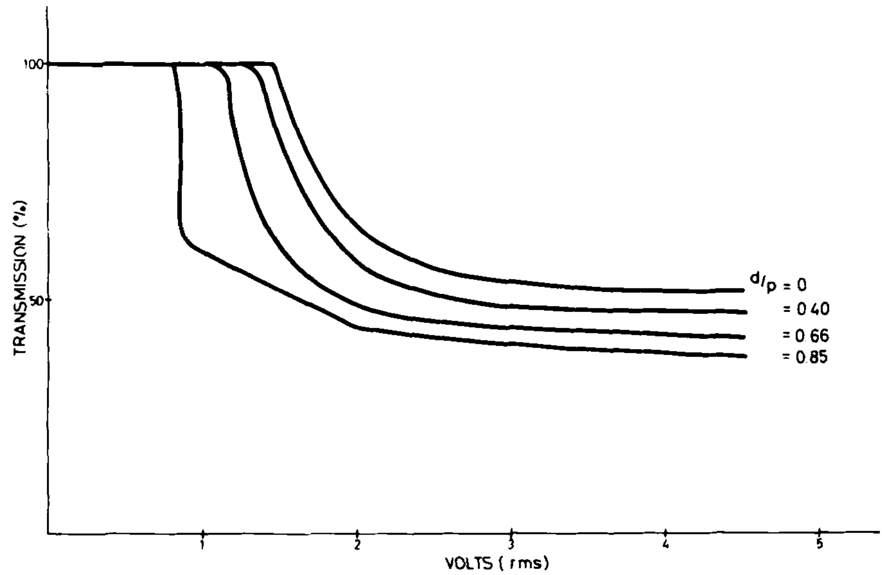

FIGURE 2 Variation in transmission as a function of the applied voltage for four different values of d/P.

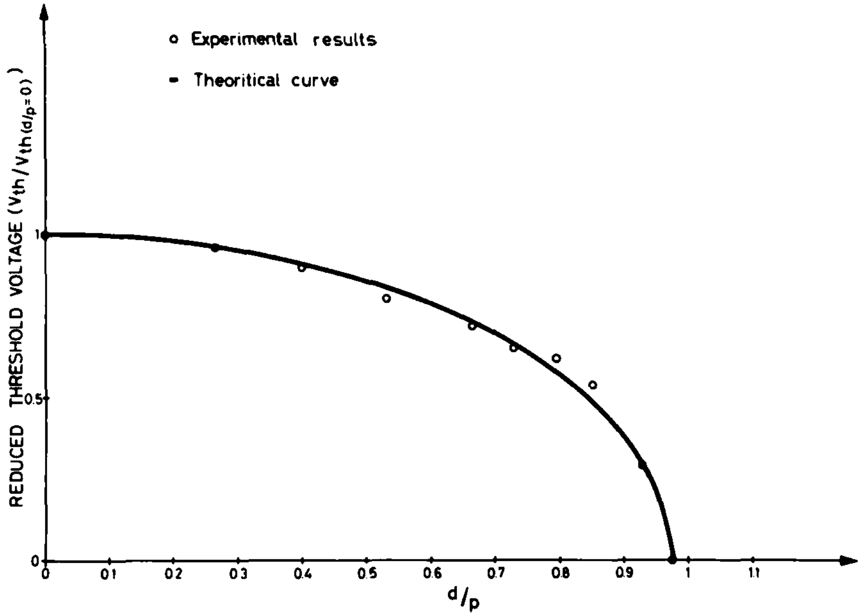

FIGURE 3 Theoretical and experimental results showing the value of the reduced threshold voltage as a function of d/P.

experimental results were obtained by holding the cell thickness fixed and varying the pitch of the mixture. The theoretical curve was deduced from equation (6) by putting $(d/P)_c = 0.975$, the value obtained from the measurements outlined above.

Response times are given in Figure 4 for the different mixtures employed. The decay time increased with the value of d/P, and tends towards infinity as the critical value, $(d/P)_c$, is approached. The sense of the variation of the rise time is the inverse of that for the decay time.

The variation of the monochromatic contrast as a function of the ratio d/P is shown in Figure 5 for three values of applied voltage. Contrast was defined as $C = (T_{OFF} - T_{ON})/T_{OFF} \times 100$ where T_{OFF} and T_{ON} are the cell transmission corresponding to the non-activated and activated states, respectively, measured at λ_{max} ($\lambda_{max} = 492$ nm for the dye D_2).

4 CONCLUSION

The results of the work reported in this paper allow the following conclusions to be drawn:

—Eq. (6), established theoretically, for the threshold voltage, and the experimental results are in good agreement.

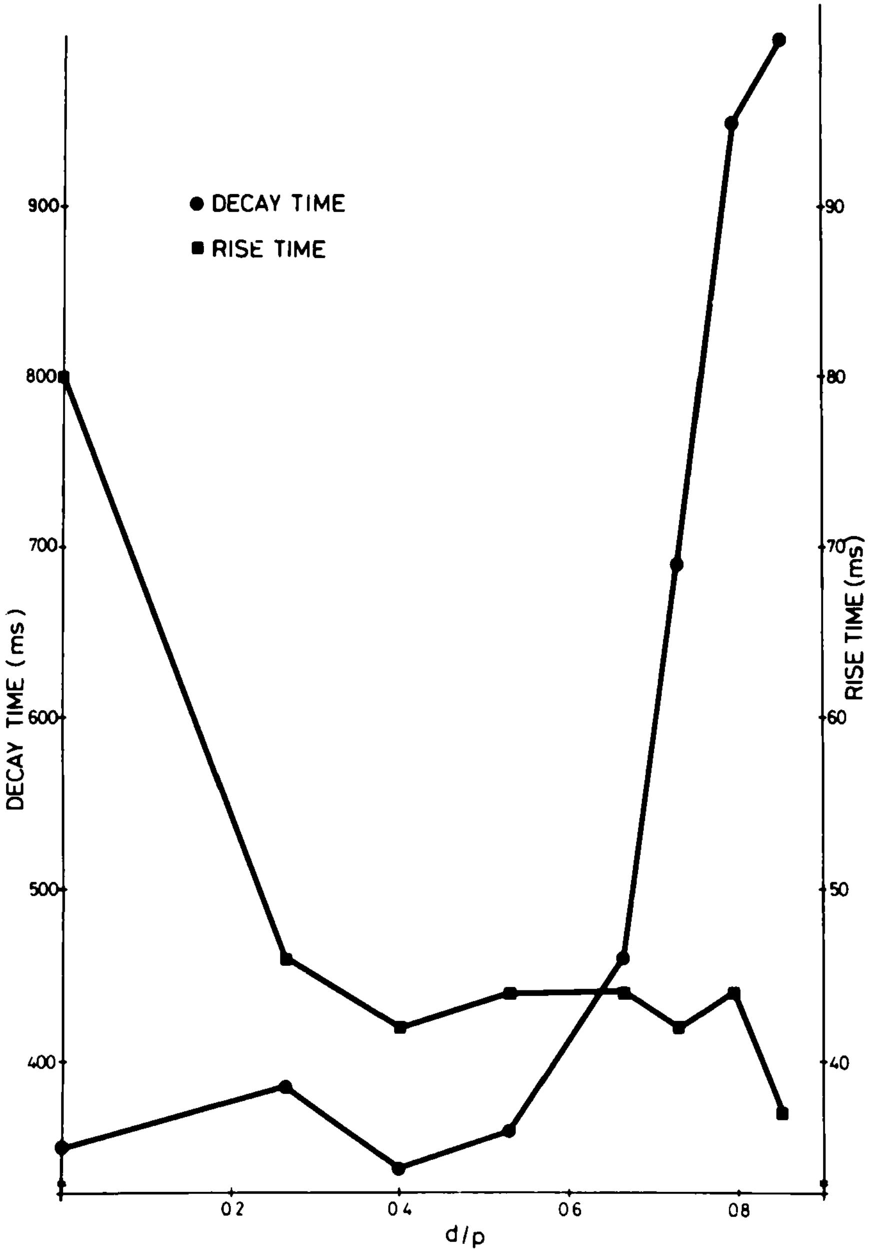

FIGURE 4 Variation of response times as a function of d/P. Applied voltage: 4.5 volts r.m.s.

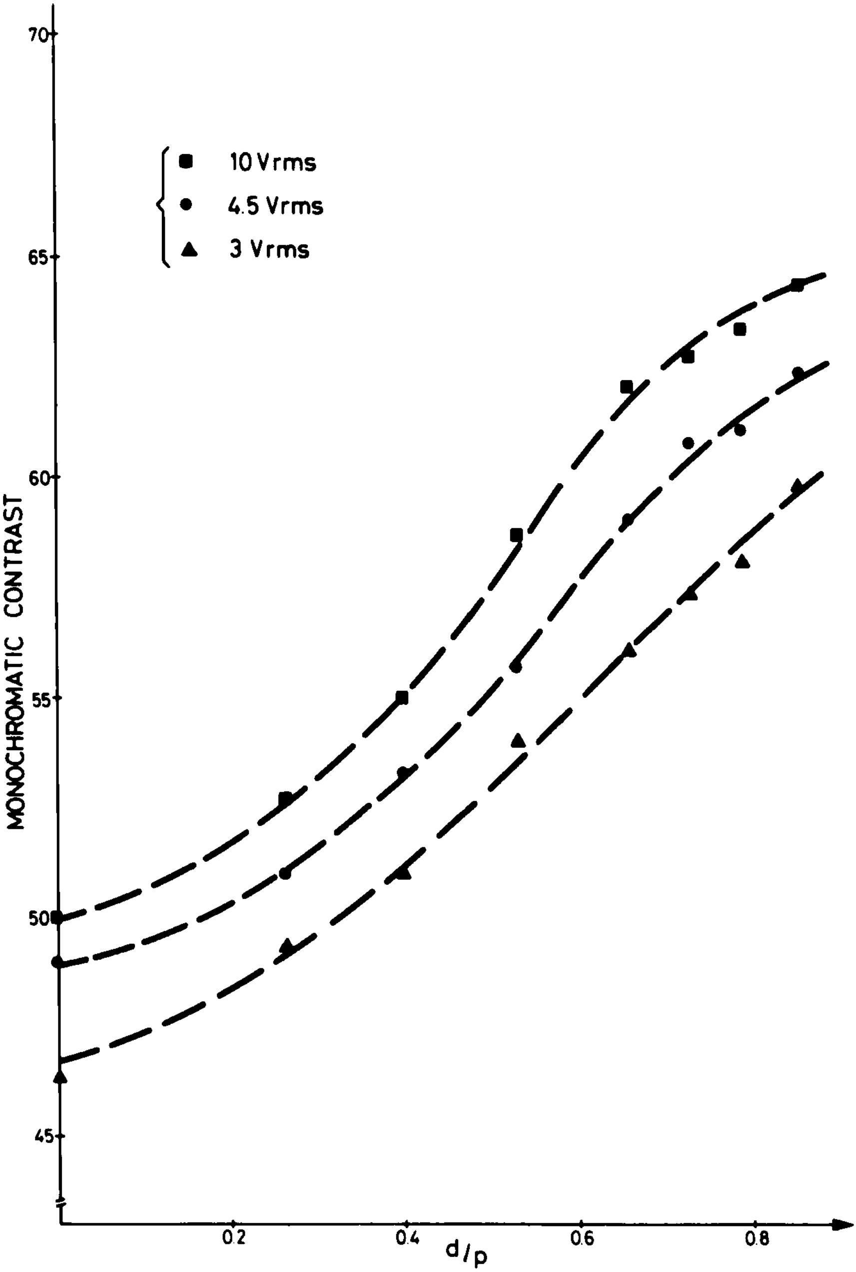

FIGURE 5 Variation of the monochromatic contrast, at $\lambda = \lambda_{max}$, as a function of d/P for three values of applied voltage. The monochromatic contrast is defined as $C = (T_{OFF} - T_{ON})/T_{OFF} \times 100$, where T_{OFF} and T_{ON} are the intensities of the transmitted light.

—The addition of a chiral component to the nematic liquid crystal results in a lowering of the threshold voltage and an improvement in the contrast of the cell. These improvements are accompanied, however, by an increase in the decay time. In practice, the choice of the ratio d/P is a compromise between the threshold voltage and the contrast on one side, and the decay time on the other. For watch display application (where the response time should be less than 0.5 s), employing mixtures similar to those used in this study, the value of d/P should be chosen to be less than 0.7.

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