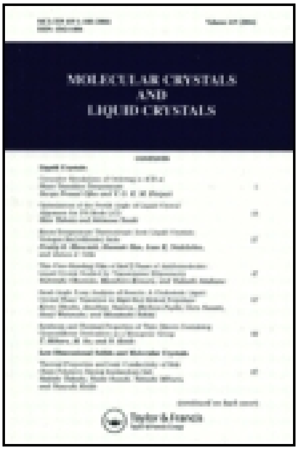

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C. M. Waters [a], E. P. Raynes [a] & V. Brimmell [a]
[a] Royal Signals and Radar Establishment, Malvern, Worcs, WR14 3PS, UK
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Design of Highly Multiplexed Liquid Crystal Dye Displays†

C. M. WATERS, E. P. RAYNES and V. BRIMMELL

Royal Signals and Radar Establishment, Malvern, Worcs, WR14 3PS, UK

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The recently invented $3\pi/2$ dye display offers, for the first time, the prospect of an RMS multiplexed highly complex liquid crystal display with an excellent angle of view. In this paper, the importance of various relevant device and material parameters are discussed and optimum conditions found for multiplexing at levels over 1 in 100.

INTRODUCTION

As liquid crystal displays have become more widely used, the information shown has become increasingly complex and the displays have been driven by multiplexed waveforms to reduce the number of interconnections. The level of multiplexing varies from 2-way in simple displays (for example those used in watches) to 64-way complex panels capable of showing over 1000 alphanumeric characters. Liquid crystal displays using the field-induced reorientation of dissolved pleochroic dye molecules have been known for several years[1] and offer a much improved viewing angle and brightness than the widely used twisted nematic displays. A significant disadvantage until recently has been the very poor multiplexing performance[2] of pleochroic dye displays, which has severely limited the range of potential applications. However Waters *et al.*[3] have recently shown that multiplexing at high levels (over 100-way) is possible in dye displays with a novel device configuration using a twist angle of around $3\pi/2$ across the layer.

†Presented at the Tenth International Liquid Crystal Conference, York, 15–21 July 1984.

THE 3π/2 DYE DISPLAY

The novel device is known as the "3π/2 device" because the range of useful twist angle is centered around 3π/2. Alternatively, the comparison with the normal twisted nematic device which has only π /2 twist gives the new device its alternative name of the "supertwist device." The OFF state is a layer with a uniform tilt angle and a nominal twist angle of 3π/2. Light is absorbed by pleochroic dye molecules dissolved in the long pitch cholesteric host. The application of a voltage causes a sharp transition to the UP state, shown by the simplified (no twist), director configurations in Figure 1, in which the director is essentially vertical in the centre of the layer. This UP state was first described by Raynes[4] and is reminiscent of the 'vertical' state described by Thurston.[5] It has a lower energy than the more usual Fréedericksz ON state (Figure 1). Switching from the twisted OFF

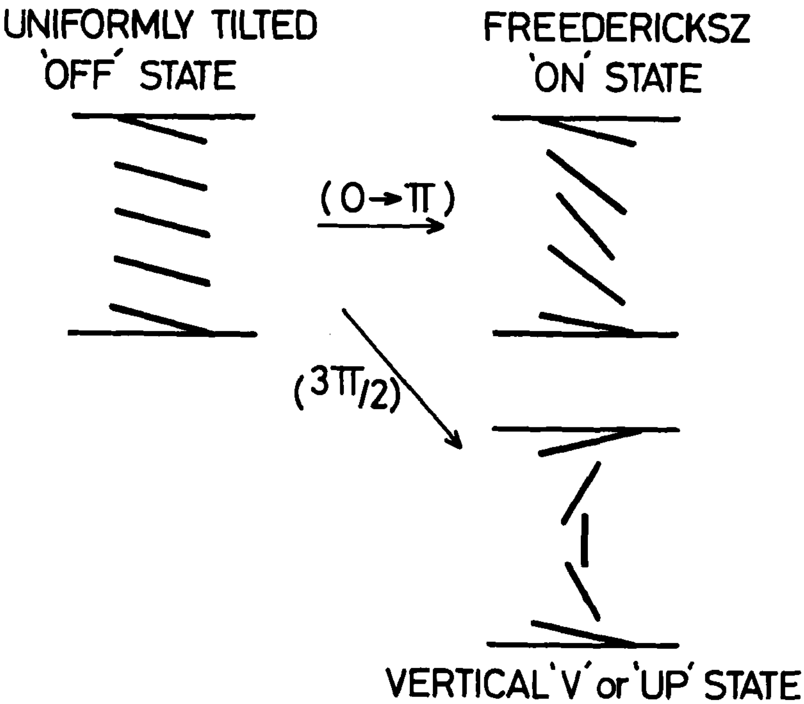


FIGURE 1 Schematic representation of simplified (no twist) director configurations. For small twist (<π), the uniformly tilted 'OFF' state transforms to the Fréedericksz 'ON' state when a voltage in excess of a threshold value is applied; for higher twist (≥5π/4), it transforms to the topologically equivalent 'V' or 'UP' state.

state to the vertical ON state lowers the absorption of incident light by the dissolved pleochroic dye molecules. Two modes of operation are possible: in one a single polarizer is used to provide polarized light which is guided by the $3\pi/2$ twisted layer and requires a material of high birefringence to achieve good contrast; in the other, the so-called White-Taylor mode,[6] no polarizers are used and a material of low birefringence is required. Figure 2 shows the appearance of a typical $3\pi/2$ display being multiplexed 32-way and operating with a single polarizer. The angle of view is excellent and the driving voltage only 2 volts, making it directly compatible with the integrated CMOS drivers developed for use with twisted nematic displays.

The $3\pi/2$ device can be bistable[7] as the applied voltage is increased, with the Fréedericksz ON state providing the barrier state between the two bistable states. The optimum condition for the RMS multiplexing corresponds to obtaining minimum hysteresis—shown by the dashed curve in Figure 3. This condition can be achieved by using the correct combination of device and material parameters. In this paper we examine the effect of the important material and device parameters on the bistable nature of the curve shown in Figure 3 and determine the optimum condition for RMS multiplexing.

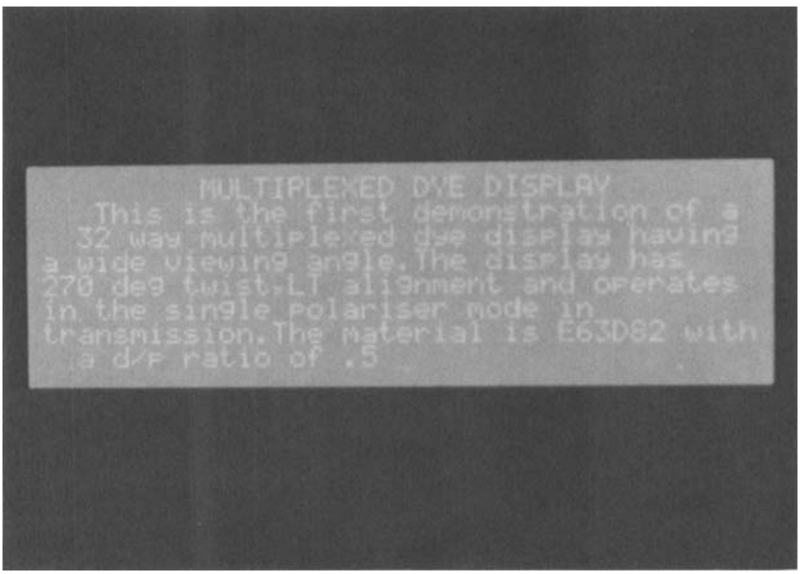


FIGURE 2 A 32-way multiplexed $3\pi/2$ display containing E63 D82 (BDH Chemicals Ltd) in an 8 μm LT cell operating in transmission using a single polarizer.

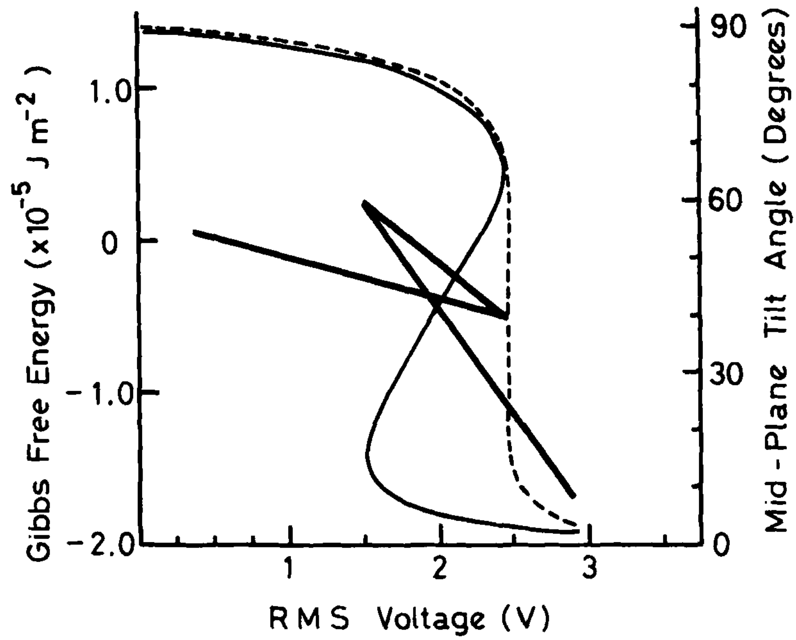


FIGURE 3 Typical Gibbs free energy (▬▬▬) and mid-plane tilt angle (- - - · ———) plotted against applied RMS voltage.

We have used Berreman's computer modelling programs[7] to calculate the Gibbs free energy and mid-plane director tilt angle (see Figure 3) and have studied the effect of varying in turn a single parameter from a set of typical device and material parameters. Experimental tests show these procedures to be valid. Under some circumstances scattering was found to occur; Berreman's programs do not deal with this occurrence. Finally, some practical examples are presented to demonstrate the optimisation and performance of the device.

I DEVICE PARAMETERS

(i) Twist angle of the liquid crystal layer

The device can be constructed with a range of twist angles, and the computed effect of this is shown in Figure 4 for the particular cases of $5\pi/4$, $3\pi/2$ and $7\pi/4$ in high tilt cells. The ratio d/P was adjusted to the minimum allowed value for each twist, and all other device and material parameters were kept constant at typical values. Figure 4 shows that both the threshold voltage and the amount of hysteresis increase with twist angle. Clearly for the material parameter used and a high tilt layer, $3\pi/2$ is close to the optimum twist angle for minimum hysteresis and maximum RMS multiplexing. However other considerations cannot be neglected. Scattering becomes more likely for the larger twist angles, and for low tilt alignment it limits the usable twist angle to $3\pi/2$ and less. High surface tilt tolerates a larger twist before scattering occurs. The optical contrast of the display is also affected by the twist angle. When the single polarizer mode is used, better contrast is produced by the superior guiding of the plane of polarized light in the smaller twist devices. Conversely the contrast of the White-Taylor mode (no polarizer) benefits from larger twist angles.

(ii) Surface alignment tilt angle

There are only two easily achievable tilt angles—a low tilt of 3° (LT—as obtained on rubbed polymers) and a high tilt of 30° (HT—as obtained on SiO_X evaporated at an oblique incidence of 5°) and their effect is shown in Figure 5. The higher tilt angle markedly reduces

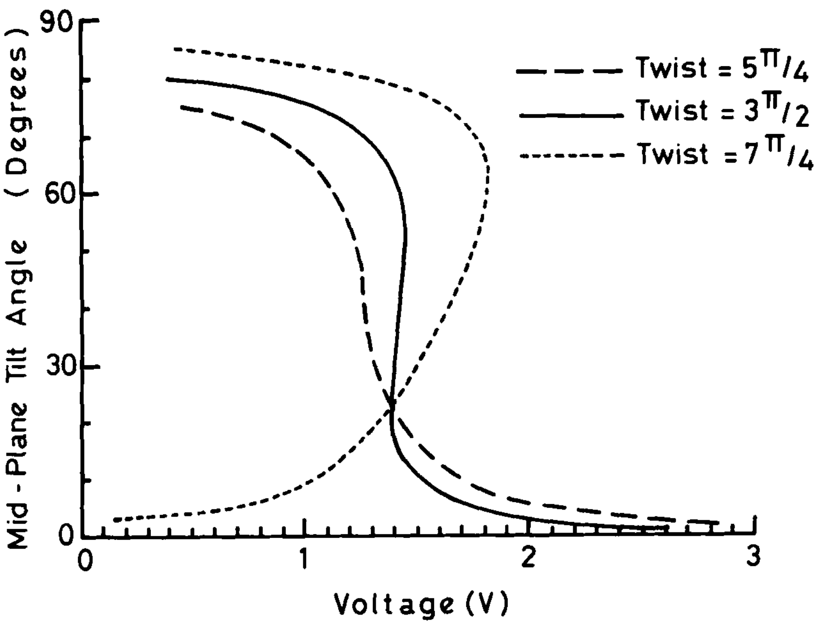


FIGURE 4 Mid-plane tilt angle against applied RMS voltage for three twist angles.

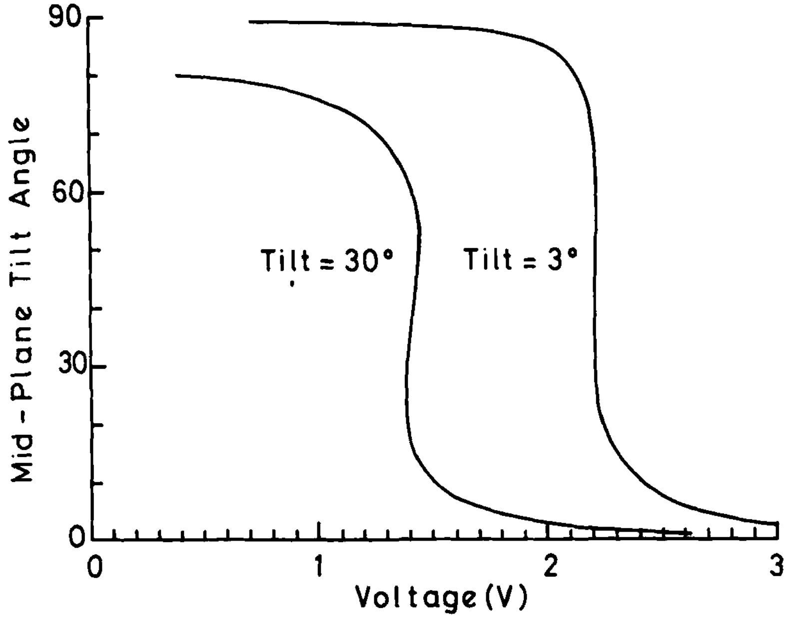


FIGURE 5 Mid-plane tilt angle against RMS voltage for HT and LT layers. Note that the mid-plane tilt angle is measured from the cell normal and the tilt angle at the surface from the cell horizontal.

the threshold voltage (a similar effect is seen in twisted nematic devices), but otherwise the effect of the tilt angle on the hysteresis is minimal. It is interesting to note that the mid-plane tilt angle of the HT layer is significantly less than the surface tilt, confirming previous analytical calculations.[8] A hybrid cell (one surface HT and the other LT) is also possible, and gives results intermediate between the two extremes. The other major effect of surface tilt is on the occurrence of scattering which is reduced in an HT layer, as discussed in both the previous and following sections.

(iii) Thickness to pitch ratio (*d/P*)

The last of the relevant device parameters is the ratio of thickness to pitch, (*d/P*). A particular twist angle is stable for only a limited range of *d/P*—for example a $3\pi/2$ twist is stable over the range $0.5 < d/P < 1.0$. Figure 6 shows the calculated variation of electro-optic performance of an HT layer as *d/P* is varied throughout the range of stability. Clearly, increasing *d/P* raises the threshold voltage and reduces the amount of hysteresis. These trends were confirmed exper-

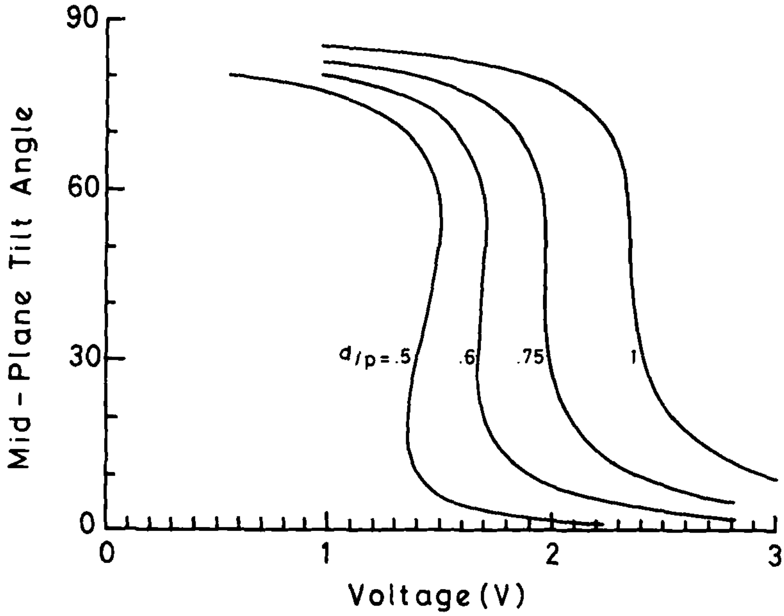


FIGURE 6 Mid-plane tilt angle against applied RMS voltage for the range of thickness to pitch ratio (d/P) permissible for a $3\pi/2$ display.

imentally by using wedges to vary d and in practice this thickness dependence of the threshold voltage can limit the level of multiplexing that is possible. The onset of scattering was also observed and it was found necessary to keep d/P close to the minimum value of 0.5 to avoid scattering in LT layers. HT layers however were much less liable to show scattering and a wider range of d/P could be tolerated. This latitude in d/P is useful, allowing the possibility of using a temperature dependent pitch to compensate for the variation of threshold voltage with temperature.

II MATERIAL PARAMETERS

We now examine the properties of the liquid crystal materials which affect the multiplexing performance of the $3\pi/2$ device.

(i) Electric Permittivities

The relevant combination of the permittivities which appears in the continuum equations is γ (where $\gamma = (\epsilon_{\parallel} - \epsilon_{\perp})/\epsilon_{\perp}$), and Figure 7

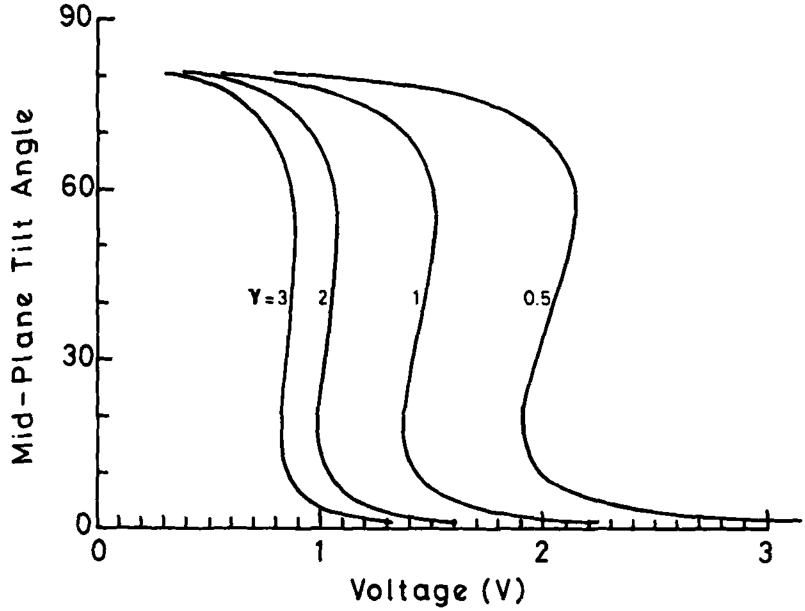


FIGURE 7 Mid-plane tilt angle against applied RMS voltage for the range of γ, the permittivity ratio, found in known materials.

shows the variation with voltage of the mid-plane tilt angle in a HT layer for various values of γ. The range 0.5 to 3.0 was chosen for γ as this covers most of the common nematic materials. The expected change of threshold voltage with γ is clearly shown in Figure 7. The other noticeable feature is the virtual independence of hysteresis on γ, at least over the range of $0.5 \rightarrow 3.0$ which is readily achievable by current materials. Similar results are found for LT layers.

(ii) Elastic constants

The splay, twist and bend elastic constants (K_{11}, K_{22} and K_{33}) play an important role in determining the performance of the device. Figures 8, 9 and 10 show the effect on the mid-plane tilt angle/voltage curve of varying each elastic constant separately, whilst keeping the other two fixed. The curves shown are for HT layers with $\gamma \approx 1$; similar effects have been found for LT layers and other values of γ.

Clearly, from Figure 8, there is only a slight effect of K_{11} on the hysteresis. By contrast, increasing K_{22} markedly decreases the hysteresis (Figure 9), whilst increasing K_{33} increases the hysteresis (Figure 10). The amount of hysteresis is therefore sensitive to both K_{22} and K_{33}, and the critical combination has been found to be the ratio

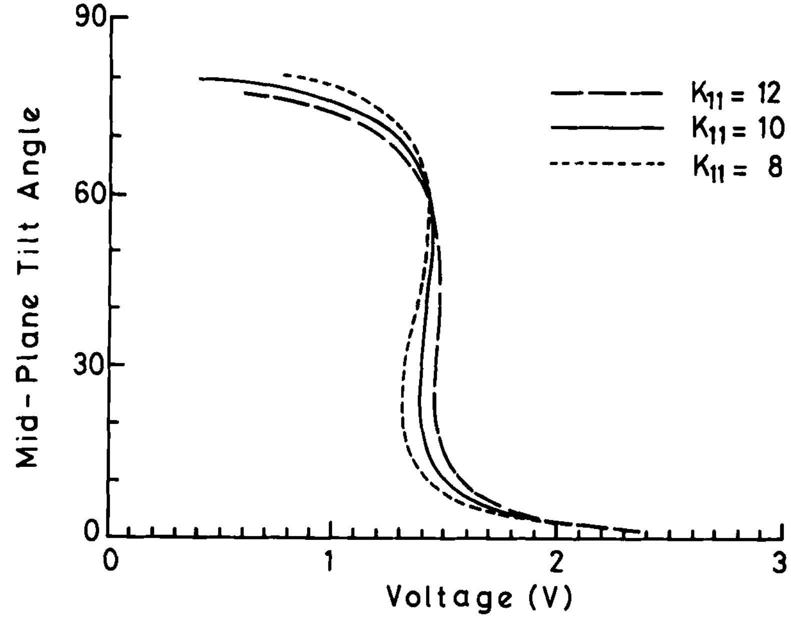


FIGURE 8 Mid-plane tilt angle against applied RMS voltage for a range of splay elastic constant K_{11}.

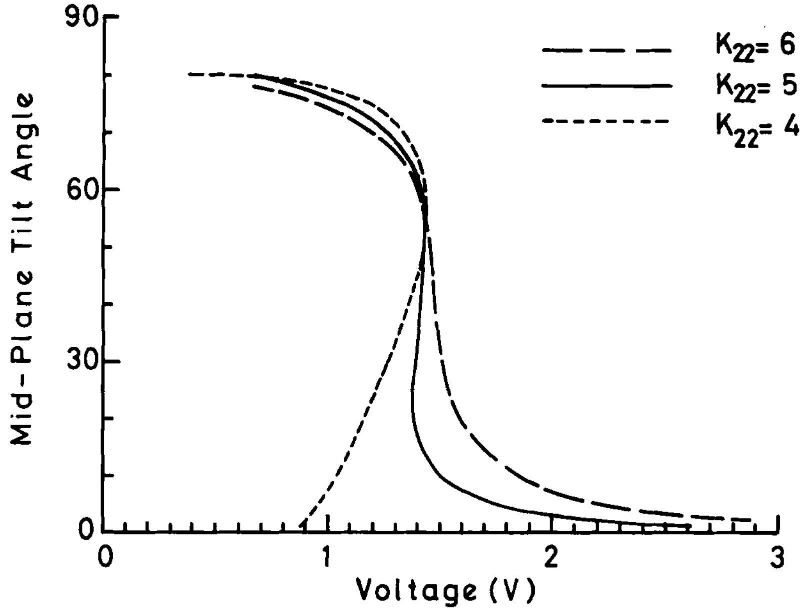


FIGURE 9 Mid-plane tilt angle against applied RMS voltage for a range of twist elastic constant K_{22}.

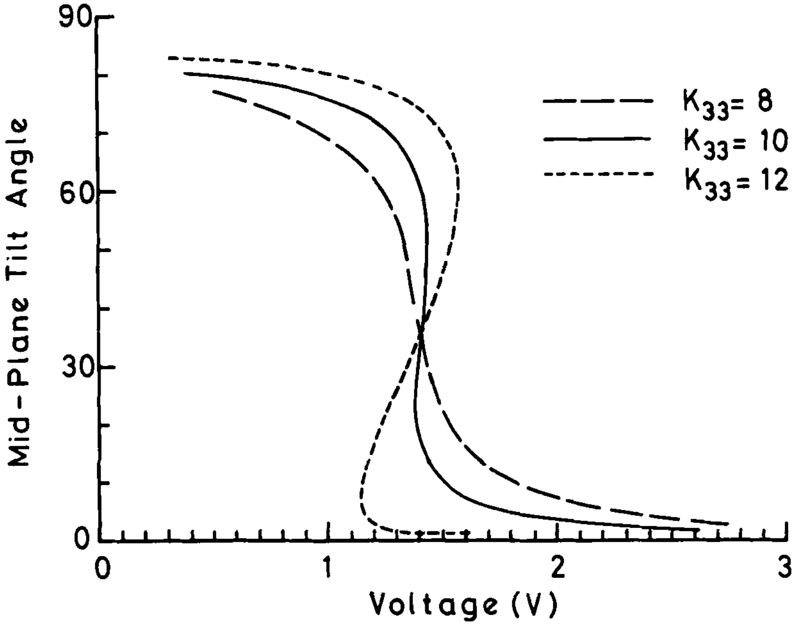


FIGURE 10 Mid-plane tilt angle against applied RMS voltage for a range of bend elastic constant K_{33}.

(K_{33}/K_{22}). This could be deduced from the insensitivity of the hysteresis to K_{11} shown in Figure 8, together with the fact that an equivalent scaling of all three elastic constants simply scales the voltage axis of the curves without influencing the amount of hysteresis. A more complete study has shown that the value of K_{33}/K_{22} for minimum hysteresis and optimum multiplexing varies with the twist angle in both HT and LT layers. Figure 11 shows the values of the ratio K_{33}/K_{22} for minimum hysteresis over the range of twist angles π to 2π. The appearance of scattering makes larger twist angles impractical. Unfortunately, measurements of K_{22} are scarce in the literature, but for the few materials examined, $2K_{22} \approx K_{11}$. This converts the vertical axis of Figure 11 into $2K_{33}/K_{11}$, a much more widely measured quantity.

(iii) Birefringence

The birefringence (Δn) of the liquid crystal has an important effect on the optical performance of the display. The single polarizer display

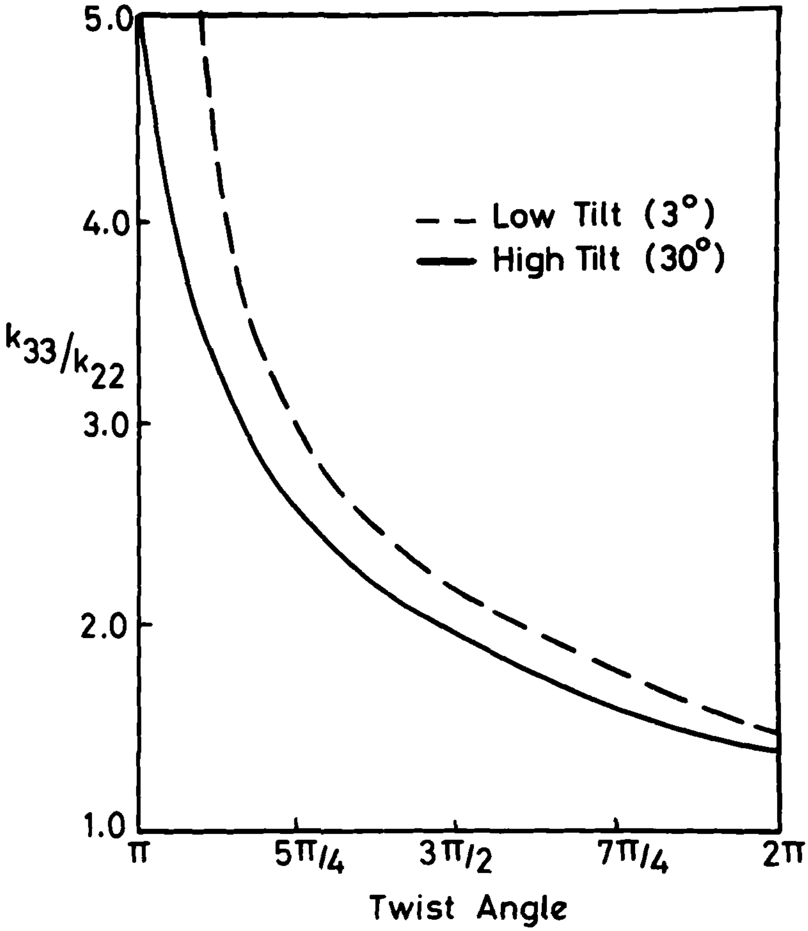


FIGURE 11 K_{33}/K_{22} for minimum hysteresis (optimum multiplexing) against twist angle of HT and LT layers. The approximate range of K_{33}/K_{22} is 2.0 to 4.0 for known materials.

depends on the guiding of the plane of polarization through the twisted layer for its effect. Guiding is more complete and the contrast higher if both Δn and the thickness d are large and the twist angle θ is small. As noted previously the smallest acceptable twist angle is $5\pi/4$, and this requires $\Delta n \geq 0.20$ for good contrast in an 8 μm layer.

Conversely the display with no polarizer only shows good contrast if the guiding of the plane of polarization is weak. This is achieved by small values of Δn and d and large values of θ. In practice the occurrence of scattering in an LT cell and of hysteresis in an HT cell limits θ to a maximum value of $3\pi/2$, and for an acceptable contrast to be achieved for this twist angle, $\Delta n \leq 0.05$.

Summary of optimum conditions

In the preceding sections we examined the conditions for optimum RMS multiplexing. Several other more obvious factors were not discussed; for example the liquid crystal material must also have a wide temperature range, a low viscosity (particularly at low temperatures) and a high dye order parameter. Even when the material has been optimized, the cell spacing must also be uniform, with variations of ± 0.1 μm restricting the maximum level of multiplexing to 1 in 100, and ± 0.5 μm to 1 in 40.

RESULTS FOR OPTIMIZED MATERIALS

As an example of the optimization of the device for RMS multiplexing we present data on devices operating in both single polarizer and White-Taylor modes.

We first consider the single polarizer mode. Figure 12 shows the voltage transmission characteristics for a LT, $3\pi/2$ device. The material used, E63 (BDH Chemicals Ltd), is based on the cyanobiphenyls and has a very wide nematic temperature range, a high birefringence ($\Delta n = 0.224$) and a large ratio of K_{33}/K_{11} ($= 1.93$). The $3\pi/2$ device shows a small degree of hysteresis and a scattering texture can be formed if the voltage is *slowly* increased above threshold. The scattering does not appear when the device is operated using RMS waveforms between the 'OFF' voltage V_1 and the 'ON' voltage V_3. However if the twist is reduced to $5\pi/4$ as in Figure 13, the hysteresis and all trace of scattering are removed, although the sharpness is maintained because of the large ratio K_{33}/K_{11}. The reduced twist is also beneficial in providing more efficient guiding of the polarized light resulting in an improved contrast ratio.

For operation in the White-Taylor mode we require a low Δn material coupled with a large twist angle. The latter condition is best achieved with a HT alignment where the scattering is supressed; however these two device parameters both tend to increase the amount of bistability, demanding a material with a low ratio of K_{33}/K_{22} (hence K_{33}/K_{11}) to reduce the hysteresis for optimised RMS performance. Figure 14 shows a device of the configuration using a commercially

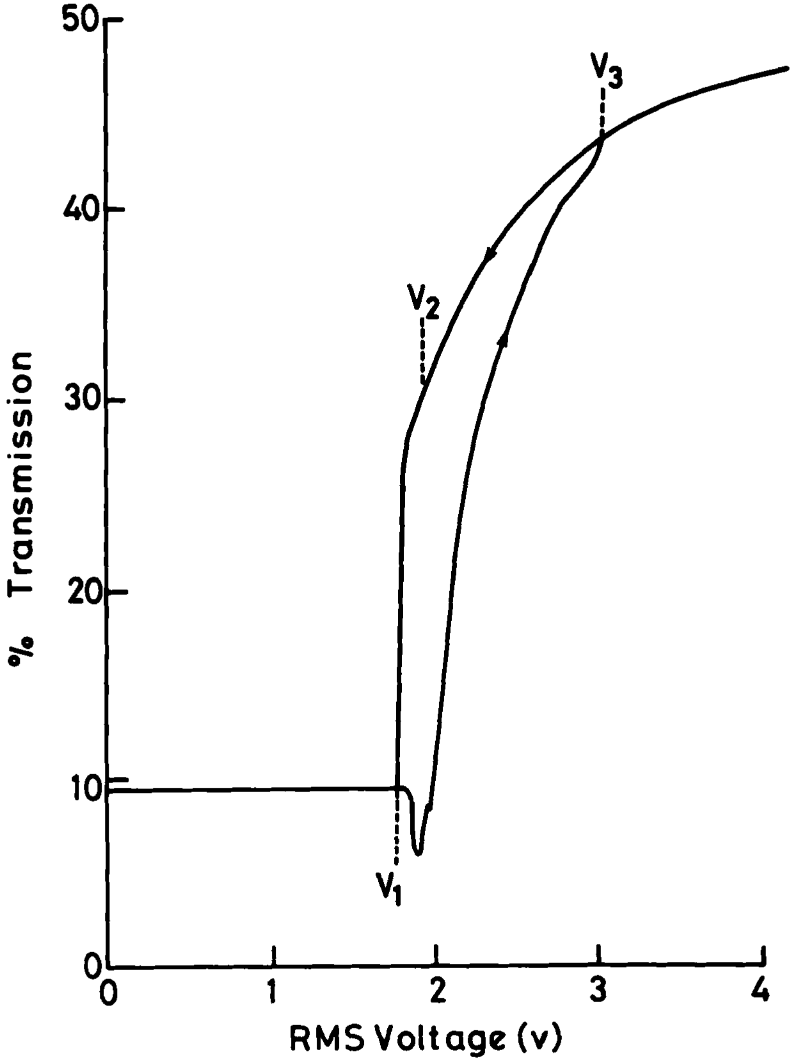


FIGURE 12 Transmission measured using a single polarizer for a slowly ramped RMS voltage for an 8 μm, 3π/2, LT layer of E63 D82 (BDH Chemicals Ltd) with $d/P = 0.5$. The scattering state observed between V_1 and V_3 for a slowly increasing voltage is not observed when the device is switched rapidly, as in RMS multiplexing, between V_1 and V_2.

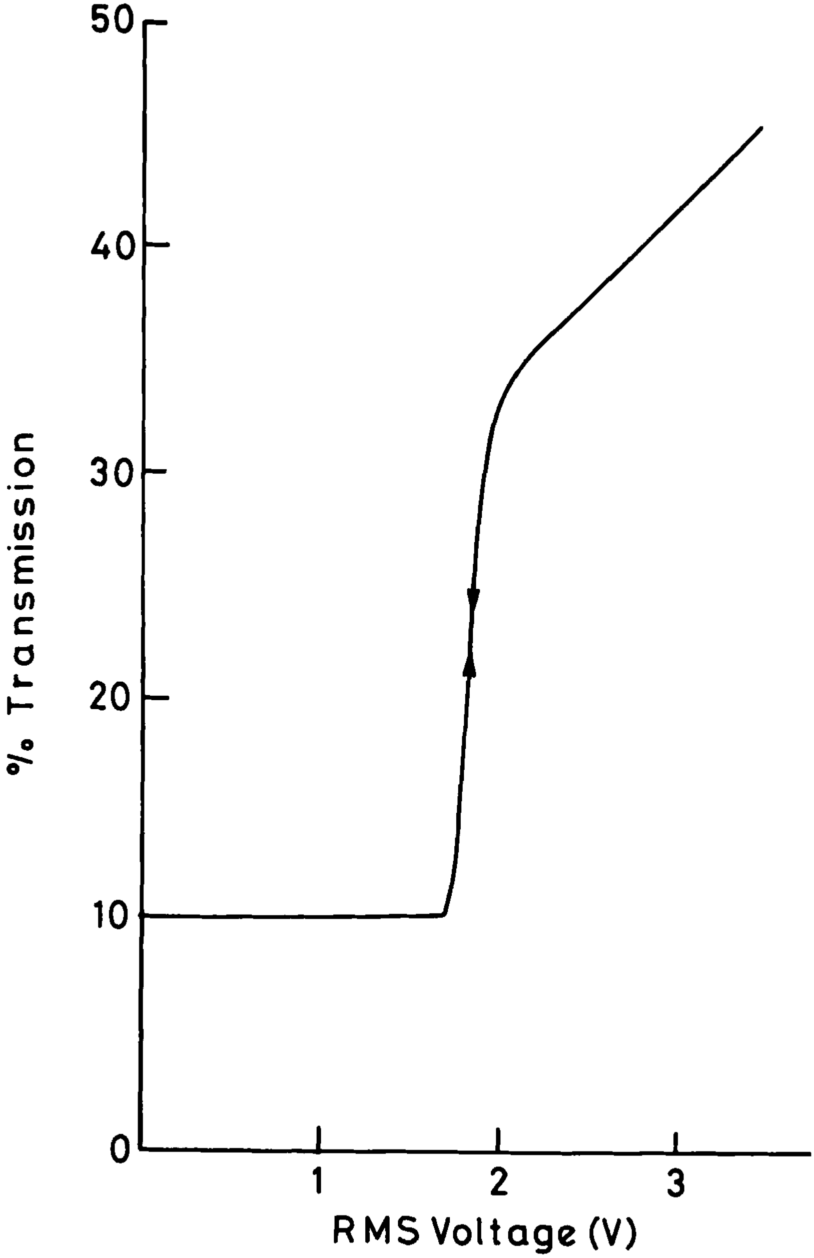


FIGURE 13 Transmission measured using a single polarizer for a slowly ramped RMS voltage for an 8 μm, $5\pi/4$, LT layer of E63 D82 (BDH Chemicals Ltd) with $d/P = 0.38$.

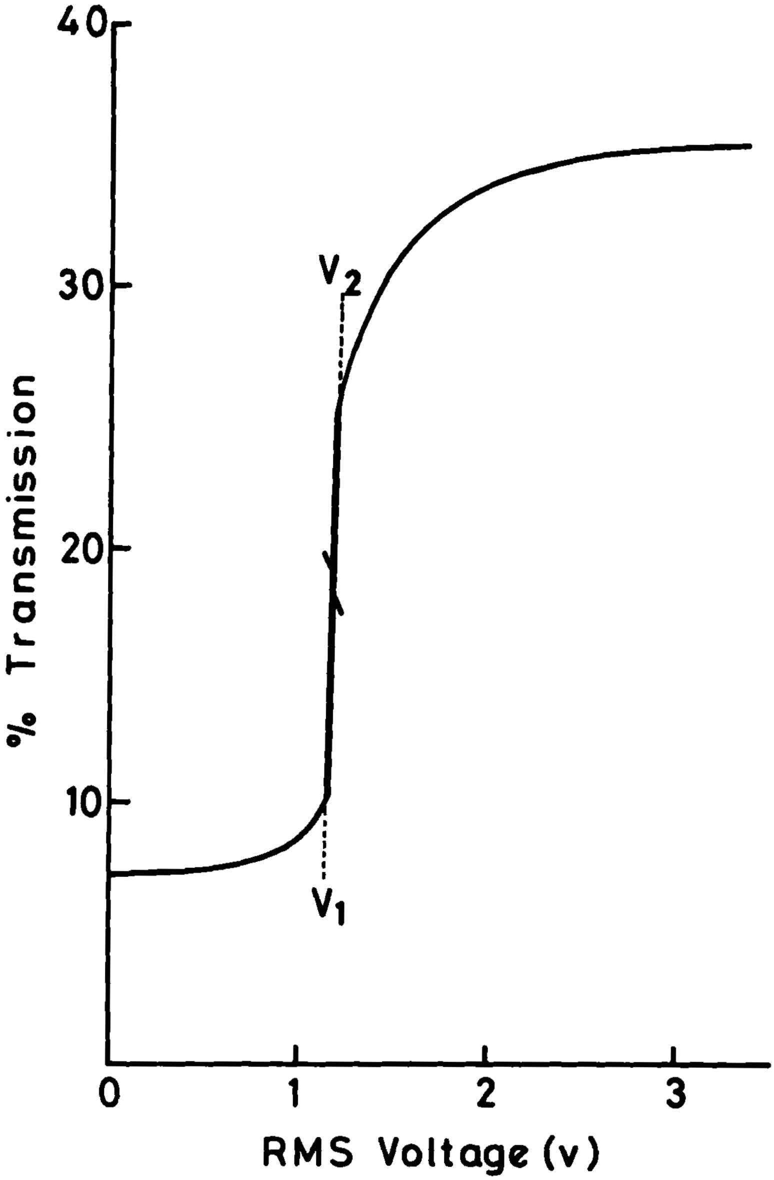
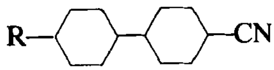
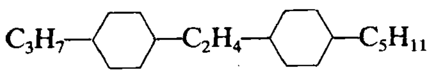


FIGURE 14 Transmission measured using a single polarizer for a slowly ramped RMS voltage for an 8 μm, 3π/2, HT layer of E70 D82 (BDH Chemicals Ltd).

available host, E70 (BDH Chemicals Ltd), which has $K_{33}/K_{11} = 1.2$. Although the hysteresis has been minimized by the low ratio of K_{33}/K_{11}, the rather large birefringence ($\Delta n = 0.187$) of E70 makes it suitable for operation only in the single polarizer mode. However no suitable low birefringence mixture is commercially available, so we have formulated a host by combining a mixture of the CCH compounds (ZLI 1695 from E Merck),

CCH 

with the dicyclohexylethane,

P35 

A mixture containing 30% of P35 in ZLI 1695 has a nematic range of 2°C to 69°C, $\Delta n = 0.056$, and $K_{33}/K_{11} \approx 1.0$. This mixture gives good multiplexing performance (see Figure 15) with a contrast ratio higher than that obtained in equivalent single polarizer displays (see Figure 12).

CONCLUSIONS

Device and material parameters have been analyzed using the Berreman's numerical modelling programs and the optimum conditions found for RMS multiplexing. Suitable materials are disclosed for both the single polarizer and White-Taylor modes.

Acknowledgment

We acknowledge D. W. Berreman for supplying his modelling programs, M. J. Bradshaw for computational assistance, BDH Chemicals Ltd and E Merck for the supply of liquid crystal materials, and Racal Display Systems for fabricating the display shown in Figure 2.

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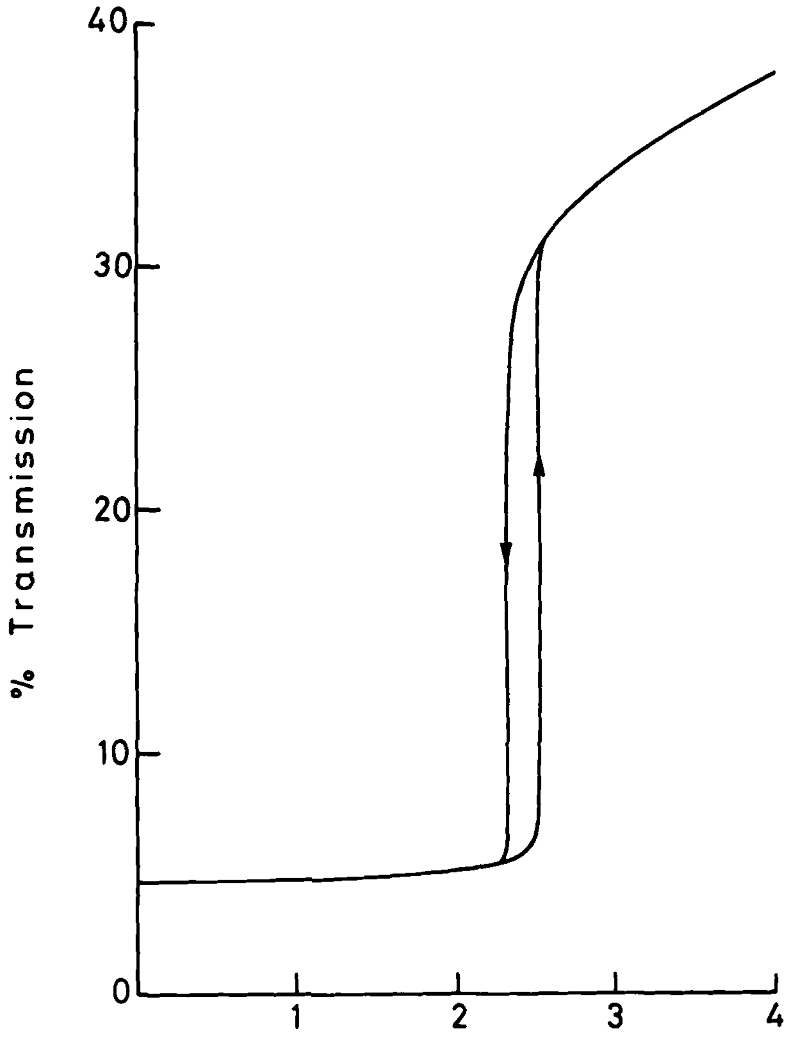

FIGURE 15 Transmission measured without polarizers for a slowly ramped RMS voltage for an 8 μm, 3π/2, HT layer of the low Δ*n* mixture described in the text.

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