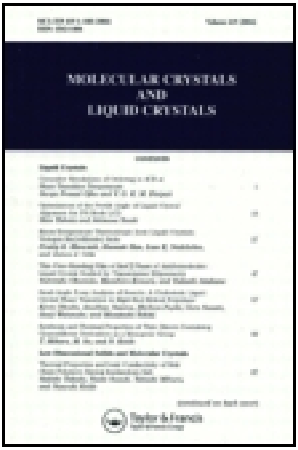

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Improving Multiplexability of Polymer-Dispersed Liquid Crystal Films by Dual Frequency Addressing

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Improving Multiplexability of Polymer-Dispersed Liquid Crystal Films by Dual Frequency Addressing

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We have studied the effect of dual frequency addressing (DFA) on the number of rows N_{max} which can be multiplexed in a liquid crystal display incorporating a PDLC film. N_{max} depends strongly on the required contrast ratio. For the film we studied and a contrast ratio of nine, only direct driving is possible without DFA. With DFA and the same contrast ratio, the number of multiplexable rows can be increased to nearly seven. Higher operating voltages are required to obtain this increased multiplexability. At maximum multiplexability, the off-state voltage increases by about 60 V_{rms} while the on-state voltage increases by less than 30 V_{rms}; most of the increase is due to the high frequency voltage component needed for DFA. To switch between the off- and the on-states, it is sufficient to switch only the low frequency component of the driving voltage; this can be done with the drivers which would be used in a direct drive mode.

INTRODUCTION

Polymer-dispersed liquid-crystal (PDLC) films, consisting of liquid-crystal (LC) microdroplets dispersed in polymer matrices, are promising materials for electro-optic applications because they can be electrically switched from a cloudy, light-scattering off-state to a transparent on-state.[1-4]

In a recent paper we investigated the effect of dual frequency addressing (DFA) on the electro-optic and light-scattering properties of PDLC films.[5] DFA relies on the fact that the dielectric anisotropy of many LC materials changes sign for a particular value of the driving frequency called the crossover frequency f_c. At frequencies below f_c, an applied voltage of sufficient magnitude will align the LC molecules along the applied field, causing the PDLC film to become transparent. At frequencies above f_c, however, the field will align the LC molecules perpendicular to the field; in this state, the film will strongly scatter light. We found that, for the films we studied, the total off-state scattering efficiency of the films was higher in this field-aligned off-state than in the natural (zero field) off-state. This increased scattering can significantly increase the contrast ratio of displays in which the transmitted light is viewed.

In this paper we show that DFA can increase the multiplexability of displays incorporating PDLC films, thus making PDLC films more attractive for use in displays with high information content. Similar effects have been observed previously in conventional LC displays in which the LC material is not confined within microdroplets.[6-7]

MULTIPLEXING AND THE ELECTRO-OPTIC RESPONSE CURVE

Multiplexing is an addressing technique used to minimize the number of electrical connections needed in a display. This can be particularly important in matrix displays in which a large number of elements or segments must be addressed. The principles of multiplexing have been described elsewhere[8] and will not be repeated here; to understand the results described in this paper, it is necessary to know only that:

1. A segment in a multiplexed LC display responds to the rms value of the voltage across it. If this voltage is above some minimum value V_{on}, the segment will turn or remain on; if it is below some lower value V_{off}, the segment will turn or remain off.
2. In a multiplexed matrix display consisting of N rows and an arbitrary number of columns, the rms voltage across a segment decreases as N increases. Since the rms voltage must exceed the value V_{on} if a segment is to remain or turn on, there is a limit to the number of rows which can be multiplexed.

Alt and Pleshko[8] have shown that the maximum number of rows which can be multiplexed in any display which responds to the rms value of an applied voltage is given by:

$$N_{max} = \left[\frac{(V_{on}^2 + V_{off}^2)}{(V_{on}^2 - V_{off}^2)}\right]^2. \tag{1}$$

The actual values of the rms voltages V_{on} and V_{off} depend on the electro-optic response curve (transmittance *vs* voltage curve) for the display and on what constitutes an acceptable contrast ratio between the on- and the off-states. The situation can be understood with the aid of Figure 1, which shows the transmittance *vs* voltage curve for a PDLC film. In displays, the off- and on-states do not generally correspond to the states of minimum or maximum transmittance. Conventionally, a display is considered to be "off" if its transmittance is less than 10% of its maximum value. It is considered to be "on" if its transmittance is above some fixed percentage of its maximum value, typically either 50% or 90%. These values give contrast ratios of five and nine, respectively, where contrast ratio is defined as the ratio of the on-state transmittance T_{on} to the off-state transmittance T_{off}. In this work we shall assume a PDLC film to be "on" if its transmittance is at least 90% of its maximum value and to be "off" if its transmittance is below 10% of its maximum value. We shall denote these transmittance levels as T_{10} and T_{90}, re-

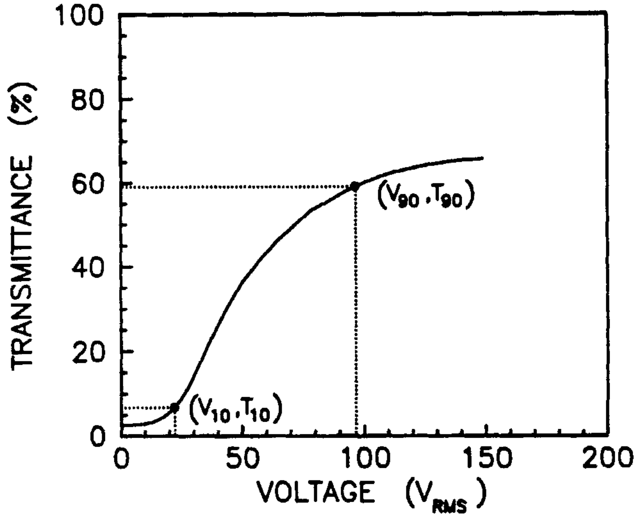

FIGURE 1 Transmittance *vs* voltage curve for a typical PDLC film showing the transmittance levels T_{10} and T_{90} and the corresponding voltages V_{10} and V_{90}. The points (V_{10},T_{10}) and (V_{90},T_{90}) would define the off- and on-states of the film for typical display applications.

spectively. The rms voltages corresponding to these transmittances will be denoted by V_{10} and V_{90}. A multiplexed display incorporating the PDLC film of Figure 1 would switch between the two states $(V_{off},T_{off}) = (V_{10},T_{10})$ and $(V_{on},T_{on}) = (V_{90},T_{90})$ shown in the figure.

Equation 1 shows that the maximum number of rows which can be multiplexed, N_{max}, depends critically on the difference between V_{90} and V_{10}; the smaller this difference, the larger N_{max}. This difference is determined by the slope of the transmittance *vs* voltage curve between the transmittance levels T_{10} and T_{90}. The steeper this slope, the larger the number of rows which can be multiplexed. We shall show in this study that the slope of the transmittance curve of a PDLC film and, hence, its multiplexability, can be increased significantly by DFA.

EXPERIMENTAL

Sample

The PDLC sample used in this study (#4053) contained the liquid crystal EK11650[9] in a (modified) commercial, UV-curable optical adhesive NOA65.[10] In the starting mixture from which the sample was formed, the LC:monomer volume ratio was 1.5:1.

Measurements

The experimental system used to study the effects of DFA on the multiplexability of PDLC films is shown schematically in Figure 2. A 100 Hz sinewave and a

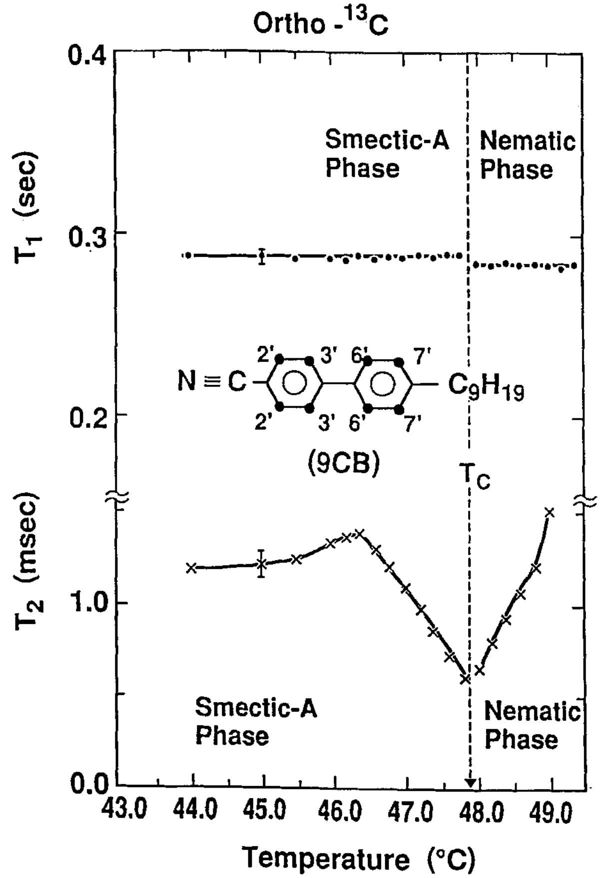

FIGURE 11 Mean values of C'_2, C'_3, C'_6 and C'_8 ortho-^{13}C relaxation times in smectic-A and nematic phases of 9CB versus temperature.

The above results lead to the conclusion that we should adopt the critical exponent of $\nu = \nu' = 0.45$ both in the para- and the ortho-^{13}C. This critical exponent is not consistent with the value of 8CB, and cannot be in agreement with any theoretically expected values although a symmetry, $\nu = \nu'$, is maintained between the Sm-A and N phases as predicted by the scaling hypothesis. The discrepancy in the universal class between the critical exponent of 8CB and that of 9CB may be responsible for the larger first-order phase transition as compared with 8CB. In fact, both the para- and the ortho-^{13}C T_1 relaxation times in 9CB are clearly discontinuous at T_c, as shown in Figures 10 and 11, so that the order parameters show a large discontinuity at the Sm-A ⟨-⟩N phase transition temperature of 9CB.[31]

In addition, it should be noted that these critical exponents are estimated from the carbon atoms composing the biphenyl core parts, which do not include a flexible alkyl end-chain in 8CB and 9CB. Hence, it may be reasonable that the critical exponents of 8CB and 9CB in this work are different from those of X-ray and DSC measurements.

tively. We found that the measured rms voltages agreed to within 3% or better with the values computed from this formula and the measured values of V_L and V_H.

RESULTS AND DISCUSSION

Effect of DFA on multiplexability

Figure 3 shows representative transmittance *vs* voltage curves for our PDLC sample for different peak values V_H of the 15 kHz voltage. The figure clearly shows that, as V_H increases, the rms voltage difference $V_{90}-V_{10}$ decreases and the transmittance rises more rapidly from T_{10} to T_{90}; this means that the multiplexability of the film can be increased by DFA.

Table I shows the rms values V_{10} and V_{90} and the maximum number of rows N_{max} which can be multiplexed for each value of V_H. The values of N_{max} were obtained by truncating the values computed from Equation 1 with $V_{off} = V_{10}$ and $V_{on} = V_{90}$ since N_{max} must be an integer. Values in parentheses give the computed values before truncation. The results show that, with $V_H = 0$, $N_{max} = 1$; this means that only direct drive is possible. As V_H increases, N_{max} increases to nearly seven.

As V_H increases, not only does the transmittance increase more rapidly from T_{10} to T_{90} but the entire transmittance *vs* voltage curve shifts toward higher rms voltages. This means that the price for increased multiplexability is higher operating voltage.

We found that, if we further increased the value of the high frequency voltage

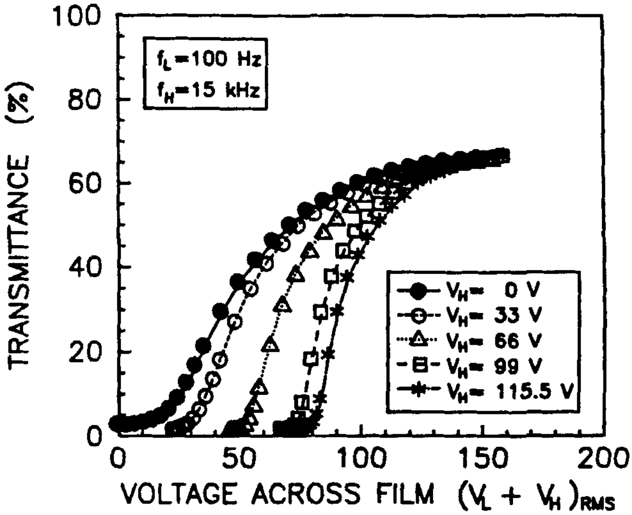

FIGURE 3 Effect of dual frequency addressing on the transmittance *vs* voltage characteristic of PDLC film #4053. The abscissa is the rms value of the sum of the amplified high and low frequency sinusoidal voltages applied to the film. The values of the 15 kHz voltage V_H which label the different curves are peak values. The symbols represent measured transmittance values; they have been connected with smooth curves for easier viewing.

TABLE I

Effect of dual frequency addressing on multiplexability of a PDLC film.

V_H (V)	V_{10} (V_{rms})	V_{90} (V_{rms})	N_{max}[a]
0	21.5	96.8	1 (1.2)
33	33.8	98.8	1 (1.6)
66	55.2	108.6	2 (2.9)
99	75.5	117.5	5 (5.8)
115.5	82.6	123.3	6 (6.9)

[a]Each integer value in this column was obtained by truncating the adjacent value in parentheses, which was calculated from Equation 1.

V_H beyond the values shown in Table I, no additional increase in multiplexability was achieved. The transmittance *vs* voltage curve continued to move toward higher voltages, but the separation between V_{10} and V_{90} actually decreased slightly and the curve rose less sharply from T_{10} to T_{90}.

As noted earlier, the acceptable on-state transmittance T_{on} and the corresponding on-state voltage V_{on} are determined by the required contrast ratio. Clearly, if we were to accept a contrast ratio below nine, V_{on} would be reduced and we could obtain higher values of N_{max} for all values of V_H.

Practical issues

Driving circuitry Some insight into the requirements to be met by the driving circuitry if DFA is to be used to multiplex a PDLC display can be obtained by using Equation 2 to investigate the behavior of the low frequency contributions to V_{10} and V_{90} as V_H increases. Peak and rms values of V_H and V_L are summarized in Table II for V_{10} and in Table III for V_{90}. Initially, the low frequency contributions to both V_{10} and V_{90} increase slightly; they reach a maximum value for V_H near 66 V (peak voltage) and then decrease as V_H increases further. The data clearly show that the low frequency contribution to V_{10} does not change significantly as V_H increases. This means that the increase in threshold voltage as multiplexibility increases is due almost entirely to the high frequency component. Similarly, the low frequency contribution to V_{90} also changes only slightly as V_H varies over a wide range.

TABLE II

High and Low Frequency Contributions to V_{10}.

V_H (V)	V_H (V_{rms})	V_{10} (V_{rms})	V_L (V_{rms})	V_L (V)
0	0	21.5	21.5	30.4
33	23.3	33.8	24.5	34.6
66	46.7	55.2	29.5	41.7
99	70.0	75.5	28.3	40.0
115.5	81.7	82.6	12.4	17.5

TABLE III

High and Low Frequency Contributions to V_{90}.

V_H (V)	V_H (V_{rms})	V_{90} (V_{rms})	V_L (V_{rms})	V_L (V)
0	0	96.8	96.8	136.9
33	23.3	98.8	96.0	135.8
66	46.7	108.6	98.1	138.7
99	70.0	117.5	94.4	133.5
115.5	81.7	123.4	92.4	130.6

To multiplex using DFA, the drive circuitry must provide the high frequency voltage needed to obtain the desired degree of multiplexing. It must also combine the high and low frequency voltages. At a fixed multiplexing level, the amplitude of the high frequency voltage would not be changed during display operation. The display would be switched off and on, i.e., between the voltage levels V_{10} and V_{90}, by switching only the low frequency voltage. It is clear from this discussion that the low frequency voltage levels to be switched would not differ appreciably from those which would have to be switched in a direct-drive mode.

Crossover frequency limitations The driving frequency of a display is often constrained to lie below a certain value (see, for example, the discussion of power consumption below); this restriction limits the choice of LC materials which may be used for DFA to those with sufficiently low crossover frequency. Furthermore, for a given LC, the value of the crossover frequency f_c increases strongly with increasing temperature whether or not the LC material is confined to microdroplets.[5] This temperature dependence restricts the temperature range over which a display can be multiplexed using DFA. For example, for the PDLC film used in our experiments, the crossover frequency increased from 162 Hz at 0°C to 2.3 kHz at 20°C to 20 kHz at 38.4°C, giving a range of about 40°C over which the film could be multiplexed when the frequency of V_L is 100 Hz.

Power consumption Since the impedance of a PDLC film decreases as the frequency of the driving voltage increases, the power consumed by a PDLC film will increase with increasing frequency. This can raise the temperature of the film and increase the crossover frequency as discussed above.

The impedance of a PDLC film depends on both the polymer matrix material and the LC material in the microdroplets. We have measured the impedance and the power consumption of a variety of PDLC compositions (all with positive dielectric anisotropy) and have found considerable variation in the frequency dependence of their power consumption. Extrapolating our low-voltage data to 100 V_{rms} (which, of course, neglects changes in impedance due to reorientation of the LC molecules within the microdroplets), we found that power consumption ranged from 5 to 60 W/m^2 at 100 Hz and from 2000 to 2800 W/m^2 at 20 kHz. Although this increase in power consumption is significant, we note that the highest power consumption at 20 kHz is comparable to the power consumption of a vacuum fluorescent display. Therefore, the circuitry to handle these power levels certainly exists. In view of the rapid increase in power consumption at higher frequencies, we believe that 20 kHz is probably a reasonable upper limit to the driving frequency useful for DFA of PDLC films. Furthermore, heating of a room-temperature PDLC film driven at 20 kHz becomes noticeable, i.e., the film becomes warm to the touch. These considerations probably limit the LC materials available for DFA to those with crossover frequencies in the 1–10 kHz range.

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