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Inversion of contrast in ferroelectric smectic C liquid crystal displays

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Contrast inversion has been observed in ferroelectric smectic C liquid crystal displays when multiplexed using a standard two-slot multiplexing scheme. This occurs when the switching response moves from the trailing half of the double pulse to the leading half at relatively high voltages and short time slots. The effect is explained with reference to the voltage–time switching dependency. Some important implications for multiplexing are pointed out.

1. Introduction

Ferroelectric smectic C liquid crystals are under intense investigation as a means of achieving large area high resolution flat panel displays. The materials exhibit fast switching times (better than 100 μs), are bistable and can thus be multiplexed at high levels using a line-at-a-time fast scan technique. Switching takes place to a pulse of sufficient voltage-time (Vt) product and is polarity sensitive, i.e. once switched by a pulse of $+Vt$ to one optical state, the device will remain in that state until it receives an equal and opposite Vt product pulse. The switched states are stabilized by the interaction of the a.c. multiplexing data waveform with the negative dielectric anisotropy exhibited by the majority of these materials. Many multiplexing schemes have been proposed for such operation but one example which is commonly used is that suggested by Harada *et al.* [1] and in a slightly simpler form by Lagerwall *et al.* [2]. This scheme is illustrated in figure 1. The leading half of the bipolar strobe pulse acts as a d.c. compensator and the trailing half, combined with the appropriate polarity data voltage on the column, switches into the desired state. Two fields, with reversal of the polarity of the strobe pulse, are necessary to facilitate this. A pulse voltage of $+(V_s + V_d)$ will switch to one state (pixels A and D) while a pulse voltage of $-(V_s + V_d)$ will switch to the opposite state (pixels B and C). All other voltages ($+/- V_d$ and $+/-(V_s - V_d)$) are designed to be insufficient to cause switching. Since switching is intended to take place to the trailing half of the strobe pulse, this scheme is termed the two slot trailing pulse.

We have observed reversal of the switching response from the trailing pulse to the leading pulse using this multiplexing scheme at relatively high voltages and short time slots. This leads to a visual inversion of contrast. This unexpected result is explained by relating the multiplexing behaviour to the response time of the material to a bipolar pulse.

2. Experimental procedure

We have studied several materials and results are given for typical fluorinated biphenyl esters [3, 4] whose properties are listed in the table. Multiplex data have been

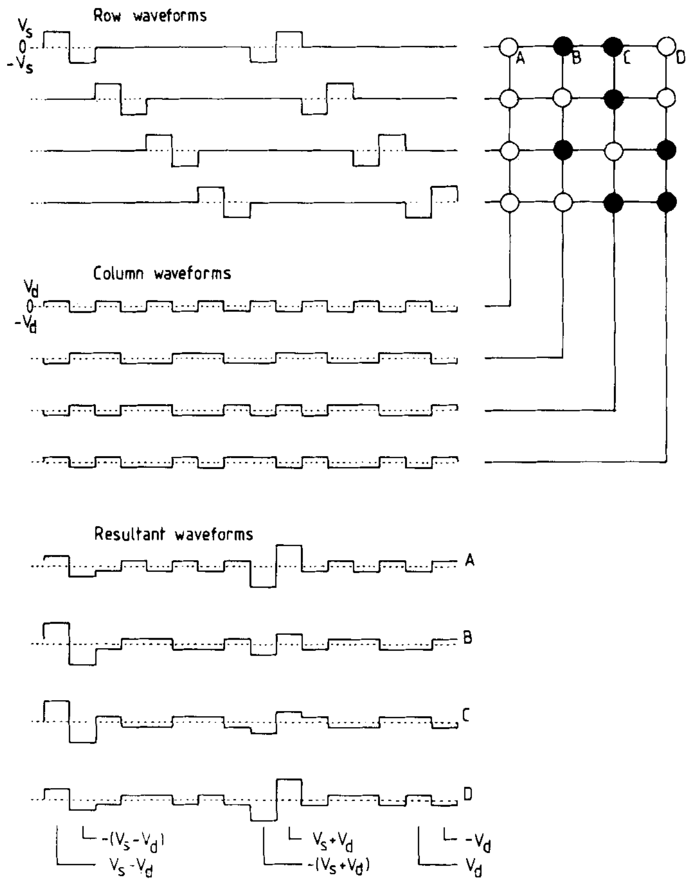


Figure 1. A typical example of the two slot trailing pulse multiplexing scheme showing four-way multiplexing. Pixel A is arbitrarily defined to be on in response to a $+(V_s + V_d)$ pulse. One time slot is the shortest single time period, the bipolar strobe pulse occupies two time slots.

Properties of the materials used in this study.

	Material A	Material B
	Transition temperatures/°C	
S_C–S_A	82	84
S_A–N	114	107
N–I	142	133
	Properties at 30°C	
P_s/nC cm^{-2}	10·2	20·5
Cone angle	24	23
$\Delta\varepsilon$	−1·8†	−1·4†

† Estimated values.

taken in two ways, either using a 16 × 16 matrix cell driven by an improved version of a matrix addressing apparatus [5] or with a cell having 1 cm^2 active area and driven by an arbitrary function generator (Wavetek model 75) under control of a small computer and whose output is fed through a high power amplifier. In all cases the cell thickness was in the region of 2 μm and alignment was by rubbed polyimide with the rubbing directions arranged anti-parallel.

Switching responses were measured with the single cell using the criterion of visibly clean switching when viewed through a microscope focussed on a 1·75 mm^2 region of the cell. The switching waveform is a bipolar pulse as used in the strobe waveform of the multiplexing scheme with a constant duty cycle of 50 : 1 and with varying amounts of a.c. bias (50 kHz square wave) superimposed on the pulse waveform. The orientation of the cell between crossed polars was such that a bright state was obtained in response to a positive voltage.

Optical response is measured with a silicon photodiode fitted with an eye-response filter and having a response time better than 10 μs.

All results quoted in this paper were taken at 30°C.

3. Pulse response

The optical response of material *A* to the switching waveform is shown in figures 2 (*a*)–(*c*). These show that with a pulse voltage of 30 V and a pulse width of 290 μs that switching is to the trailing pulse but if the pulse width is reduced to 200 μs then the response is to the leading pulse. Switching is between similar transmission levels in each case. This is explained as follows. Following the trailing pulse there is some relaxation to an intermediate state, the next leading pulse is able to switch fully from this intermediate state requiring the adjacent following trailing pulse to switch from a fully switched state. Greater energy (or a greater Vt product) is required to switch from the fully switched state than from the intermediate state. At a fixed voltage, as the pulse width is reduced, there comes a point at which the leading pulse is able to switch but the trailing pulse is not. This is the point at which the contrast inverts from the normal mode of trailing pulse switching to the inverted mode of leading pulse switching.

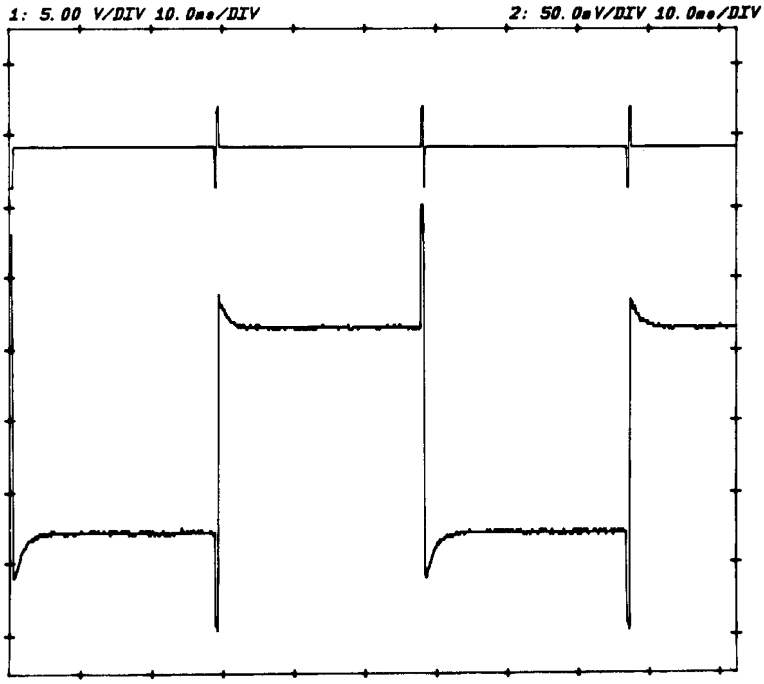
The effect of applying a.c. is to reduce the relaxation immediately following the pulse giving greater separation of the transmission levels between pulses. It also affects the voltage at which leading pulse switching occurs. This is achieved by stabilisation of the switched states by the interaction of the a.c. field with the negative dielectric anisotropy. There is therefore less relaxation and the leading pulse requires a greater Vt product to switch so that the leading pulse switching region moves to a higher voltage.

Figure 3 shows the regions of normal (trailing pulse) and inverted (leading pulse) switching mapped onto the logarithmic voltage-time plane. Three regions are identified, a region in which no switching (or only partial switching) occurs (*C*), a region of normal contrast switching (*A*) and a region of inverted contrast switching (*B*). The area of the region of inverted contrast is reduced as the a.c. voltage is increased. From figure 3 it can be seen that for the conditions of figure 2, i.e. +/− 30 V bipolar pulse and 0 V a.c. bias, that trailing pulse switching extends from pulse widths greater than 1 ms to approximately 280 μs. Leading pulse switching operates over the range of approximately 240 μs to 130 μs pulse width. At times shorter than this the visual criterion for clean switching breaks down and the cell appears patchy. As the time is further reduced the transmission levels of the switched states tend to equalize as there is no latching of these states.

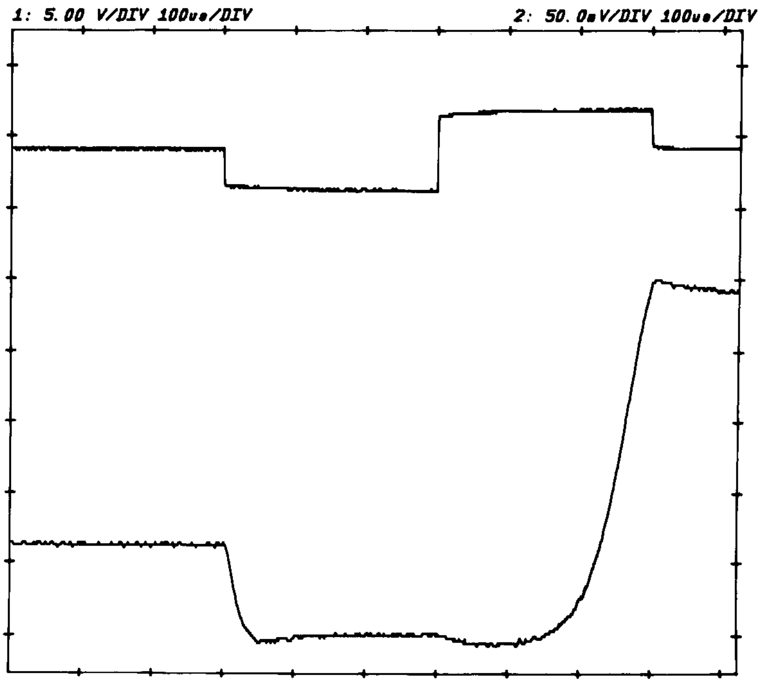
4. Sharpness of the transmission-voltage response

The partial switching region can be further investigated by measuring the difference in transmission levels between the two partially switched states as a function

(*a*)


1: 5.00 V/DIV 10.0ms/DIV
2: 50.0mV/DIV 10.0ms/DIV

(*b*)


1: 5.00 V/DIV 100us/DIV
2: 50.0mV/DIV 100us/DIV

(c)

(d)

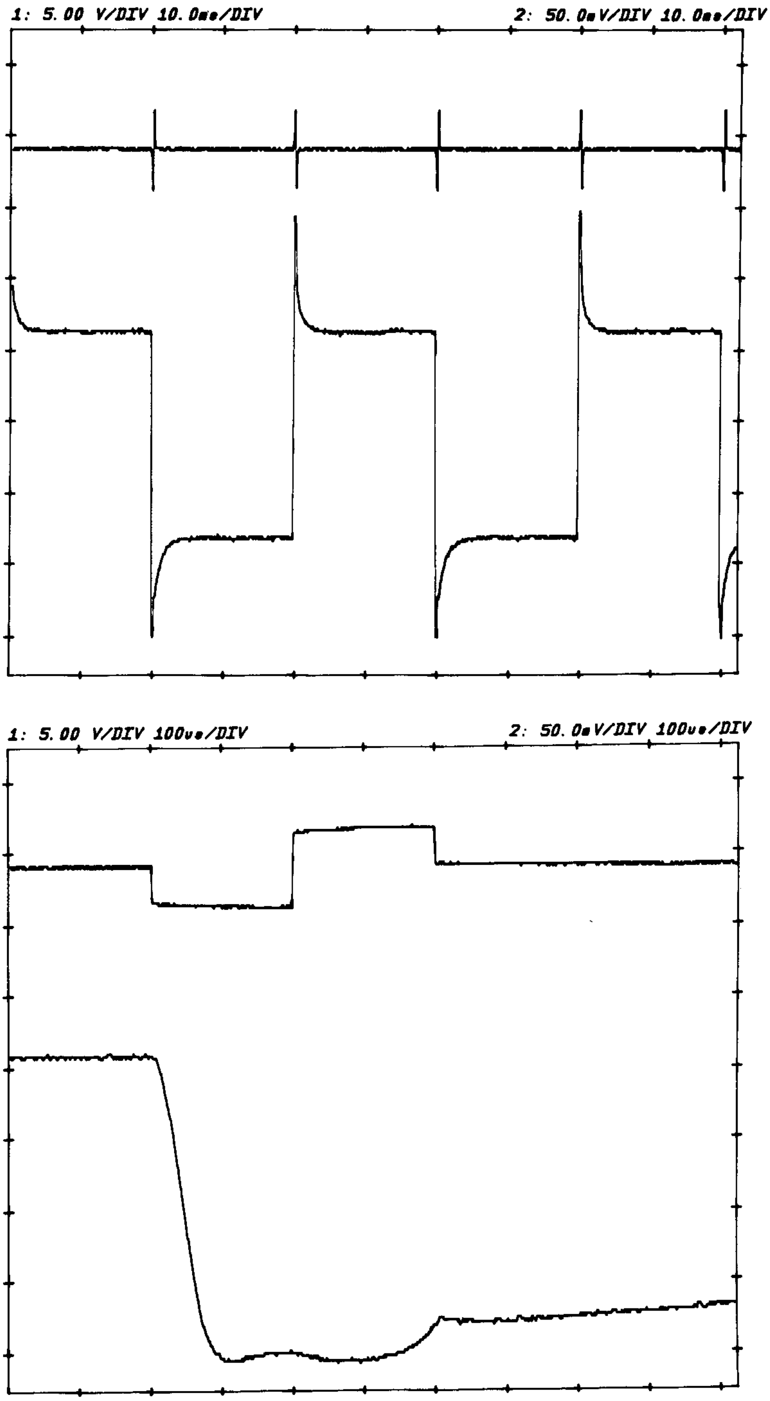


Figure 2. The optical response (lower trace) of material *A* to a bipolar pulse (upper trace) of +/−30 V with no a.c. bias applied. The bipolar pulse is of the same form as the row waveform shown in figure 1 but with an interpulse gap of 98 time slots. The horizontal scale is 10 ms/div. for (*a*) and (*c*) and 100 μs/div. for (*b*) and (*d*); the vertical scale is arbitrary. (*a*), (*b*) 290 μs time slot-trailing pulse switching; (*c*), (*d*) 200 μs time slot-leading pulse switching.

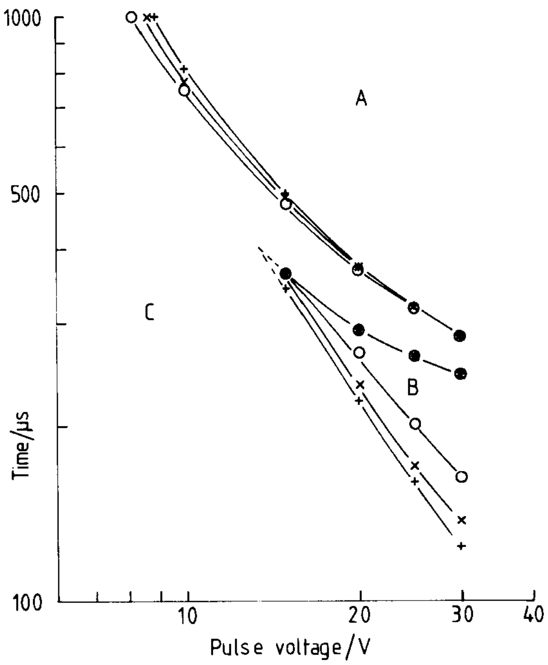


Figure 3. The response time as a function of voltage to a bipolar pulse for material *A*. The bipolar pulse is of the same form as that used in the strobe waveform of figure 1 but with an interpulse gap of 98 times slots. Region *A* is trailing pulse switching; region *B* is leading pulse switching; region *C* is zero or partial switching. +, zero volts a.c.; ×, 5 V r.m.s. a.c.; O, 7·5 V r.m.s. a.c.

of voltage at fixed pulse width, results are given in figure 4. These show three cases of different pulse widths covering trailing pulse switching (figure 4 (*a*)), leading pulse switching ((figure 4 (*b*)) and where both trailing and leading pulse switching occur as the voltage is raised ((figure 4 (*c*)). Outside this region there is still some optical response but the decay is rapid and no bistability exists on the timescales of the measurement.

It has been shown [6] that these sharpness plots can be used to estimate the range of suitable $V_s : V_d$ ratios at which the material may be multiplexed. If V_{sat} is defined as the voltage required for full switching and V_{th} is the voltage below which there is no optical response then when multiplexing, $(V_s + V_d)$ need be no larger than V_{sat} and $(V_s - V_d)$ should be no larger than V_{th}, i.e.

$$\frac{V_{sat}}{V_{th}} = \frac{V_s + V_d}{V_s - V_d}$$

and

$$\frac{V_s}{V_d} = \frac{V_{sat}/V_{th} + 1}{V_{sat}/V_{th} - 1}$$

gives the condition for maximum $V_s : V_d$ ratio. If the display is operating on a curve as shown in figure 4 (*c*) and the $(V_s - V_d)$ pulse is arranged to lie in the region of opposite contrast to the $(V_s + V_d)$ pulse then there will be an enhancement of contrast as $(V_s + V_d)$ switches to the trailing pulse and $(V_s - V_d)$ switches to the leading pulse which are the same optical states.

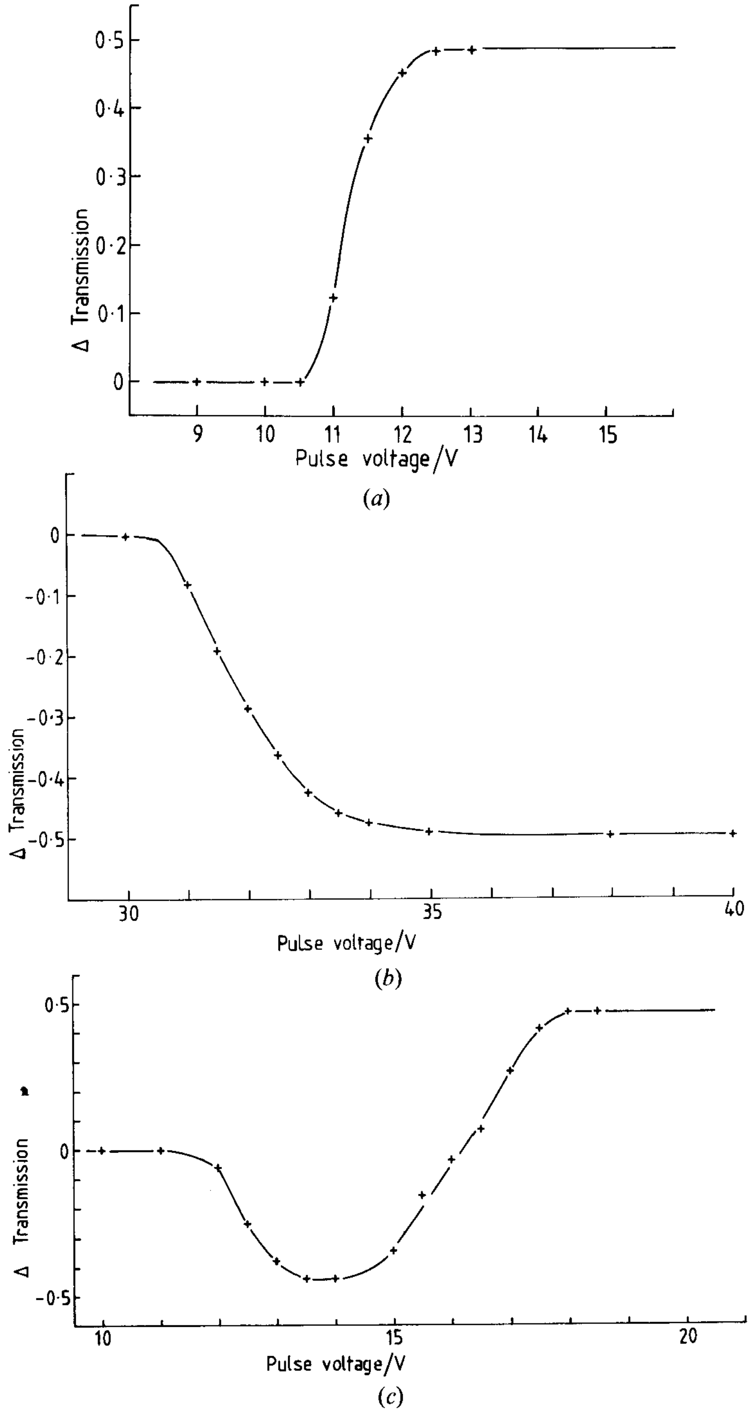


Figure 4. The difference in interpulse transmission levels (arbitrary units) of material *A* as a function of voltage when driven with a bipolar pulse train (as shown in figure 2) and with zero volts a.c. bias. The response shown is for a negative leading pulse. (*a*) 600 μs time slot—trailing pulse switching; (*b*) 100 μs time slot–leading pulse switching; (*c*) 400 μs time slot—initially shows leading pulse switching (11 V–16 V) followed by trailing pulse switching (> 16 V).

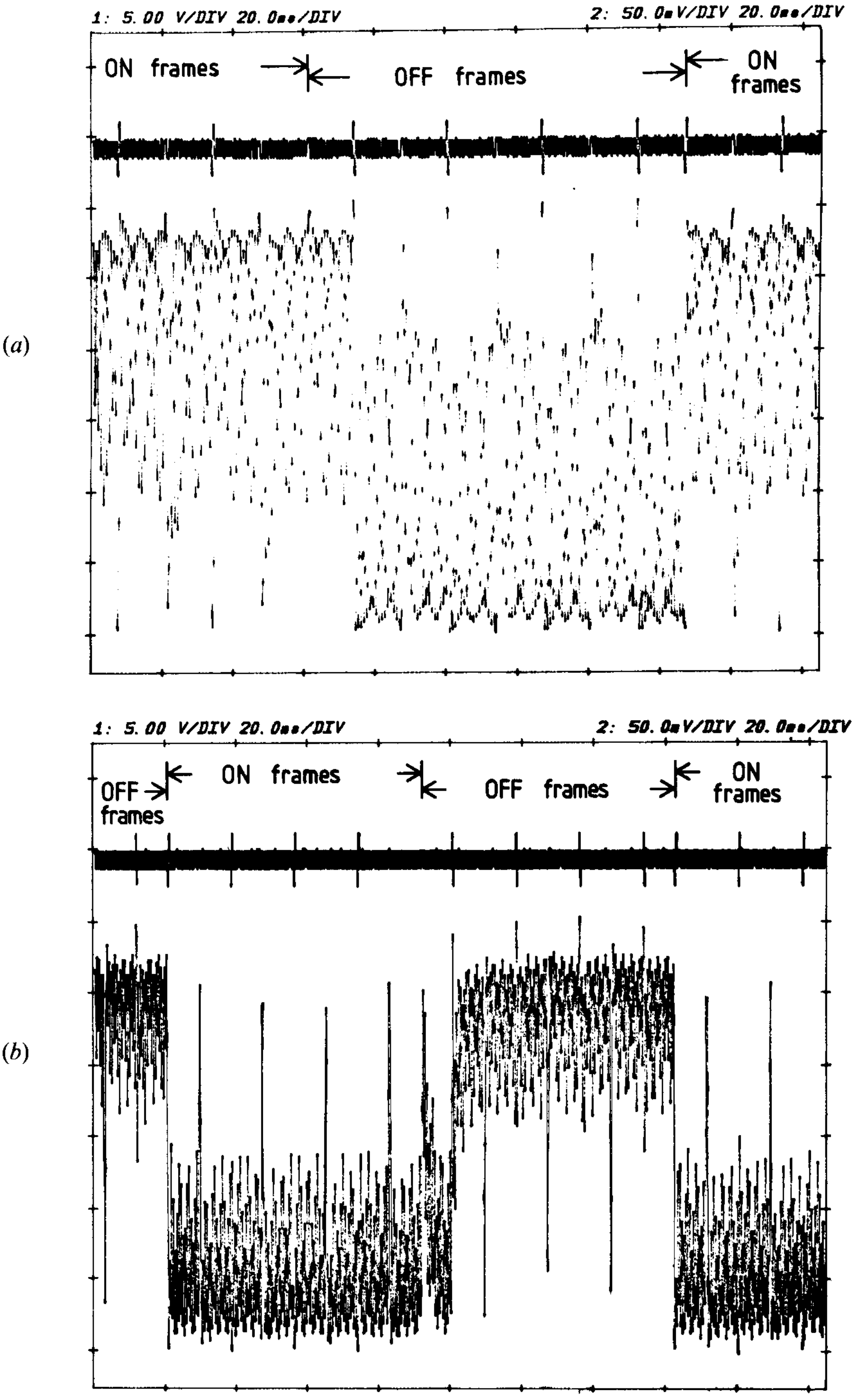
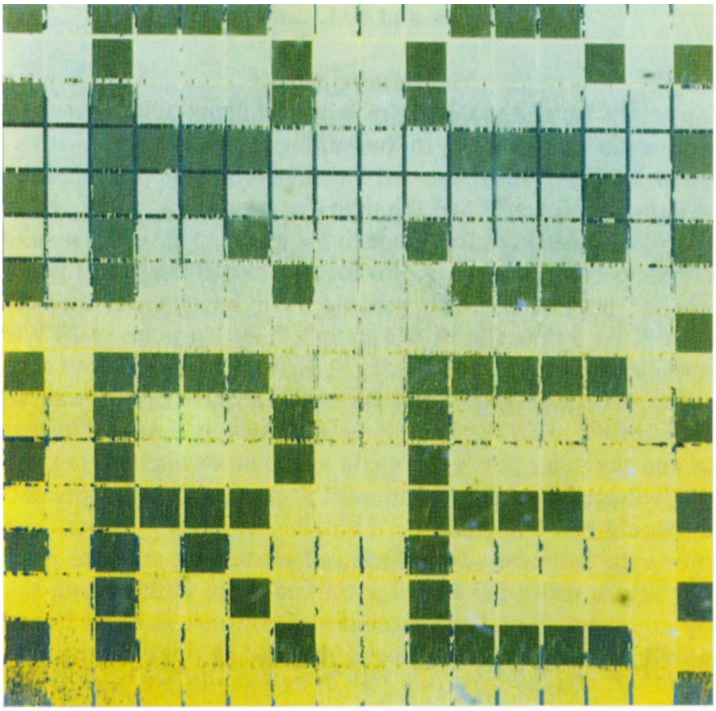
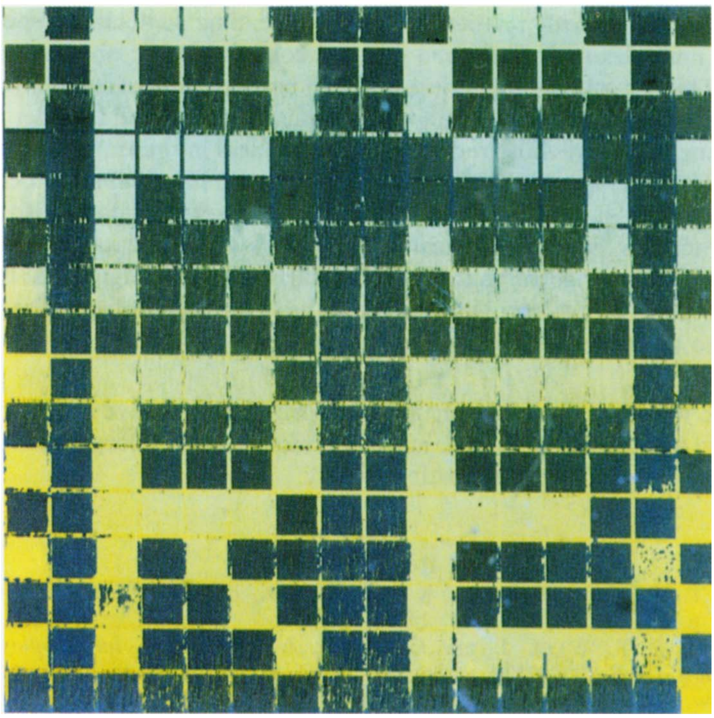


Figure 5. The multiplexing response of material *A* (optical response—lower trace, multiplexing waveform—upper trace) to a 16-way multiplex drive, $V_s + V_d = 20\,V$, $V_d = 6{\cdot}66\,V$. Simulation of four frames with the pixel on followed by four frames with the pixel off. The horizontal scale is 20 ms/div., the vertical scale is arbitrary. (*a*) 416 μs time slot—normal contrast i.e. high transmission when pixel is on. (*b*) 277 μs time slot—inverted contrast i.e. high transmission when pixel is off. There is some interference, noticeable in the optical response as a low frequency superimposed ripple, caused by beating between the sampling rate of the digital storage oscilloscope and the multiplexing waveform.



(*a*)



(*b*)

Figure 6. The matrix cell containing material *B* being multiplexed 16 ways using the two slot trailing pulse multiplexing scheme and showing contrast inversion and enhancement between (*a*) and (*b*). (*a*) $V_s + V_d = 9\,V$, $V_d = 3\,V$, one time slot = 390 μs, normal contrast; (*b*) $V_s + V_d = 28{\cdot}5\,V$, $V_d = 9{\cdot}5\,V$, one time slot = 51 μs, inverted contrast. Actual size of the display is 0·4″ × 0·4″.

5. Multiplexing results

Multiplexing results for this material are shown in figure 5. In figure 5 (*a*) normal contrast is shown as the cell responds to the trailing ($V_s + V_d$) pulse with a time slot of 416 μs. Clean switching can be observed but the contrast is poor due to the large response to the data waveform. When the time slot is reduced to 277 μs the contrast inverts (figure 5 (*b*)) as switching takes place to the leading ($V_s + V_d$) pulse. Contrast is also improved as there is less response to the data waveform, since its Vt product is reduced, at the shorter time slot. This behaviour can be related to the voltage–time response of figure 3. At a time slot of 416 μs the ($V_s + V_d$) pulse of 20 V is situated within the normal contrast region and the ($V_s - V_d$) and V_d pulses, both of 6·66 V, are situated in the non-switching region where there is a transient optical response. When the time slot is reduced to 277 μs the ($V_s + V_d$) pulse is situated in the inverted contrast region and the other pulses are again in the non-switching region. Thus we could predict the voltages required to multiplex at particular time slots and the type of contrast that would be obtained.

Figure 6 shows the response of a matrix cell containing material *B* to differing multiplexing conditions using the two slot trailing pulse multiplexing scheme and clearly showing an inversion and enhancement of contrast at short frame times as switching is moved from the trailing pulse to the leading pulse switching region.

6. Conclusion

Contrast inversion has been observed using the two slot trailing pulse multiplexing scheme and explained with relation to the voltage–time switching response. The inference for multiplexing is that good inverted contrast can be obtained at shorter time slots and higher voltages than those at which normal contrast is obtained. A high strobe voltage is required but the data voltage must remain small in order to ensure a broad leading pulse switching region. Good sharpness in the transmission-voltage characteristic is therefore also necessary to achieve good discrimination between the ($V_s + V_d$) and ($V_s - V_d$) pulses. Short time slots and low data voltages also minimize contrast degradation due to the optical response following the data waveform. Over a restricted operating range the contrast can be enhanced by arranging that the optical response is to the ($V_s + V_d$) trailing pulse and the ($V_s - V_d$) leading pulse such that both switch to the same optical state.

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