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J. A. M. M. Van Haaren[a]; W. J. A. M. Hartmann[a]; A. G. H. Verhulst[a]
[a] Philips Research Laboratories Eindhoven, Eindhoven, The Netherlands

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Switching on stray electric fields in ferroelectric liquid crystal cells

by J. A. M. M. VAN HAAREN*, W. J. A. M. HARTMANN†
and A. G. H. VERHULST

Philips Research Laboratories Eindhoven, Prof. Holstlaan 4,
NL-5656 AA Eindhoven, The Netherlands

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In liquid crystal dot-matrix displays light may leak through the display area between the pixels. To obtain sufficient contrast this non-pixel area has to be made non-transmissive. For ferroelectric liquid crystal (FLC) displays this may be done by switching the material in the gaps between the picture elements to a non-transmissive state by the stray electric fields that occur during application of voltages to the pixel electrodes. This is experimentally studied for test cells with an electrically modified smectic layer structure. The gap region considered is an asymmetric environment of the FLC material, as the transparent conductive coating has been removed on one substrate, whereas on the other substrate a conductor covers the glass. The FLC molecules in the non-pixel area prefer to direct their dipoles towards the covered substrate. To switch the FLC material with the stray electric fields, it is a prerequisite to outweigh this preference. We made spatially resolved observations for various gap widths and various applied voltages on 2 μm thick FLC layers. With bipolar voltage pulses of 64 μs width each, amplitudes of about 25 V are needed to switch the FLC in 3·2 or 4·0 μm wide gaps. It was found to be more difficult to switch gaps that are 7 μm wide than was anticipated on the basis of the results for 4 μm gaps. This is attributed to the surface polarization charge due to the FLC permanent dipoles built up at the FLC–glass interface. Experimental results supporting this explanation are presented.

1. Introduction

Displays using liquid crystals as electro-optical modulators are attracting much attention. A number of companies are mass-manufacturing video displays based on the twisted nematic effect. Application of this effect in video displays calls for the introduction of an array of solid state switches on one of the glass substrates. The defect-free production of this so-called active matrix is technologically involved. For this reason, liquid crystal effects that do not need an active matrix are also of interest. A widely studied example of effects of this type is the one using ferroelectric liquid crystals (FLC) in the surface stabilized geometry [1]. This effect may be used to display video images [2] using liquid crystal cells with glass substrates covered with transparent conductors patterned in columns for one substrate and rows for the other one. To make the grey tones that are needed to display video images, the texture method [3] may be employed.

In video displays with a simple rows-and-columns electrode configuration, light leaks around the pixel areas and this has a disastrous effect on the attainable contrast,

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*Author for correspondence.

†Present address: Philips Flat Panel Displays, P.O. Box 218, NL-5600 MD, Eindhoven, The Netherlands.

even if the pixels themselves function perfectly. The liquid crystal material covering the gaps between the columns or the rows cannot be addressed directly by the driving voltages. Between crossed polarizers, therefore, part of the non-pixel area will be non-transmissive and the rest will be transmissive, thus deteriorating the contrast obtained. For displays with dimensions that are of current interest (50–200 μm pixel size and about 4 μm gap widths), a sufficient contrast ratio (100) can only be obtained with a structure that prevents transmission of light through the area between the pixels.

An elegant way to realize this so-called black matrix was first demonstrated by Wakita *et al.* [4], employing the bistable nature of the surface stabilized FLC effect. In this method, the liquid crystal material in the gap region is switched to a state that does not affect the polarization of the light after passing the front polarizer. Consequently, light passing the display at the non-pixel area is absorbed at the rear polarizer. This switching of the liquid crystal at the non-pixel area is induced by the stray electric field that extends into the gap, while addressing the FLC in the adjacent pixels. We studied the response of FLC to stray electric fields, in a part of the cell where one of the substrates is covered by a transparent conductor, while the conducting film on the opposing substrate has been removed locally. We focused on smectic layer structures that have been reoriented by an electric field from chevron to quasi bookshelf [5–7]. In this paper we have left out the details of the addressing scheme for video displays, and consider only variations of the amplitude and the width of the bipolar pulses.

2. Experimental

Experiments were performed on test cells specified in the table. One of the glass substrates of each cell was covered with indium–tin oxide (ITO), in which narrow gaps had been etched. Variations in the width of these gaps were less than 5 per cent of the gap width. This glass plate was used to assemble a liquid crystal cell using a glass substrate with two electrodes as the opposing substrate. Both substrates were covered with thin poly(vinylalcohol) alignment layers. These layers were rubbed: for the first cell the rubbing direction was parallel to the gaps, and for the other cells the rubbing direction made a 45 degree angle with the gaps. The substrates were assembled in such a way that the rubbing directions of the opposing substrates were parallel and that the two electrodes were oriented perpendicularly to the indium–tin oxide gaps. The thickness of the FLC layer was 2 μm.

The FLC layer was treated with a 25 Hz square-wave voltage of typically 30 V amplitude for a few minutes to change the smectic layer-structure in the cell [3, 5–8]. The effects of this treatment are twofold: It gives the smectic layers a so-called quasi-bookshelf geometry, with an increased optic switching angle and electro-optic modulation depth, and it results in an increase of the threshold for electro-optic switching of the FLC.

Bipolar pulses were supplied to switch the FLC. During each 20 ms frame time the bipolar pulse consists of two similar pulses with opposite polarity and with amplitudes up to 30 V and pulse widths of 32, 64, 128 or 256 μs. In each frame, the two pulses followed one another immediately. Each second pulse had a polarity that stimulates switching to the black state. Between the two pulses in one frame and the ones in the next frame, the cell was switched to 0 V. We made microscopic observations of the shrinking of the white domains in the gap region and measured the width of the white domains (in the direction perpendicular to the edges of the electrodes) from photographs taken via the microscope.

Parameters for the cells used in the present experiment.

Cell number	FLC mixture	Spontaneous polarization/nC cm^{-2}	PVA layer thickness/nm	Rubbing direction relative to gaps/degree
1	CS 1028 (Chisso)	−35	25	0
2	CS 1031 (Chisso)	−28	7	45
3	Felix T 107 (Hoechst)	45	7	45
4	Felix T 107 (Hoechst)	45	7	45

3. Results and discussion

After filling the test cells and cooling them to the ferroelectric S_C^* phase, the FLC director selects one out of two possible orientations: one orientation with the permanent polarization, which is coupled to the director, up and the other orientation with the polarization down. In a symmetric environment there is no preference for either an upwards- or a downwards-directed polarization, and both black and white domains occur. However, an asymmetry in the environment (for example, the presence of indium–tin oxide (ITO) on one of the substrates and not on the opposing substrate) may introduce a preference for either upwards or downwards polarization. This preference is particularly relevant for cells with thin orientation films, like the ones used in the present experiment. The preference for one of the director orientations due to the presence of ITO on one substrate and not on the opposing substrate occurred in all the FLC cells in this experiment. For the three materials studied here, the polarization turned out to be directed towards the ITO-covered electrode [9]. The same was concluded for the FLC material ZLI 3654 (E. Merck, $P_S = -29\,\text{nC}\,\text{cm}^{-2}$).

This preference is beneficial for the achievement of the black matrix at one type of gaps between the electrodes in the display (for example, the horizontal gaps), but it is not at the other type (for example, the vertical ones). For a well functioning electric field-induced black matrix, it is essential that the driving voltages are able to establish a black matrix in a gap in which the FLC director prefers a transmissive state. To accomplish this, advantage may be taken of differences between gaps in a row of the display on the one hand and gaps in a column on the other. Several measures may be devised to manipulate these asymmetries profitably. For instance, different widths may be chosen for the horizontal and the vertical gaps, the rubbing direction can be chosen parallel to one type of gap, or the differences between the voltages felt by the FLC material in the two types of gaps may be exploited. (The horizontal gaps undergo voltages from pixel selection on one side of the gap and from non-selection at the other. In the case of pixels separated by a vertical gap, the reset, select and non-select voltage pulses are applied to both pixels simultaneously. There is some freedom in choosing the amplitude and duration of these pulses, especially of the reset pulses, and this may be used to design a driving scheme which is able to make both types of gaps switch to the black state.)

The smectic layer structure was modified by a low frequency electric field pretreatment, which was applied to the electrodes on both sides of the gaps. We used 25 Hz square waves with 30 V amplitude for a few minutes. The voltage needed for these texture changes depends on the FLC material used [2]. Modifying the smectic layer structure in the gap regions proved to be possible up to a certain specific gap width, which differed for the various FLC materials and rubbing treatments. Results are given in figure 1, where the horizontal axis denotes the gap width, and the vertical axis

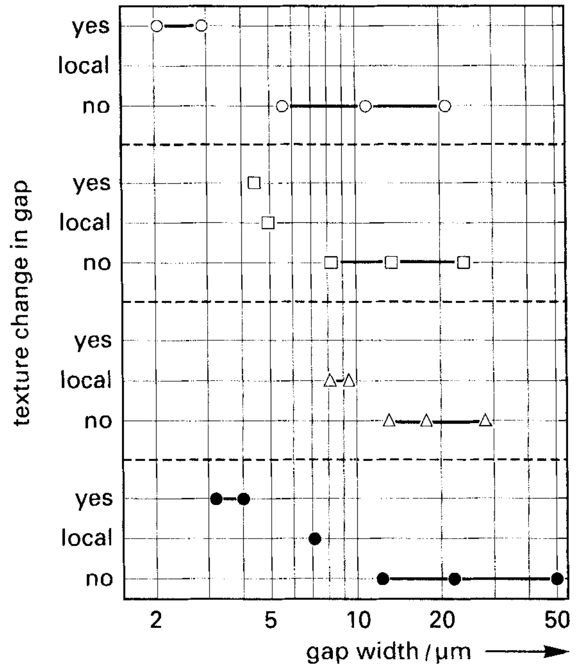

Figure 1. Texture change obtained in the gap using a 30 V, 25 Hz square wave voltage. The horizontal axis indicates the width of the gap considered. The vertical axis denotes the three possible assessments: 'yes' if the modified texture extended all over the gap, 'no' if the initial texture remained all over the gap, with the possible exception of a relatively small part at the edges of the gap, and 'local' if the texture extended locally across the gap, but the texture lines were interrupted at some positions in the centre of the gap. From top to bottom, the results are given for cells 1–4 (see the table). In cells 1, 3 and 4, the voltage treatment resulted in texture III lines in the pixel area and in the narrow gaps. In cell 2 the applied voltages could only establish texture II in the gaps, while texture III was obtained in the pixel area.

indicates whether texture II or texture III (see [2, 3, 5–8]) could be generated in the gap or not. (As the FLC material in cell 2 (CS 1031) has a high threshold for texture changes, the voltage treatment employed created a change to texture II for the pixels and the narrow gaps.) Three answers to this question could be identified: the modified texture was present all over the gap (indicated as 'yes' along the vertical axis in figure 1); the initial texture was maintained all over the gaps, with the possible exception of a relatively small part of the gap at the edge of the pixel ('no'), or the modified texture extended locally over the entire gap width, while on other parts of the gap it was interrupted in the central part of the gap ('local').

We studied whether pulses applied to the pixels were able to switch the FLC material in the gap region from the preferred state caused by the asymmetry in the ITO coverage to the reversed state. With proper orientation of the cell between crossed polarizers, this switching was made to happen from a transmissive to the non-transmissive state. The switching occurred via the shrinking of domains in a transmissive state. This was observed to be a slow process, and the response also depended on the history. In general, care was taken to start from a reproducible, well-defined initial state. The contraction of the domains varied over the gap region. We measured the width (perpendicular to the electrode edges) of the transmissive domains

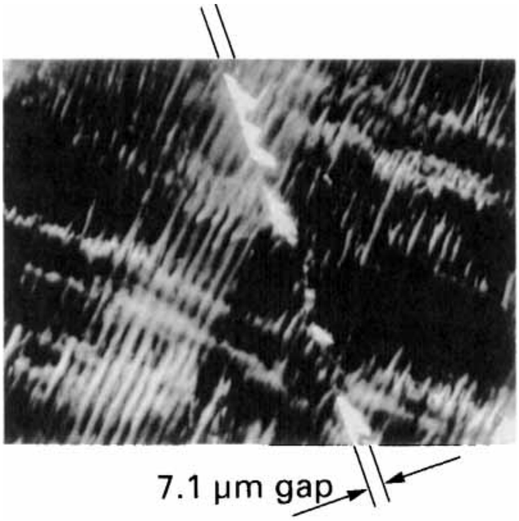

Figure 2. Example of shrunken white domains in the 7·1 μm gap (cell 4) between two electrode parts of the test cell that have been switched to the black state, In these black areas the texture lines, which were brought about by the voltage treatment, are visible and they are observed to extend across the gap region. Bipolar voltage pulses of 30 V amplitude and 128 μs duration were used to switch the cell to the black state. The picture was taken after repeating these bipolar pulses wvery 20 ms during on minute. The width of the pictured area of the cell is 230 μm.

at various positions along the gap as a function of the amplitude of the driving voltages. These measurements were performed for various gap widths.

Bipolar pulses were applied in which the trailing pulse had a polarity that tended to switch the FLC in the gap region to the black state. It was observed that the repetition of the pulses caused a gradual shrinking of the white domains. Before this switch to the non-transmissive state, we applied bipolar pulses with a trailing pulse which supported the reset to the white state. We chose to take a reset period of one minute. After this, we applied black-switching pulses during one minute and then the widths of the remaining white domains were measured. Figure 2 shows an example of the shrunken white domains in a cell switched to its black state.

Figures 3 and 4 show the widths of the white domains for a 4·0 μm and a 3·2 μm gap, both in cell 4 at different positions along the gap. We used pulses of 64 μs width and amplitudes as indicated along the horizontal axes in the figures. The white domains diminish for voltage pulses with pulse heights between 15 and 30 V, and both gap regions behave in a similar way.

The behaviour of the FLC in the 7·1 μm gap of cell 4 differs from that in the narrower gaps. For this gap, 64 μs pulses were insufficient to switch a significant part of the gap region to the black state. We therefore chose to vary the width of the pulses at 30 V amplitude instead of the height with fixed pulse width. In the experiment, we increased the pulse width by *factors* of 2, which leads to an exponential increase of the pulse area of the switching pulses. Figure 5 shows the resulting domain widths as a function of the width of the pulses. As the pulse area determines the FLC switching in fair approximation, we must conclude that it is significantly more difficult to switch a 7·1 μm gap than to switch a 3·2 or a 4·0 μm gap. For the next higher gap width in cell 4 (12·4 μm), it was not possible to make the FLC switch to its black state anywhere in the

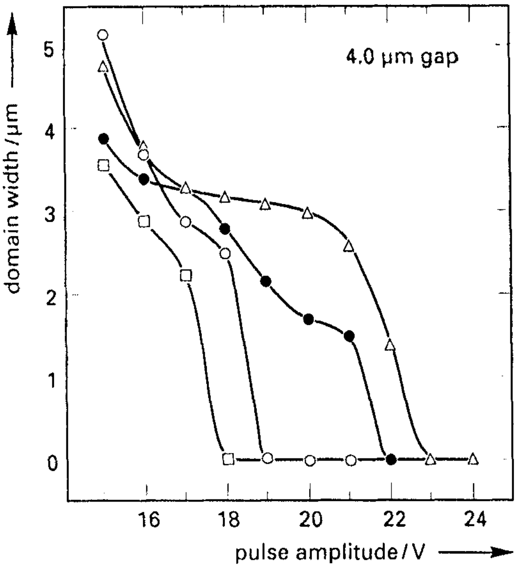

Figure 3. Width of white FLC domains for the 4·0 μm gap in cell 4 (see the table) at four different positions along the gap as a function of the amplitude of the bipolar voltage pulses. Each of the pulses is 64 μs wide, and the compensation pulse immediately precedes the writing pulse. The pair of pulses is repeated every 20 ms. The domain widths were measured after 1 min. Before application of pulses aimed to switch the cell to its black state, the cell was reset to its white state with similar pulses, but of opposite polarity.

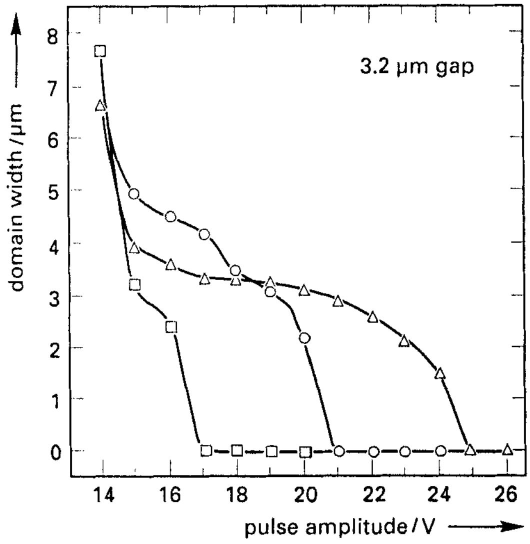

Figure 4. Width of white FLC domains for the 3·2 μm gap in cell 4 at three positions along the gap as a function of the amplitude of the bipolar voltage pulses with 64 μs wide pulses. The pair of pulses is repeated every 20 ms for 1 min, whereafter the domain widths were measured. Before application of the black-switching pulses, the cell was reset to its white state with similar pulses, but of opposite polarity.

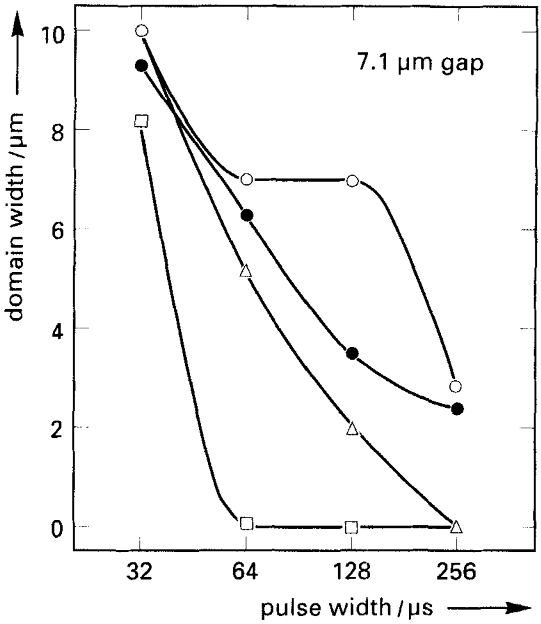

Figure 5. Width of white FLC domains for the 7·1 μm gap in cell 4 at four positions along the gap as a function of the width of the bipolar voltage pulses. The pulse widths have been increased by factors of 2. The amplitude of each of the pulses is 30 V. The compensation pulse immediately precedes the writing pulse. The pair of pulses is repeated every 20 ms for 1 min, whereafter the domain widths were measured. Before application of the pulses aimed to switch the cell to its black state, the cell was reset to its white state with similar pulses of opposite polarity.

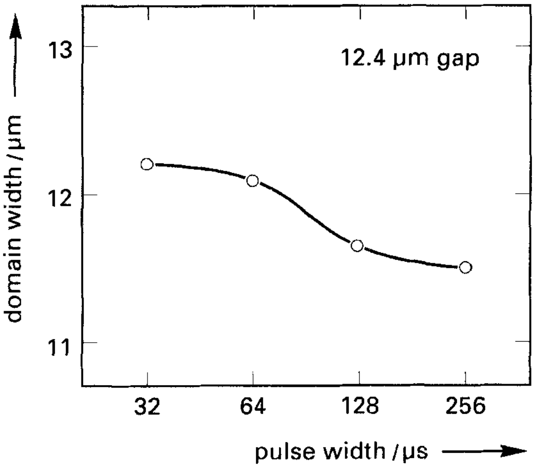

Figure 6. Width of white area for the 12·4 μm gap in cell 4 as a function of the width of the bipolar voltage pulses. The amplitude of each of the pulses is 30 V. A compensation pulse immediately precedes the writing pulse. The pair of pulses is repeated every 20 ms and the domain widths were measured after 1 min. Before application of the pulses aimed to switch the cell to its black state, the cell was reset to its white state with similar pulses of opposite polarity.

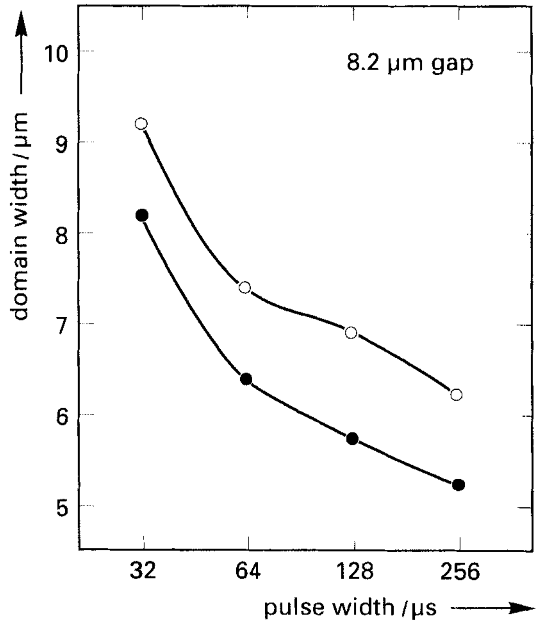

Figure 7. Width of white area for the 8·2 µm gap in cell 3 (see the table) as a function of the width of the bipolar voltage pulses. The amplitude of each of the pulses is 15 V (○) of 30 V (●). The compensation pulse immediately precedes the writing pulse. The pair of pulses is repeated every 20 ms for 1 min, whereafter the domain widths were measured. Before application of pulses aimed to switch the cell to its black state, the cell was reset to its white state with similar pulses, but of opposite polarity, The cell did not respond to voltage pulses of 16 µs pulse width and amplitudes up to 30 V, nor did it respond to 32 µs, 15 V pulses. The data point indicated by the ○ symbol in the diagram at 32 µs pulse width was taken with an 18 V amplitude.

central part of the gap region, even with 30 V high and 256 µs wide pulses (see figure 6). The same holds for the smallest gap in cell 3, as is shown in figure 7. Figure 7 shows data for two amplitudes (15 and 30 V) and various pulse widths. It was found that 30 V pulses of 64 µs or more lead to smaller white domains than 15 V pulses with twice the width of the ones with 30 V amplitude.

We have noted that the gap width has a pronounced effect on the texture change and the switching of the FLC in the gap. Qualitatively, this may be explained by the decrease of the stray electric fields with increased gap widths. However, it will be shown that the decrease of the electric field in the gap arising from increase of the gap width is a moderate effect. To evaluate the electric field strength, we have to solve the Poisson equation for a geometry involving different materials (FLC, glass), specified by different values for the dielectric permittivity. We used a commercially available software package (PE2D [10]) to solve this problem for a 2-dimensional geometry. The package allows for the incorporation of different dielectric permittivities; we used $\varepsilon = 4$ for the FLC layer and $\varepsilon = 6{\cdot}6$ for the glass [11]. Unfortunately, the PE2D package cannot cope with the anisotropy and the ferroelectric character of the liquid crystal layer. We calculated contour plots for the electrostatic potential near gaps of various widths. For not too large values of the ratio of the gap width and the thickness of the FLC layer, the patterns of equipotential lines resemble that for a parallel-plate capacitor, not only between the electrodes, but also in the gap region.

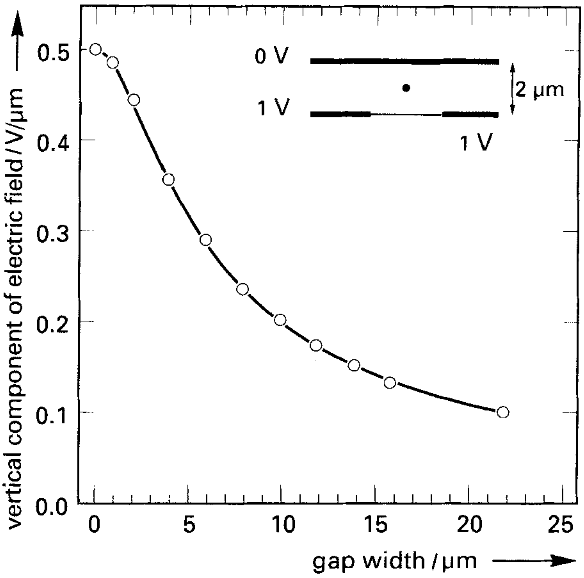

Figure 8. Vertical component of the electric field E_y in the centre of the gap (●) as a function of the gap width, as calculated with the PE2D program. The configurations considered consist of three electrodes: one at 0 V and two at 1 V on the opposing substrate, separated by a gap of the indicated width. The dielectric permittivity of the FLC equals 4·0. The permittivity of the glass is 6·6.

We calculated the vertical component of the electric field (for 1 V applied voltage) in the centre of the gap and at 1 μm height for various gap widths. Figure 8 shows the results. The electric field in the gap decreases with increasing gap width, but the decrease is not very large. As the product of amplitude and width of the voltage pulse is a rule of thumb parameter for predicting the occurrence of FLC switching, one might conclude that it should be possible to compensate for the decrease of the electric field strength by widening the pulse by, for example, a factor 4. However, we observed that this is not true: the 7·1, 8·2 and 12·4 μm gaps were far more difficult to switch than the 4·0 or the 3·2 μm gaps. We also found that for the 8·2 μm gap (see figure 7) a doubling of the amplitude of the pulses was more effective than a doubling of the pulse width (for pulses wider than 64 μs).

The impossibility described above of switching the FLC in the wide gaps with broad voltage pulses cannot be explained with the calculated values for the electric field strength. The ferroelectricity of the liquid crystal is an important aspect of the explanation. The liquid crystal in the gap can be represented schematically by the electronic circuit depicted in figure 9. The circuit contains a pulse generator and two capacitors—the capacitor C_{flc} formed by the liquid crystal layer in the gap, and C_s which represents the capacitances in series with C_{flc}. In the pixel area, this series capacitance is formed by the orientation (and top-coat) layers. As these layers are thin, C_s is large compared to C_{flc}. However, as will be explained below, C_s and C_{flc} may be of the same order of magnitude in the non-pixel area. Figure 9 also shows the distribution of the free charge denoted by Q and the surface polarization charge AP due to the permanent polarization of the ferroelectric liquid crystal. Here A is the area considered and P is the polarization of the liquid crystal, being equal to $+P_s$ for dipoles that are directed downwards, and $-P_s$ for upwards-directed dipoles. (For the sake of simplicity,

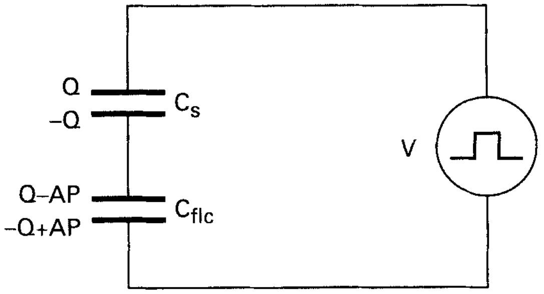

Figure 9. Equivalent circuit used to derive the voltage distribution for pulses applied to the FLC in the gap region. The circuit contains a pulse generator and two capacitors: the capacitor C_{flc} formed by the liquid crystal layer and C_s representing the capacitances in series with C_{flc}. The parameter Q denotes the free charge on the capacitor plates and AP is the surface polarization charge due to the permanent polarization of the ferroelectric liquid crystal, where A is the area considered and P is the FLC polarization ($P = \pm P_s$).

we assume that the smectic layers are upright and that the dipoles are in the same direction over the entire area of the capacitor concerned.)

Before we make this argument more quantitative, we would like to comment on the significance of the width of the voltage pulses applied to an FLC layer with mobile ions. An electric field in the FLC layer tends to align the dipoles in the electric field direction and redistributes the ions in the layer [12]. In the present experiment, the switching of the director is a faster process than the ionic transport. Consequently, the director switches under the influence of the externally applied electric field before the redistribution of the ions acts to decrease the internal electric field in the FLC layer. The relaxation time of the voltage across the FLC layer, due to the redistribution of the ions, depends on the configuration, more specifically on the value of the resistance and the capacitance of the FLC layer and, as the cell remains connected to the external voltage source, on the series capacitance C_s. The relaxation time at least equal to $\rho\varepsilon_{\mathrm{flc}}\varepsilon_0$, where ρ and $\varepsilon_{\mathrm{flc}}$ are the resistivity and the dielectric permittivity of the FLC material, and ε_0 is the vacuum dielectric permittivity. It may be derived that for $C_s = C_{\mathrm{flc}}$, the relaxation time is $2\rho\varepsilon_{\mathrm{flc}}\varepsilon_0$. We measured $\rho\varepsilon_{\mathrm{flc}}\varepsilon_0$ for the cells used in this experiment with a Diamant bridge [13] using a 100 Hz triangular wave voltage of 10 V amplitude. We found $\rho\varepsilon_{\mathrm{flc}}\varepsilon_0 = 35$ ms for the cells 1 and 2 and $\rho\varepsilon_{\mathrm{flc}}\varepsilon_0 = 5$ ms for the cells 3 and 4.

Returning to the model of figure 9, the following relation may be shown to hold for voltage pulses with amplitude V and a width that is short compared to the time that ions in the FLC layer need to redistribute in the field

$$\frac{V_{\mathrm{flc}}}{d} = E_{\mathrm{flc}} = \frac{C_s V - AP}{d(C_s + C_{\mathrm{flc}})}. \tag{1}$$

Here V_{flc} is the potential difference across the FLC layer, d the thickness of the layer, E_{flc} the electric field in the layer and AP the surface polarization charge described above. A sufficiently large applied voltage V leads to a value for E_{flc} and P of the same sign as for V. However, this need not hold for V values or C_s values that are too small. In that case, a different situation arises: the applied voltage sets up an electric field that tends to align the dipoles, but if they were to align in the field direction, a net electric field E_{flc} favouring the reverse orientation of the dipoles would occur. An exact solution has to take into account effects due to the ions in the FLC layer and consider the dynamics of both the polarization reversal and the ionic displacement [12, 14, 15];

consequently, the problem calls for the use of numerical methods. Here, we would like to confine ourselves to the conclusion that directing the dipoles uniformly should be done with voltages having an absolute value exceeding AP_s/C_s.

This condition leads to a threshold for voltage steps which is independent of the duration of the applied voltage. We tested this by applying DC voltage steps to the electrodes adjacent to the 22 μm gap in cell 4. These voltage steps were applied to generate an internal electric field that lasts as long as possible. The redistribution of ions in the cell causes a decrease of the internal electric field in the cell, with a relaxation time that is larger than $\rho\varepsilon_{\mathrm{flc}}\varepsilon_0$ (= 5 ms in cell 4). Between the measurements we applied a 10 V voltage of opposite sign to reset the FLC and the ions in the gap. It was observed that the voltage steps were not able to switch the FLC in the entire gap region from the transmissive to the non-transmissive state. The width of the white area in the gap region depended on the applied voltage and on the considered position in the gap, as shown in figure 10.

The mechanism outlined above provides a qualitative explanation for the observed linear dependence of the width of the white area on the applied voltage. To arrive at this explanation, we first have to evaluate the voltage at the FLC–glass interface in the gap region. For these calculations we used the PE2D program, which does not allow incorporation of the ferroelectricity of the liquid crystal material. The evaluated potential is essentially $C_sV/(C_s+C_{\mathrm{flc}})$, as occurs in equation (1), with $V=1$ V. Near the electrodes C_s is large, giving a potential close to 1 V. In the centre of the gap there is a region, with a width about half the gap width, where the potential does not vary too much with position. If a voltage that is somewhat larger than needed to switch the FLC in the pixel area is applied, some of the FLC in the gap area is switched as well.

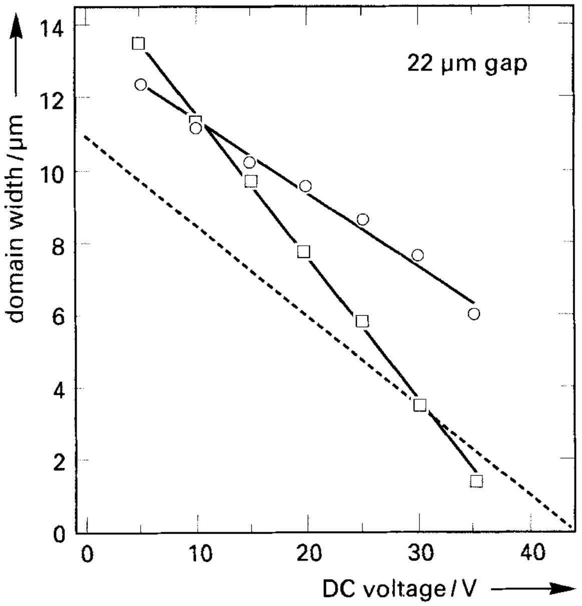

Figure 10. Width of the transmissive area in a 22 μm gap in cell 4 as a function of the applied voltage step. Results for two positions are represented by □ and ○ symbols. A 10 V voltage of opposite sign was applied between the measurements, to reset the FLC in the gap. The dashed line gives the result of the analysis leading to equation (5).

However, if $C_sV/(C_s+C_{flc})$ is less than $AP_{s}/(C_s+C_{flc})$ in a part of the gap, some of the dipoles are directed upwards (i.e. in parallel with the externally applied electric field), whereas the others are directed downwards. The area with the dipoles directed parallel to the externally applied electric field is denoted by A_p, and the area with the dipoles in the reversed direction by $A-A_p$. As the voltage across the FLC in the gap is a minimum at the centre of the gap, the A_p area grows from the adjacent pixels towards the centre of the gap. The A_p part of the gap grows until the internal electric field has decreased to zero. This is described by the following relation:

$$\frac{C_sV}{C_s+C_{flc}}=\frac{(A_p-(A-A_p))P_s}{C_s+C_{flc}} \quad \text{so} \quad V=\frac{(2A_p-A)P_s}{C_s}, \tag{2}$$

where V is the externally applied voltage, This relation describes the observed linear increase of the area with the dipoles parallel to the applied electric field upon increase of the voltage (see figure 10).

To test the validity of this, the argument is made somewhat more quantitative. Equation (2) is rewritten as:

$$A_p=\frac{1}{2}\left(\frac{VC_s}{P_s}+A\right). \tag{3}$$

To obtain an approximate expression for C_s, we averaged $C_sV/(C_s+C_{flc})$ over the 22 μm gap width, which yielded 0·366 V for $V=1$ V. From this we estimated $C_s\simeq C_{flc}/1{\cdot}73$. Using $C_{flc}=\varepsilon_{flc}\varepsilon_0A/d$, where ε_{flc} is the dielectric permittivity of the FLC material, equation (3) may be rewritten as

$$\frac{A_p}{A}\simeq\frac{1}{2}\left(\frac{V\varepsilon_{flc}\varepsilon_0}{1{\cdot}73dP_s}+1\right). \tag{4}$$

The extension of the domains along the gap direction can be eliminated from equation (4). Using w_p for the width of the domain with dipoles directed parallel to the externally applied electric field and w for the width of the gap (22 μm), we obtain

$$\frac{w_p}{w}\simeq\frac{1}{2}\left(\frac{V\varepsilon_{flc}\varepsilon_0}{1{\cdot}73dP_s}+1\right)\Rightarrow\frac{w-w_p}{w}\simeq\frac{1}{2}\left(1-\frac{V\varepsilon_{flc}\varepsilon_0}{1{\cdot}73dP_s}\right). \tag{5}$$

The result of equation (5) is depicted in figure 10 with a dashed line. It should be noted that the result of this analysis does not depend heavily on the value used for ε_{flc}: With $\varepsilon_{flc}=5{\cdot}0$ (instead of 4·0 which was used in the calculations above), 0·330 V is found for the average value of the potential, yielding $C_s\simeq C_{flc}/2{\cdot}03$. However, the slope of the line that would result in figure 10 differs only 7 per cent from that obtained with $\varepsilon_{flc}=4{\cdot}0$.

It must be remembered that the approach described above is an approximate one. The evaluation of C_s as a single value related to the capacitance of the FLC layer in the gap is not exact. In a rigorous derivation, the variation of the capacitance C_s with the position in the gap would have to be accounted for. Furthermore, the distinction between the dielectric properties of the FLC accounted for in the PE2D calculations and the ferroelectric properties incorporated in equation (2) is a simplification. However, errors due to this simplification are expected to be small as the equipotential pattern resulting from the PE2D calculations is fairly uniform. Additionally, we neglected the role of the ions in the FLC layer. Bearing this in mind, the agreement between the experimental data and the results of the derivation given above is satisfactory. It supports the idea that the response of the FLC is determined not by the decrease of the stray electric field in the gap, but by the depolarization field due to the dipoles in the FLC, together with the value of the series capacitances that exist between the pixel electrodes and the FLC–glass interface.

From equation (5) it also follows that the value of P_s is of direct influence on the domain width obtained. The voltage needed to eliminate the white domain in the gap decreases linearly with P_s. However, a much lower P_s opposes the field reorientation of the smectic layer structure from chevron to quasi-bookshelf, as for this reorientation a high P_s is advantageous.

4. Conclusions

We have presented an experimental study of FLC switching at a local interruption in the electrodes on one substrate of the cell. Two types of gap regions may be discerned in a display: gaps with indium–tin oxide (ITO) on the upper substrate, but not on the lower one and gaps with ITO on the lower substrate, but not on the upper one. With thin orientation layers, the FLC is found to prefer a director pattern in which the permanent dipoles are directed towards the ITO-covered substrate. Consequently, one type of gap in a display tends to be black, whereas the other prefers a transmissive memory state. Experiments were done to test the effect of stray electric fields used to change the smectic layer structure in the gaps and to make the latter type of gaps black.

The experimental results (obtained on cells with a 2 μm FLC layer thickness) indicated a remarkable difference between the response of the narrow gaps (3·2 and 4·0 μm gaps) and wider gaps (7·1, 8·2 and 12·4 μm). The smectic layer structure in the narrow gaps could be modified by low frequency, stray electric fields and the memory state could also be switched by stray electric fields. In the wider gaps, the electric field pre-treatment intended to introduce the quasi-bookshelf geometry was less effective and it was far more difficult to switch the wider gaps with stray electric fields. We calculated the electric field strengths in the gap to find the reason for this difference. Differences in the stray electric field are insufficient to explain the observed variation in response. To explain the observations, one has to consider the capacitance between the FLC–glass interface in the gap and the nearest electrode on the same substrate. This capacitance may be of the order of the capacitance of the FLC layer for wide gaps. In that case, the permanent dipoles in the FLC cause a significant depolarization field which prevents FLC switching with too small voltages. Experimental results are presented to support the validity of this argument.

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References

[1] Clark, N. A., and Lagerwall, S. T., 1980, *Appl. Phys. Lett.*, **36,** 899.

[2] Hartmann, W. J. A. M., Verhulst, A. G. H., Luyckx-Smolders, A. M. M., and Stommels, F. J., 1991, *Proc. SID*, **32,** 115.

[3] Verhulst, A. G. H., Hartmann, W. J. A. M., Stommels, F. J., and Luyckx-Smolders, A. M. M., 1990, *Proc. Eurodisplay '90, 10th Int. Display Res. Conf.*, Amsterdan, p. 150.

[4] Wakita, N., Iwai, Y., Uemura, T., Fujiwara, S., Gohara, Y., Ota, I., Masumoto, Y., Miyatake, Y., Tsuda, T., and Horio, Y., 1989, *Second International Conference on Ferroelectric Liquid Crystals*, Göteborg; 1991, *Ferroelectrics*, **114,** 27. Iwai, Y., Wakita, N., Uemura, T., Fujiwara, S., Gohara, Y., Kimura, S., Masumoto, Y., Tsuda, T., Horio, Y., and Ota, I., 1989, *Proceedings of Japan Display*, 180.

[5] Dübal, H.-R., Escher, C., and Ohlendorf, D., 1988, *Proceedings of the Sixth International Symposium on Electrets*, Oxford, p. 344.

[6] Sato, Y., Tanaka, T., Kobayashi, H., Aoki, K., Watanabe, H., Takeshita, H., Ouchi, Y., Takezoe, H., and Fukuda, A., 1989, *Jap. J. appl. Phys.*, **28,** L483.

[7] Hartmann, W. J. A. M., and Luyckx-Smolders, A. M. M., 1990, *J. appl. Phys.*, **67,** 1253.

[8] Verhulst, A. G. H., and Stommels, F. J., 1991, *Third International Conference on Ferroelectric Liquid Crystals*, Boulder; 1991, *Ferroelectrics*, **121,** 79.

[9] The convention used to express the direction of the polarization in its sign is as follows: if the smectic-layer normal, the director and the polarization form a right-handed system, the polarization is positive; for a left-handed system, the polarization is negative. See, for example, Lagerwall, S. T., Otterholm, B., and Skarp, K., 1987, *Molec. Crystals liq. crystals*, **152,** 503.

[10] PE2D is a product of Vector Fields Limited, 24 Bankside, Kidlington, Oxford OX5 1JE, England.

[11] The permittivity for the glass was measured on $30 \times 30 \times 1{\cdot}5\,\mathrm{mm}^3$ B270-glass plates (made by DESAG, Grünenplan, Germany) with a General Radio 1693 RLC-bridge using AC voltages of 1 to 200 kHz and 0·5 V RMS value.

[12] Diamant, H., Drenck, K., and Pepinsky, R., 1952, *Rev. scient. Instrum.*, **28,** 30.

[13] Escher, C., Dübal, H.-R., Harada, T., Murakami, M., and Ohlendorf, D., 1989, *Second International Conference on Ferroelectric Liquid Crystals*, Göteborg; 1991, *Ferroelectrics*, **113,** 269, and references therein.

[14] Pauwels, H. J., and Cuypers, F. H., 1989, *Second International Conference on Ferroelectric Liquid Crystals*, Göteborg; 1991, *Ferroelectrics*, **113,** 37.

[15] Yang, K. H., Chieu, T. C., and Osofsky, S., 1989, *Appl. Phys. Lett.*, **55,** 125. Yang, K. H., and Chieu, T. C., 1989, *Jap. J. appl. Phys.*, **28,** L1559. Chieu, T. C., and Yang, K. H., 1989, *Jap. J. appl. Phys.*, **28,** 2240. Chieu, T. C., and Yang, K. H., 1990, *Appl. Phys. Lett.*, **56,** 1326.