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The possibilities of ferroelectric liquid crystals for video displays

W.J.A.M. Hartmann
A.G.H. Verhulst
J.A.M.M. van Haaren
F.J.J. Blommaert

Abstract — Different approaches were used to examine the possibility of using surface-stabilized ferroelectric liquid-crystals (SSFLCs) in video displays. The advantages of such displays lie in the viewing-angle independence and the high switching speed. The large number of gray levels needed for video can, in principle, be obtained by digital or analog techniques. From simulation experiments on a high-resolution CRT, it is estimated that for video, for the case of equidistant luminance levels, 128 levels for each primary colour are needed. Discrete gradation by means of bi-level subpixels (spatial dither) is simulated for projection and direct-view displays. Efficient subpixelation (minimum number of extra connections) results in perceptual artefacts when the three primary colours (RGB) are projected onto each other, as in a projection system. In the case of a direct-view display with mosaic colour filter, the layout of this mosaic turns out to be more important than subpixelation. Analog gradation methods are based on in-pixel domain switching effect. They require accurate control of the multidomain structures. Active-matrix addressing for the SSFLC strongly enhances the reproducibility of the multidomain gray levels via the charge-control process. This is demonstrated on test displays. Passive-matrix addressing takes advantage of the bistability and switching speed of the SSFLC effect. One approach to control the multidomain gray levels in passive-matrix addressing is the "texture method," which is based on a distribution of the threshold voltage for switching within each pixel. The mechanism, the addressing scheme, the obtainable contrast in the different textures, the applicability of various FLC mixtures, and the resulting temperature sensitivity are discussed. The performance of test displays, operating at video rate, is evaluated. Several issues, such as temperature sensitivity, texture stability, and hysteresis in the transmission-voltage curve have to be further improved.

Keywords — Active matrix, charge control, ferroelectric liquid crystal, FLC, gray scale, image artefact, image impairment, image quality, multidomains, passive matrix, spatial dither, SSFLC, subpixels, texture change, texture method, video display.

1 Introduction

Surface-stabilized ferroelectric liquid-crystal (SSFLC)¹ video displays must be competitive with the currently available displays such as the active-matrix-addressed TN-LCD and the cathode-ray tube (CRT). From this comparison, one can derive the video requirements. When using SSFLCs, the most significant requirements to be met are:

- (a) Colourless switching between black and white because, when full colour is synthesized by combining three primary colours, well-saturated colours should be obtainable.
- (b) The required number of rows in a TV display is 576 (for PAL), which will increase in the near future (high-definition tv).
- (c) Due to the fact that all information must be refreshed with a frequency of 50-Hz (PAL) or 60-Hz (NTSC), the row-addressing time is fixed (64 μ s for PAL).
- (d) The transmission in the bright state should be as large as possible.
- (e) The obtainable contrast ratio must be $\geq 100:1$.

- (f) The gradation method must allow more than 100 gray levels, as will be shown below.

The colourless black and white states are obtained with crossed polarizers and a cell thickness $< 2 \mu\text{m}$. With respect to the maximum-transmission requirement, one should note that polymer-aligned SSFLC samples usually exhibit an optical switching angle between both bistable memory states of $\approx 15^\circ$ (instead of the preferred 45°) due to a tilt of the smectic layers towards the glass plates (chevron structure²). This results in maximum transmission of $\approx 25\%$. When the $\approx 40\%$ transmission of the two polarizers is taken into account, the overall transmission is as low as $\approx 10\%$. The maximum transmission can be increased considerably by a low-frequency electrical pre-treatment that erects the smectic layers³⁻⁶ (bookshelf geometry) or by using a high-pretilt orientation (*e.g.*, oblique evaporated SiO_2 ^{7,8} or high-pretilt polyimide⁹⁻¹¹). In this respect, naphthalene-based FLC material¹² is also very interesting, for it exhibits a more or less bookshelf geometry spontaneously. The required contrast ratio can only be obtained with a uniform director pattern, so twisted states have to be avoided. The gradation requirement calls for new approaches when considering the

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W.J.A.M. Hartmann was with Philips Research Laboratories. He is now with Flat Panel Display Co., B.V., P.O. Box 218, Eindhoven, The Netherlands.

A.G.H. Verhulst (author for correspondence) and J.A.M.M. van Haaren are with Philips Research Laboratories, P.O. Box 80.000, Eindhoven, The Netherlands; telephone 31-40-74-25-38; fax 31-40-74-33-50.

F.J.J. Blommaert is with the Institute for Reception Research, P.O. Box 513, Eindhoven, The Netherlands.

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SSFLC structure, as it is in contradiction with the bistable character of the structure.

This paper describes experiments at Philips Research to obtain the required gradation using different approaches. Discrete gradation techniques using subpixelation are discussed in Section 2. Two analog gradation techniques based on in-pixel/multidomain switching, *viz.*, the "charge-control mechanism" (obtained with the help of an active matrix) and the "texture method" (passive matrix), are described in Section 3.

2 Discrete gradation

2.1 Perceptual quality of pictures with discrete gray levels

To judge the feasibility of discrete gradation in SSFLC panels, a number of perceptual questions are of interest. These questions have been addressed by studying digitized video images that were displayed on a high-resolution Conrac 7211 colour CRT after appropriate computer processing using a Gould deAnza IP8400 image-processing system. The displayed images were judged by a four-member panel consisting of the authors. Owing to the small number of observers and the limited computation and display capacities, the conclusions should be considered with some care.

The first question to be addressed for application of discrete gradation is what number of luminance levels is sufficient for displaying video images. In fact, this question cannot be answered straightforwardly since the answer depends on the quantization function, which describes the distance between two subsequent luminance levels as a function of luminance.

The required quantization function is determined by the characteristics of human vision. According to Weber's law,¹³ the ratio $\Delta L/L$, with ΔL the just-noticeable luminance difference and L the background luminance, is constant. This would imply that the luminance steps that constitute the luminance scale should increase linearly with luminance. However, Weber's law holds for laboratory conditions in which the eye is fully adapted to the background luminance. In normal viewing conditions, this seldom occurs. Hence, under TV-viewing conditions, luminance steps are generally chosen to be less dependent on luminance level. Typically, the step distances are taken as a compressive power function $\Delta L \propto L^\alpha$ with $0 < \alpha < 1$. Since the video signal depends in a similar way on the CRT screen luminance ($V \propto L^{1/\gamma}$ with $\gamma \approx 2.5$), equidistant quantization of the video signal is often applied. By implementing quantization functions for various values of α , we indeed established that quantization for α -values in the order of 0.5 gave optimal results, although the exact power was found to be not very critical. For α approaching 0, however, quantization effects became visible in low luminance gradients, while for $\alpha \rightarrow 1$ these effects became noticeable at high luminance levels.

If a gray scale is realized by subpixelation, the quantization function is determined by the size ratios between

(a)

(b)

FIGURE 1 — Video test image with (a) continuous (analog) gradation and (b) 16 gray levels per colour.

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subpixels. If, for example, the subpixels are chosen to be of equal size, the quantization is equidistant in luminance steps (*i.e.*, $\alpha = 0$). It will be clear from the foregoing that such a quantization function is suboptimal for the visual system. However, we wanted to find the number of gray tones necessary for this kind of subpixelation. Therefore, the gray levels were assigned in such a way that the entire luminance range was divided into a variable number N (N equals either 4, 8, 16, 32, 64, 128, or 256) equidistant luminance levels for the red, green, and blue primaries. This was achieved by changing the initially equidistant quantization of the video signal into a quantization that results in equidistant levels of the screen luminance. The images used were (1) a one-dimensional luminance gradient $L(x) \propto x^\gamma$, in which x is the horizontal screen coordinate and γ is the CRT gamma factor used above, (2) a model portrait, and (3) a shot from a green-grocer's shop. Furthermore, the average luminance of the individual images was varied. We also studied five other images, which turned out to be less critical to quantization of the luminance range.

It was found that if the number of gray levels was too small, spurious contours were visible, as is shown in Fig. 1. The minimum number of gray levels needed to avoid these artefacts depended on the picture considered. The most

FIGURE 2 — (a) Proposed pixel layout for realizing 64 equidistant gray levels with 3 sub-columns and 2 sub-rows. (b) Proposed symmetrical version.

critical pictures were the ones containing large areas with a small gradient in luminance. Furthermore, the effects became more pronounced if the averaged luminance decreased. We concluded that 128 equidistant luminance levels for the red, green, and blue primaries were sufficient for most images. For less critical pictures, 64 luminance levels gave acceptable results as well.

2.2 Proposal for efficient pixel subdivision

From the quantization simulation, a number of 128 discrete gray levels turned out to be necessary for video application. To address such a large number of subpixels with a minimum number of additional external connections, a new layout for the subpixels has been proposed.¹⁴ In this layout the subpixels are formed at the intersection of N sub-columns and two sub-rows. The sub-columns have widths in a ratio $1:2:4: \dots : 2^{N-1}$, and the two sub-rows have widths in the ratio $1:2^N$. In that case all gray tones between 0 and $2^{2N} - 1$ can be formed, amounting to 2^{2N} levels. This layout differs from previously proposed layouts in a more efficient use of the external connections: each of the gray levels can be formed by addressing the columns and the rows in a single unique way. The layout of Fig. 2(a), in which $N = 3$, yields 64 gray levels, whereas 256 levels are obtained with $N = 4$. It is also possible to make a more symmetrical version of such a layout by splitting the columns in two parts and positioning the parts symmetrically around the narrowest (unsplit) column placed in the centre of the picture element. As is shown in Fig. 2(b), the widest row is also halved and positioned around the narrowest one. The two halves of each split column should be connected, for instance, at the end of the column. This layout has perceptual advantages, as will be discussed in the next section. In the case of a direct-view display, application of this symmetric version also makes the positioning of a colour-filter matrix less critical, as the largest area fractions are at the pixel boundaries. By incorporating a black matrix in the colour filter pattern and extending the outer-subpixels somewhat into the area covered by the black matrix, the structure gets some tolerance to misalignment.

2.3 Perceptual quality of pictures with black and white subpixels

The simulations in Sec. 2.1 indicated that 128 equidistant luminance levels are sufficient for displaying video images. In Sec. 2.2 we introduced a pixel geometry that provides the necessary number of luminance levels with a minimum number of additional external connections. However, the price paid for the efficiency of this pixel layout is the loss of freedom to position the black and white areas within the pixel for a given gray tone, once the display layout has been chosen. Therefore, it is important to test the perceptual quality of the images displayed with this particular pixel layout. In this respect, one has to make a difference between a projection display, in which the three primary colours are usually projected onto each other, and a (colour) direct-view display, in which the colours are positioned adjacent to each other. Both options will be considered subsequently.

2.3.1 Projection simulation

These simulations were performed by numerical processing of still video images. In these simulations, the resolution of the computer-generated CRT pictures caused the following experimental problem: the image processor provides a 512×512 matrix filled with video information, *i.e.*, gray-level data for each of the primary colours. In the present simulation, the gradation of the gray-level data for each of the 512×512 matrix elements is removed and replaced by gray levels formed by assigning black and bright subpixels to a new picture element. The smallest detail of the video images, as provided by the image processor and the CRT monitor, corresponds to the smallest subpixel. It will be clear that there is a tradeoff between the number of subpixels per pixel (the number of gray levels) and the total number of pixels which can be realised in the 512×512 matrix. A compromise has been chosen by displaying 64 gray levels, which takes a 7×9 block per pixel and enables displaying of about 64×64 picture elements on the monitor. In this simulation, the images for the primary colours have been superposed, which fits the situation for projection television.

Simulations have been performed for four subpixel geometries (see Fig. 3): (a) the asymmetric and (b) the symmetric binary structures introduced in Sec. 2.2, (c) a structure in which the pixel is filled by forming columns starting at the left boundary of the pixel, and (d) a structure in which the pixel is filled up spirally, starting in the centre of the pixel. Each pixel in both binary pixel layouts consists of a rectangle that is seven elements wide and nine elements high (see Fig. 2). For the pixel subdivision with columns or spirals, each pixel consists of 8×8 elements.

In the four layouts for the subpixels, various artefacts emerge. Two causes for artefacts are summarised in Table 1 and are discussed in the remainder of this section. However, we note that it turned out to be rather difficult to identify causes for artefacts, though the artefacts themselves may be clearly visible in the displayed pictures.

(a)

(b)

(c)

(d)

FIGURE 3 — Pictures from simulation results of images with gray tones made by pixel subdivision, displayed on a Conrac 7211 CRT monitor. For each type of subpixel configuration [binary asymmetric (a), binary symmetric (b), columns (c), and spirals (d)], three pictures with 48×48 pixels are shown as well as an enlarged view of 6×6 pixels. The images for the various primary colours have been projected onto each other, as is apparent in the 6×6 pixels picture.

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TABLE 1 — Causes for perceptual artefacts for various subpixel layouts.

Cause for artefact	Subpixel layout			
	(a) binary asymmetric	(b) binary symmetric	(c) columns	(d) spirals
Changes in texture appearance	Yes	Yes	No	No
Shift in position of optical centre of gravity	Abrupt	No	Gradual	No

For parts of the image with the same gray tone, the periodic structure generated in each picture element is visible, giving the impression of a certain texture. In adjacent parts of the picture, where another gray tone is displayed, the type of texture may have changed as well. The boundary line between these areas is emphasized due to the change in texture. In the method with 0–63 gray tones, this effect is present at gray tones 7 and 8: at level 7 a vertical period structure exists and at level 8 a horizontal one exists. For transitions between gray tones with a similar periodicity, such as the transition between levels 6 and 7 or between 8 and 9, the effect does not occur. The occurrence of these contours depends not only on the layout of the subpixels in the picture element, but also on the layout of the pixels in the display: the changes in texture may lead to clustering of black or white subpixels for pixels in adjacent columns. An example is shown in Fig. 4, in which the clustering gives rise to a black area of almost the size of an entire pixel. In the case of a horizontal luminance gradient, this results in a vertical black line in a part of the image that is at an intermediate gray level [see Fig. 3(a)]. This line may be disrupted by staggering the rows. Indeed, staggering was found to improve the perceptual quality of the images.

The two binary subdivisions of the pixel differ in the position of the optical centre of gravity for the various gray levels. For the asymmetrical subpixelation (a), this optical centre shifts from one side of the pixel to the other one. [In the configuration of Fig. 2(a), the shift is from left to right, with increasing luminance, and there is an abrupt, relatively large displacement of this centre at the transition of gray level 31 to 32 in the 64-level case.] For the symmetrical subdivision, the position of the optical centre is fixed in the centre of the pixel. This property makes the symmetrical one superior. The optical centres of gravity for the three primary colours coincide, whereas for the asymmetric subpixel layout the position of the optical centre depends on the displayed gray tone. So, for the asymmetric configuration, the optical centres for the primary colours generally do not coincide, leading to spurious coloured contours.

To make the observations quantitative, we measured the viewing distances to the monitor at which artefacts in the various subpixelated images become invisible. To this aim, we displayed the images on a Barco TVM3 high-resolution colour monitor in a tunnel that enabled viewing distances up to 50 m. In Table 2 the results (averaged over the

FIGURE 4 — Pixels at levels 31 and 32 for the asymmetric 0–63-level configuration as proposed in Fig. 2(a).

observers) obtained with four different images and four subpixel layouts are given.

From Table 2 it is clear that subpixelation with spirals or columns causes artefacts that are less prominent than with binary subpixelation. Furthermore, the luminance gradients turn out to be more sensitive to artefacts than the portrait and the snapshot from the green-grocer's shop. The values in Table 2 may be compared with the normal (recommended) viewing distance for a display with the same pixel size. On the Barco TVM3 monitor in the present experiment, the pixel size is $5 \times 5 \text{ mm}^2$. For a video display with 720×576 pixels, this would yield a display of 3.6 m in width and 2.8 m in height. The recommended viewing distance of video pictures is about six times the picture height,¹⁵ yielding 17 m in this case. From the table, we see that luminance gradients displayed with both binary subpixel layouts contain artefacts that are visible at and beyond the recommended viewing distance of 17 m. The column and spiral layouts are on the borderline of this, but these layouts cannot be operated in an SSFLC display in an efficient way. To obtain a picture that is free from artefacts with one of the binary subpixel layouts, one would have to increase the (area) density of the picture elements on the display with a factor of about 4. This makes the number of sub-columns and sub-rows in an SSFLC display larger by a factor of 2,

TABLE 2 — Distances (in meters) at which artefacts become invisible for four different images and four subpixel layouts. The pixel size is $5 \times 5 \text{ mm}$.

Image	Subpixel layout			
	(a) binary asymmetric	(b) binary symmetric	(c) columns	(d) spirals
Horizontal luminance gradient	37	33	19	20
Vertical luminance gradient	40	34	19	15
Portrait	20	15	10	10
Green grocer's store	15	11	11	10

FIGURE 5 — The multidomain switching process.

which has detrimental effects on the interconnection pitch, the number of drivers, and the pixel aperture.

2.3.2 Direct-view simulation

We also considered the portrait displayed in a way that is relevant for direct-view displays, *i.e.*, with the RGB colour-filter parts adjacent to each other. For the colour-filter layout, we studied two possibilities: (1) square filters for each of the three primary colours that are positioned along the diagonal of the picture, and (2) square filters positioned in columns. For these colour filters, we used the same four subpixel layouts that have been used above. For the direct-view simulation pictures, the luminance was three times lower than for the projection ones. The distances at which we considered the images free from artefacts are given in Table 3. These distances have to be compared with the normal (recommended) viewing distance, which in our case (pixel area is 25 mm^2 for each primary) was about 17 m.

The results show that for direct-view displays, the subpixel layout is less important than for projection displays. The layout of the colour-filter mosaic turns out to be more important. The average viewing distance for square filters in columns divided by the average value for the square filters along the diagonals yields 1.44. From calculation of the Fourier components of the periodic structures of these colour filters one finds $\sqrt{2}$, which is in close agreement. For the portrait, the diagonal colour-filter layout turns out to be on

TABLE 3 — Distances (in meters) at which the portrait was considered to be free from artefacts for two colour-filter layouts and four subpixel layouts. The pixel area is 25 mm^2 for each primary.

Colour-filter layout	Subpixel layout			
	(a) binary asymmetric	(b) binary symmetric	(c) columns	(d) spirals
Square filters along the diagonals	20	17	19	20
Square filters in columns	25	25	30	28

the borderline of giving artefacts at the 17-m (recommended) viewing distance.

2.3.3 Moving images

It has also been tested whether contours are less disturbing in moving images, as they might be smeared out. In a simulation with digitized gray tones in two sequences of images, this proved not to be the case: the contours turned out to be pronounced in these moving images as well. (For this simulation, the gray tones have been composed from black and white subpixels in the spiral configuration, but with only 16 gray levels to achieve sufficient resolution.)

2.4 Conclusions

Concerning discrete gradation, we found that 128 equidistant luminance levels are sufficient to display most video images. With respect to the use of subpixels to obtain such a gradation, it was concluded that for colour projection (with the three primary colours projected onto each other) the most efficient subpixel layouts cause perceptual artefacts which are visible up to about two times the recommended viewing distance. To avoid such effects one would have to increase the pixel density, but this adversely affects the (already very high) number of external connections and drivers, and the pixel aperture. For direct-view colour displays we observed that perceptual artefacts occur at about the recommended viewing distance. Furthermore, the subpixel layout is found to be less important than the colour-filter layout. The requirements on the colour-filter configuration are well known from the work on TN active-matrix LCDs, where for video applications mostly the delta structure for RGB is used.

3 Analog gradation

Bistable SSFLC cells can exhibit multidomain formation; this can be used to obtain analog gradation, as a multidomain structure is perceived as a gray level. As illustrated in Fig. 5, the switching from one state to the other (occurring upon voltage inversion) takes place via the nucleation and growth of domains of one of the two states. In fact, it was suggested by Maltese *et al.*¹⁶ to modulate these multidomain structures via the pulse width of a switching pulse. However, to realize more than 100 gray levels (each of which has to be exactly reproducible), the nucleation and growth of the do-

FIGURE 6 — The charge-controlled FLC switching mechanism.

FIGURE 7 — Microscopic appearance of the charge-controlled gray levels and the addressing scheme that was applied (solid lines, switch is closed; dashed lines, switch is open).

FIGURE 8 — Transmission-voltage dependence of charge-controlled gradation.

mains is not stable enough; an additional control of this process is required. To achieve this control, the following methods will be discussed: charge-controlled domain switching and local FLC threshold variation.

3.1 Charge-controlled domain switching

In the SSFLC structure, the electrical difference between the two states lies in the sign of the surface charge (the spontaneous polarization, P_s). As reported earlier,¹⁷ an SSFLC cell can be loaded with a certain amount of charge by impressing a voltage onto it. If the cell is electrically isolated directly afterwards, the SSFLC structure will switch (partially) to the other state. As is shown in Fig. 6, this means that an amount of surface charge $\Delta Q = 2P_s\Delta A$ is transported to the other side of the sample, which results in a compensation of the surplus charge that was put on the sample initially. The switched area ΔA , and consequently the transmission, is thus quantitatively controlled by the initially impressed charge.

By making the addressing pulse width significantly smaller than the FLC switching time, the gray levels are, in principle, not influenced by "kinetic" factors such as domain nucleation or growth speed or by the cell thickness. The temperature dependence is related to that of the polarization only. Figure 7 shows the microscopic appearance of the gray levels and the addressing scheme that was applied. The

FIGURE 9 — The active-matrix-addressed FLC video display in which the charge-controlled gradation is applied.

minimum domain diameter is $\approx 2 \mu\text{m}$. The addressing scheme consists of an invariable reset pulse (V_b) to obtain an identical starting situation, followed shortly afterwards by a variable selection pulse (V_s) which determines the multidomain gray level. The resulting transmission-voltage dependence is given in Fig. 8.

In fact, we demonstrated a video display in 1988,¹⁸ based on an active-matrix α -Si TFT array. This active matrix is necessary because the charge-control mechanism requires electrical isolation of the pixel, which cannot be obtained in passive-matrix addressing. A photograph of the display is shown in Fig. 9 and some data are listed in Table 4. The display is operated in the initial chevron smectic-layer configuration. The optical angle between the two "single-domain" memory states is $\approx 15^\circ$. These states occur at select voltages of 2 and 5.5 V (see Fig. 8). At intermediate voltages, the multidomain structure is generated. At voltages higher than 5.5 V, a continuous director shift on the cone occurs¹⁹ (non-multidomain structure), and the director position is stabilized by the remaining voltage on the cell. For voltages below 2 V, the voltage that remains after blanking and select causes a continuous director shift on the other part of the cone. The optical angle between the two extreme states (at 0 and 6 V) is $\approx 40^\circ$. Therefore, the luminance and contrast are relatively high. From these displays it was concluded that, in principle, the mechanism is able to realize a sufficient gradation and that the video requirements can be fulfilled. In comparison to active-matrix addressed TN LC-TV, significant improvements are obtained with respect to viewing angle and switching speed.

TABLE 4 — Active-matrix-addressed FLC video display.

Array	α -Si TFT (Philips Research Laboratories Redhill-UK)
Size	2" diagonal
Number of pixels	108 (H) $\times$ 96 (V)
Thickness	$< 2 \mu\text{m}$
FLC	ZLI3654 (Merck)
Alignment	nylon 6.6, one-side rubbed
Drive frequency	50 Hz
Drive voltages	$-6/+6 \text{ V}$
Row select-time	64 or 32 μs
Switching speed	$< 500 \mu\text{s}$
Contrast ratio	100:1 (in pixel)
Transmission	70% of // polarizers

3.2 Local FLC threshold variation

In this approach, which is intended for passive-matrix addressing, it is not the local electric field that is varied (which is often proposed in the literature), but the switching behaviour of the FLC layer itself. As was recently reported, one

FIGURE 10 — Micrographs of the various textures in an SSFLC sample: (a) texture I, (b) texture II, and (c) texture III. The arrows indicate the rubbing direction.

requirement to obtain such a local variation is based on the different textures occurring in SSFLC samples: the texture method.²⁰ In the following section, the application of the texture method to realize a video display is described.²¹ Therefore, attention is paid to the choice of the texture in which the display is operated, to the addressing scheme, to the demands on the liquid-crystal material, and to the display configuration. To start, a review of the texture method is given.

3.2.1 The texture method

Low-frequency electric fields applied to SSFLC samples cause an irreversible reorientation of the smectic-layer structure.¹⁹ With increasing electric fields, the observed texture of the sample changes from the initial virgin texture [texture I, Fig. 10(a)], via a rather inhomogeneous roof-type texture [texture II, Fig. 10(b)], to a more uniform striped texture [texture III, Fig. 10(c)].²² These textures are interpreted as being the result of an uprighing of the chevron

smectic-layer structure to one with a smaller tilt towards the substrate normal. Theoretically, a smaller smectic-layer tilt results in a larger optical angle between the planar memory states and, due to the longer switching path on the smectic-C cone, the threshold voltage increases.

It was verified by small-spot optical measurements that the uprighing of the smectic layers occurs in a locally distributed way, and thus a distribution of the threshold voltage arises.²⁰ Texture I possesses a uniform chevron smectic-layer structure with a constant layer tilt δ_0 towards the substrate normal. Texture II comprises a broad range of smectic-layer tilts varying from δ_0 to a lower value. In texture III the range of layer tilts converges again, but now towards the lower value. We recently investigated the smectic-layer structure of texture III by means of small-spot measurements.⁶ We concluded that the striped structure of texture III is the result of a two-step process (during the field treatment), starting with the generation of a large number of parallel running zig-zag lines of the lightning type, whereafter the upright smectic-layer parts in the bulk of these lines are extended to the surfaces, giving a zig-zag- or chevron-like inplane smectic-layer configuration.

The integrated transmission-voltage curve (obtained by applying an addressing scheme as described in the next section), which is measured with a pixel-size spot, exhibits the familiar bistable discontinuous behaviour in texture I and changes to a slanting curve in texture II, which again becomes steeper in texture III (see Fig. 11). The slanting curves in texture II and III make an analog gradation possible. The switching angle between the two memory states in texture I is approximately 12° . The value in texture II, averaged over the entire pixel, usually lies between 20 and 35° , depending on the field treatment, and in texture III it can be from 32 to 45° . This explains the difference in maximum transmission of the three curves.⁴

The (domain) gradation is now controlled by the texture and the associated threshold-voltage distribution, and not by the domain nucleation and growth kinetics as was the case in texture I.¹⁶ The fineness and uniformity of the field-

FIGURE 11 — Curves of integrated transmission (measured with a pixel-size spot) vs. voltage, obtained on the different textures using the addressing scheme of Fig. 12.

FIGURE 12 — Addressing scheme to enable passive-matrix-addressed gradation in SSFLC displays by amplitude modulation: row signal, column signal, and resulting pixel voltage.

induced texture, and thus the uniformity from pixel to pixel, can be controlled by the concentration and positioning of the cell spacers. Because both the reorientation electric field and the switching electric field depend on the thickness of the FLC layer, a compensation of thickness variation occurs, giving this gradation method some tolerance to cell-gap variation.²⁰

3.2.2 Addressing scheme

A preferred addressing scheme for SSFLC video displays²³ is depicted in Fig. 12. The typical repetition rate is 50 Hz (PAL) and the available row select-time is 128 μ s (half-resolution), 64 μ s (full resolution) or 32 μ s (high definition). All drive voltages are bipolar to ensure that there are no dc electric fields, which may degrade the liquid-crystal material. Therefore, the available pulse time for switching is only half the row-select time (2-slot scheme).

TABLE 5 — FLC mixtures in texture III.

Material	P_s (nC/cm ²)	V_{III} (V)	V_{th} (V)	V_{sat} (V)
Merck 90964	38	10	12	18
BDH 866	28	12	14	21
Felix T103	46	15	10 (17)*	15 (25)*
Felix T108	47	15	9 (17)* (32)**	14 (23)* (39)**
CS1028	35	22	8 (14)*	12 (19)*
CS1031	29	50	5 (10)* (19)**	9 (16)* (25)**

Data taken with 1.4 μ m test samples with 7 nm PVA alignment layers at 20°C. Switching-pulse width is 64 μ s, (*) 32 μ s or (**) 16 μ s.

The rows are sequentially selected by a bipolar pulse with amplitude V_s . Immediately before selection, a reset is performed by a broad bipolar pulse with amplitude V_r . This reset assures that an identical starting situation (preferably the black state) is obtained before a gray level is written, which is necessary to obtain a reproducible gradation.^{16,18} The reset takes two row-select times (or more), meaning that the row drivers have to address at least three rows simultaneously. The gray level is determined by a bipolar column pulse with a variable amplitude V_d , which modulates the effective pixel voltage during selection. The amplitude of the pixel voltage in the second half of the row-select time (the switching pulse, $V_s \pm V_d$) determines the amount of switched area starting from the reset situation, thus the gray level. Electronically, it is preferred to address such a large amount of gray levels by amplitude modulation, rather than pulse width or phase modulation. Because the reset pulses are of double width, their voltage-time product is not influenced by V_d and the reset is not affected. Due to the bipolar nature of the column signal, the response to these pulses during non-selection (*i.e.*, crosstalk) only appears as a periodical variation in transmission intensity and hardly changes the mean value of the gray level. High-frequency ac stabilisation^{24,25} is not applied because it would bring about an unnecessary increase in power consumption of the display driving. The settings of the drive voltages depend on the transmission-voltage curves as given in Fig. 11, according to:

$$V_r \geq V_{sat}$$

$$V_s = \frac{V_{sat} + V_{th}}{2}$$

$$0 \leq |V_d| \leq \frac{V_{sat} - V_{th}}{2}$$

and thus during selection

$$V_{th} \leq V_{pixel} \leq V_{sat}$$

3.2.3 Texture II or texture III

As was shown in Fig. 11, texture III has a steeper transmission-voltage curve than texture II. For this reason, the maximum bias V_d/V_s is lower. Additionally, texture III exhibits a smaller response to V_d than texture II because the director position is located closer to the side of the smectic-C cone.⁴ These two factors will lead to much smaller crosstalk in texture III than in texture II.

We measured the contrast ratio under actual driving conditions (including the maximum required V_d) as a function of the effective optical switching angle. It was found that the contrast ratio in texture II only reaches values like 20:1, whereas it amounts to 200:1 in texture III. Therefore, texture III is preferred. A disadvantage of texture III lies in the somewhat higher pulse amplitudes. Microscopically, the gray levels in texture III appear as in Fig. 13.

FIGURE 13 — Micrographs of the gray levels in texture III.

3.2.4 Ferroelectric liquid-crystal material

Several FLC mixtures have been tested for this application. Provided that a good orientation is obtained in texture I, most of them exhibit the above-mentioned behaviour in the subsequent textures. To carry out the chevron reorientation, the value of the spontaneous polarization should not be too low.^{4,19} A high switching speed is required because the necessary pulse amplitudes increase in the subsequent textures. Table 5 presents some results on materials from Merck, BDH, Hoechst (Felix), and Chisso (CS). The value V_{III} denotes the amplitude of a 25-Hz square-wave voltage at which the irreversible reorientation to texture III occurs⁴ and can therefore be used as an indication of the chevron reorientability. In texture III (with an effective switching angle $\geq 35^\circ$), the values V_{th} and V_{sat} are obtained using the drive scheme of Fig. 12. Those materials which require the lowest V_{th} and V_{sat} are preferably used. For the application, it is preferred to use CMOS driver ICs, meaning that the required voltages should not exceed 20 V. As can be seen, mixture CS1031 can be operated in full-resolution video drive (32- μ s switching pulse width) with moderate drive voltages. At the moment, high-definition driving (16- μ s pulse width) requires elevated temperatures.

There is a strong sensitivity of the threshold and saturation voltages to temperature. This is illustrated in Fig. 14, where the brightness (luminance), and the voltages for 10% transmission, V_{10} , and for 90% transmission, V_{90} , are given vs. temperature for a test cell with Felix T105 in texture III. The variation at room temperature is about 0.3 V/ $^\circ$ C.

3.2.5 Display configuration

The test display is 2.5 in. in diagonal and has 140 rows and 170 columns. The alignment layer is a chemically modified

FIGURE 14 — Temperature dependences of the brightness and the switching pulse amplitudes for 10 and 90% transmission (V_{10} and V_{90}).

polyvinyl alcohol (PVA), which is moisture resistant. The alignment layer thickness is 7 nm; a thin layer is preferred, as it gives a large series capacitance.²⁶ Several polyimides have been tested as alignment layers, but the resulting bistability is not sufficient for video-rate passive-matrix addressing. Both alignment layers are strongly rubbed in parallel directions. Weaker rubbing results in poorer performance.⁴ Quartz spacer beads (Shinshikyu-W) are deposited at a high concentration of 150 per pixel (1800 mm⁻²) to increase the texture uniformity. Spacer diameter and thus cell gap is 1.4 μ m. This low value was chosen because a thin cell requires smaller pulses. Consequently, the product $d\Delta n$ is approximately 0.21 μ m for most of the aforementioned materials (Δn at 560 nm is mostly around 0.15). This differs considerably from the characteristic value for zero-order birefringence: 0.28 μ m ($\lambda = 560$ nm). However, the colourless appearance and the maximum intensity of the complete spectrum, corrected for the human eye sensitivity, do not change significantly in the $d\Delta n$ range between 0.20 and 0.28 μ m.

The display is filled with the FLC material in the isotropic phase, cooled down to room temperature and sealed. Then the chevron reorientation treatment is performed. First, a 1-V 25-Hz square-wave voltage is applied for 60 s to shrink the remaining needlelike zig-zag defects.⁴ This treat-

TABLE 6 — Passive-matrix-addressed SSFLC video display based on texture-III method.

Size	2.5-in. diagonal
Number of pixels	170 (H) $\times$ 140 (V)
Pixel size	318 $\times$ 260 μ m
Frequency	50 Hz
Row select-time	128 μ s (half-res.)
Alignment	PVA 7 nm
Cell thickness	1.4 μ m
Black matrix	None
FLC	Felix T103
Temperature	25 $^\circ$ C
Pre-treatment	1-25 V
V_r V_s V_d	17 12 3 V
Contrast ratio	80:1 (in-pixel) 30:1 (overall)
Transmission	75% of // polarizers

FIGURE 15 — The 2.5-in. passive-matrix-addressed FLC video display.

ment is consecutively repeated with a stepwise-increasing amplitude from 2 V to V_{III} to obtain texture III. The display, which possesses just 140 rows, is driven as if it were a half-resolution or part of a full-resolution or a high-definition black-and-white television display with a 50-Hz picture-refresh frequency.

3.2.6 Display performance

Figure 15 shows some photographs of the black-and-white display at half-resolution video driving. Table 6 shows some characteristics and performance data of the display.

The contrast ratio within a pixel is 80:1, but the overall contrast ratio on the display is only 30:1, due to the absence of a black matrix on the 10- μ m-wide gaps between the ITO electrodes, where the FLC is partially in the white state. The image is practically viewing-angle independent. On the display, crosstalk phenomena or flicker cannot be observed. In full-resolution video driving, the performance of the displays is unaltered, only the required drive voltages increase, as indicated in Table 5.

During slowly moving scenes, a faint after-image effect can be noticed, possibly due to the accumulation of ionic impurities²⁶ and the fact that a hysteresis²⁰ occurs in the transmission-voltage curves (approximately 300 mV). The display can be operated from 10 to 45°C, although the drive voltages have to be readjusted. When the display has been heated above a certain temperature (within the smectic-C* phase), the reorientation treatment needs to be redone. This is due to the fact that such a temperature cycle brings back the smectic layers more or less to the virgin chevron structure.

3.2.7 Evaluation of the texture method

It is demonstrated that the texture method can be used to realize analog (continuous) gradation in a passive-matrix-addressed FLC display. In addition, the method possesses some tolerance to cell-gap variation,²⁰ which is a very important technological advantage. The resulting displays pos-

sess a wide viewing angle, operate at video speed, and the passive-matrix technology yields a high aperture per pixel and opens the possibility of applying a field-induced black matrix,²⁷ instead of a photolithographic black matrix.

The remaining problems are:

- backswitching phenomena due to the high P_s of the FLC material, which demands the use of very thin alignment layers (now 7 nm PVA) and no barrier layer²⁶ for preventing top-down short circuits in the display;
- the uniformity of the field-induced texture has to be controlled over the display area, independently of alignment nonuniformities;
- the transmission-voltage curve shows a hysteresis, despite the repeated reset. This hysteresis is mainly caused by a so-called surface memory effect which is not understood yet. The hysteresis should be less than the voltage difference between two adjacent gray levels to obtain a well-defined gradation (*e.g.*, <50 mV);
- the temperature sensitivity of the threshold and saturation voltages is high (~ 0.3 V/°C). This inhibits the application of the texture method (and of all analog gray-scale methods for passive-matrix driving proposed thus far) for large direct-view displays,²⁸ for the temperature variation in these displays can be as much as 15°C.
- the maximum operating temperature of the display is strongly limited, due to the reorientation of the smectic layers towards the virgin chevron structure upon heating above a certain temperature and cooling down to room temperature.

4 Conclusions

Detailed conclusions are given at the end of the corresponding sections. Here we restrict ourselves to the more general conclusions.

When considering the application of the SSFLCs for video displays, the requirements with respect to gradation, speed, luminance, and contrast have to be satisfied. To achieve sufficient luminance (and contrast) when using the bistable memory states, it is necessary in general to use a high-pretilt alignment or a bookshelf geometry. A bookshelf geometry can be obtained by electrical reorientation of the smectic-layer structure (FI-QBG or texture III) or by using a naphthalene-type FLC. The necessary gradation for a video display can be obtained by digital or analog methods, resulting in a discrete or analog gradation, respectively.

Discrete gradation, based on space integration of completely black or white SSFLC (sub)pixels, was investigated for projection and for the direct-view types of displays by simulation experiments on a high-resolution CRT. In general, subpixelation is more difficult for projection displays due to the very small ITO lines and the high density of interconnections and drivers. The simulation experiments showed that severe image artefacts occur in the projection situation, while this was not the case in the (colour) direct-view situation. So, gradation by means of subpixelation is more suitable for colour direct-view displays. With presently available FLC mixtures, the requirements with respect to switching speed cannot really be fulfilled, although the gap is not very large any more.

Analog gradation: (a) Charge-controlled multidomain switching provides a well-controlled gradation, but requires the use of an active matrix for addressing. With increasing effort in active-matrix TN-LCDs, this method might be a good candidate for second-generation video LCDs. The advantages are then a very large viewing angle and the possibility of a higher frame rate. (b) Local FLC switching-threshold variation by using the texture method is shown to be able (in principle) to meet the video requirements with respect to speed, contrast, and transmission, but shows severe problems with respect to reproducibility, hysteresis, and temperature sensitivity.

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Wilbert J.A.M. Hartmann studied chemistry and physics at the University of Nijmegen in The Netherlands. After graduation in 1985, he joined the Philips Research Laboratories in Eindhoven. Since that time he has worked in the Display Principles and Devices department, focusing on the fundamentals and display applications of ferroelectric liquid-crystal effects. In 1990 he completed his Ph.D. thesis entitled,

"The surface-stabilized ferroelectric liquid-crystal structure and its bistability." In 1992 he joined the Philips Flat Panel Display Co. in Eindhoven, where he is now a project leader in the development of active-matrix LCDs.

A.G.H. (Ton) Verhulst joined the Philips Research Laboratories in Eindhoven in 1962. He has been engaged in research on different types of magnetic memories for computer application. During that time he studied at the Technical University of Eindhoven. He joined the research group for Display Principles and Devices in 1982 and investigated interface charging in micro-mechanical displays. Since 1987

he has been involved in research on ferroelectric liquid-crystal displays, mainly focusing on video applications.

J.A.M.M. (Jos) van Haaren received his Ph.D. in solid-state physics from the University of Nijmegen, The Netherlands, in 1988. In 1988 he joined Philips Research Laboratories, where he is currently working on various aspects of liquid-crystal displays.

Frans J.J. Blommaert received his M.Sc. degree in physics and his Ph.D. in technical sciences at the Technical University, Eindhoven, The Netherlands. Since 1975 he has been associated with the Vision Group of the Institute for Perception Research (IPO) in Eindhoven. His major research interests are in fundamental and applied vision research, e.g., brightness and color perception, letter recognition, and perceptual quality of displayed images. Since 1986 he has been associated part-time with the Philips Research Laboratories as an advisor on perceptual aspects of display principles.