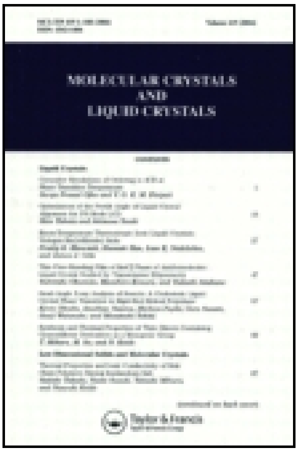

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Advances and Problems in the Development of Ferroelectric Liquid Crystal Displays

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ADVANCES AND PROBLEMS IN THE DEVELOPMENT OF FERROELECTRIC LIQUID CRYSTAL DISPLAYS

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Abstract Recent advances in the development of ferroelectric liquid crystal displays are briefly reviewed, with special attention to the problems and solutions concerning cell bistability, matrix addressing techniques, the realization of gradation displays and the system integration of FLC displays. New dynamic models for matrix addressing are introduced.

Keywords: ferroelectric, liquid crystals, displays, matrix addressing

INTRODUCTION

Eleven years after the publication of the fast bistable switching in Surface Stabilized Ferroelectric Liquid Crystal (SSFLC) cells, by N. A. Clark and S. T. Lagerwall,[1] and six years after the first matrix display prototypes,[2,3] very impressive results have been obtained for several prototypes,[4,8] each one representing a technical milestone.

The prototypes considered are (exept the old one reported in Ref. 3) all based on cell gaps of 2 μm or less, in spite of much effort to develop special techniques for thicker cells, mainly by ATT, Thomson, Hitachi and Toshiba. All are based on LC materials of moderate spontaneous polarization.

The 1985 Seiko Instruments display[2] was 400 ways multiplex-driven and its 12 inch useful diagonal has not yet been significantly surpassed. Colour by microfilters, an almost twice as fast addressing technique and video rate were progressively introduced by Toshiba from 1986 to 1988[4] in displays featuring the same size and dot complexity. Video rate and advanced addressing techniques were also demonstrated, in smaller b/w displays, by European groups, corresponding to the British JOERS/Alvey consortium[5] and to the French LETI. In 1988, the latter group was the first to present a TV gradation display.[6] Moving images having nine grey shades were obtained by mixed temporal and spatial dithering. A fully multiplexed b/w display having the record size of 14 inch diagonal and record complexity of 1120 x 1280 dots on a 0.2 mm pitch was demonstrated by Canon at the same conference.[7] The LETI and Canon displays were rugged enough to be transported. The following year, a fully multiplexed (slow) trichrome projection display having 2000 x 2000 RGB pixels (in three 6 inch panels) on a 0.04 mm pitch was demonstrated by Matsushita.[8] Special addressing techniques were reported, to drive the interpixel gaps in a black state, and high light transmission was obtained by high tilt SiO alignment producing large relaxed cone angles. This made possible also the construction of a bright and fast, 400 way multiplexed, reflective 12 inch display, which was shown to visitors.

In spite of these unsurpassed FLC records in size and complexity among all LC display techniques, no relevant presence in the enlarging market of flat display panels can yet be observed. In fact progress has often been achieved in the absence of a sound physical knowledge. The scientists working on the industrial development of FLC display panels are aware that the available shades, contrast, temperature range and ruggedness, all require improvements and that much better results will be obtained when all the effects involved are clearly understood.

This has been the subject of most recent research activity, so that in the last two years, a large quantity of scientific literature, dealing with physical and chemical studies, has appeared. Faster materials having subtle addressability properties have been found and important techniques have been demonstrated in small panels.

All the advances in this field cannot be described in a single paper; hence this one will only consider some selected topics. The main focus is on recent developments, as well as on problems as yet unresolved, concerning bistability and contrast, matrix addressing, realization of gradation displays and system integration of SSFLC displays. The physical aspects have been covered by another presentation in the same Conference and the wide and sound review by Lagerwall, Clark, Dijon and Clerc[9] can be referred to for introductory knowledge and for a detailed discussion of the earlier developments.

MATERIALS, BISTABILITY AND CONTRAST

Two discoveries concerning materials have been at the root of the appearance of the first SSFLC prototypes. The first was that useful liquid crystals could be obtained by mixing a non-chiral SmC host having a large phase existence range, with a suitable chiral dopant inducing spontaneous polarization.[10] The second was that good layer alignment could be obtained on anisotropic surfaces during cooling through a phase sequence in which a pitch-compensated cholesteric phase and a SmA phase are encountered before the SmC* phase.[11]

Since these discoveries, the target of material research has been that of fast switching materials and impressive progress has been made. Representative values for switching time in matrix-addressed displays dropped from 150 μs in 1985 to 50 μs in 1988 and 15 μs in 1990.[2,6,12] Most progress has come from improvements in the LC rotational viscosity, in spite of the development of high polarization materials by many chemical laboratories.

At present the requirements are being identified for more complex material properties and new research targets are been introduced. One is a small temperature dependence of the critical voltage-time product for latching. The large temperature dependence of the rotational LC viscosity should be reduced and it can in part be compensated for by a varying spontaneous polarization. Another target is the resistance to damage to the alignment of the smectic layers, produced by mechanical and voltage stresses, which is related to complex, and only partly understood, "piezoelectric" effects in the SSFLC cell.[13]

In first generation FLC displays, with the unique exception from Matsushita,[8] the extinction angles of the stable states differed by much less than the ideal value of twice the SmC cone angle, which should be found in the bookshelf uniform alignment. This angle is only obtained (approximately) between on-voltage states.

To measure the degree of bistability, a quantity smaller than one can be introduced, which can be named memory capability. Instead of making reference to the extinction angles, it can be defined in the optical response,[14] as in Figure 1. The symmetrical response is considered of the cell placed between polarizers oriented at 22.5° to the smectic layers, when opposite voltage pulses separated by large time intervals are applied.

Even though good displays have been produced with memory capabilities smaller than one half, much better ones are expected if bistability is improved. The percentage of transmitted light, which is of great system importance, will have the largest benefits, with the contrast also being improved.

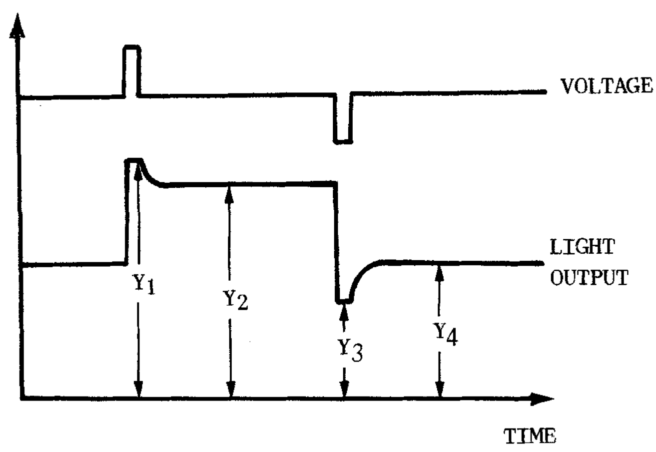

FIGURE 1 Memory capability can be introduced to measure the bistability from a user point of view. It is defined in the optical response of a symmetrical cell as $(Y_2-Y_4)/(Y_1-Y_3)$ (Tokyo Univ, Ref. 14).
Jpn. J. Appl. Phys. 28, p. 116, with permission

A simple way to improve,[15,16] or even create,[3,17] bistability is the use in the addressing waveforms, between selections, of holding and data voltages having high frequency components of rms amplitudes large enough to improve the angles of the memorized states by the effect of dielectric torques. This is usually called ac stabilization but hf stabilization is a more appropriate term. Large improvements are obtained in contrast and brightness, at the expense of considerable electric power, provided that permanent voltage damage does not occur.[15,16]

It was difficult to understand the reasons for the reduced bistability. Partial explanations have been a tilted director at the boundary surfaces and non-uniformity of the director within the thickness, corresponding to splayed or twisted configurations.[18] States with reduced extinction angles are stabilized by the electric field from the internal polarization, especially in the presence of the usually employed dielectric layers over the electrodes.[19] The use of slightly conductive layers, such as polyimide doped with charge transfer complexes, was found to cause large improvements in bistability.[14]

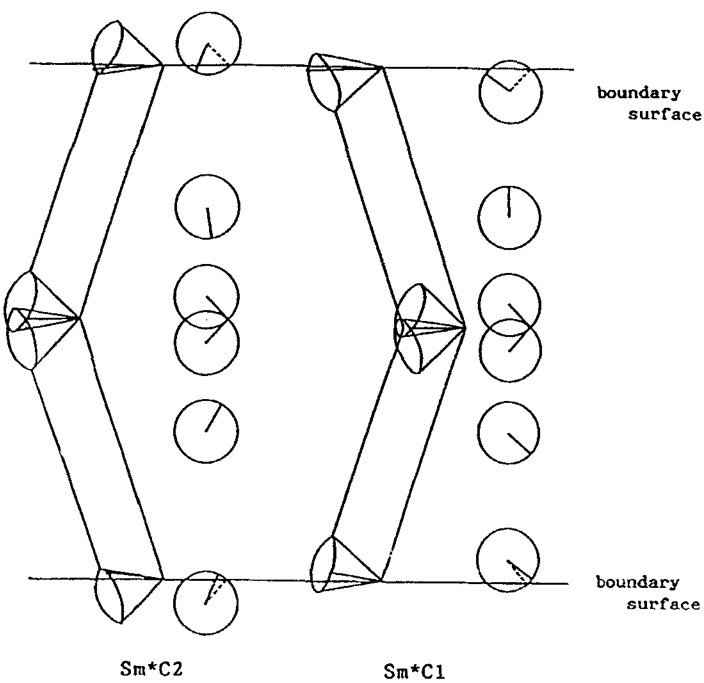

FIGURE 2 Two possible layer and director structures in a ferroelectric liquid crystal cell (Canon, Ref. 23).

The main reason for the reduced bistability can now be identified in a chevron structure of SmC layers tilted from the vertical and broken in a middle plane. The tilt depends on the contraction in thickness of the smectic layers, created at the N*-SmA transition, when the cell is cooled to the operating temperature in the SmC phase.[20] If the amount of layer contraction is reduced, larger extinction angles are found which lead to better light transmission and bistability.[21] For high Ps materials, high electric fields at low frequency have been found to be able to stretch the chevrons, so reducing the tilt of the layers and improving bistability, even if defects are produced.[22]

Two possible layer structures are shown in Figure 2, corresponding to layer tilt in two directions that respect the boundary conditions on the director. This is usually the case and zones form that are separated by complex wall defects. These defects are visible as characteristic zig-zags which degrade the quality of the black state.[20]

In the first Canon prototype published, care was taken to select only one of the two possible layer structures, by imposing the correct tilt to the director on the surfaces.[23] However, the resulting director configurations were reported to be the twisted-splayed ones also indicated in Figure 2. A contrast ratio of only five was obtained and this was due to the small difference of the extinction angles of the two configurations shown, in which only the central surface is switching between large angles.

There is now a new Canon display, that is scheduled for presentation in a short time. It features a much better contrast ratio of at least 30 obtained by means of an improved layer and director structure. Its pixels are subdivided into two dots of different areas, to obtain four grey shades by spatial dither. The previous size, pixel count and multiplexing ratio have been approximately maintained and the refresh rate has been much improved.[24]

MATRIX-ADDRESSING

Matrix addressing of FLC panels is not straightforward. Its basic principle is usually stated as follows:

Fast switching between two optical states is caused by the right combination of fixed selection voltages applied during a short line-selection time and data depending voltages added to them in a line-access time interval. The optical state is maintained when holding and data voltages only are applied.

However there is no generally agreed operational definition of "optical state", "mantaining" and "switching" that does not make reference to particular waveforms. In reality, a continuum of optical outputs is observed, presenting a wide range of fast and slow changes effected by the data voltages, and no feature can be detected in the optical response to identify the moment at which state switching takes place. Some observation time, larger than a rather long characteristic time for the bifurcate relaxation of the cell (about 1ms), is necessary to define whether an "optical state" has been memorized. The term "switching" is often used with reference to any wide change in the optical response. In my opinion a clear distinction is necessary and it is better to name "latching" or "memorizing" the process after which a given optical state can be detected.

In a very first approximation, the transmitted light at each instant L(t) is a non-linear instantaneous one-to-one function of the time-integral A(t) of the applied voltage V(t) (if the starting conditions are arbitrarily fixed). This entails perfect memory of any transmitted light level as long as the voltage applied has a zero mean value. As a first consequence, only dc-balanced data and holding voltage segments can be used in the addressing waveforms between consecutive selections, to allow memory of the selected state. This was found experimentally very early[25] and is still generally agreed to be the case.

This kind of model is indeed found if the non-uniform liquid crystal in the cell is approximated by a single uniform director in a tilted layer, as in Ref. 26, and if only the spontaneous polarization torques are considered.

However, if the model were exact, any dc-balanced data waveform added to any selection waveform, would produce no effect at all on the final value of the transmitted light.[27] Consequently, latching could not be controlled by the data waveform and matrix addressing would be impossible. Indeed, for intermediate output values, only small deviations are found from the voltage-integral dependence. Larger ones occur for very high or low voltages. These deviations are due to the elastic torques responsible for the relaxation phenomena and the bistability of the cell, at low or intermediate voltage, and to the dielectric torques, at high or intermediate voltage.

Smooth saturations at minimum and maximum levels are found in the transmitted light, making any measurement difficult. However, the saturations appear to be experimentally related to latching and there is general agreement that, in the first approximation, latching occurs if a "critical pulse area" or "threshold for latching" A_c is exceeded in the applied waveform.[28,36]

There is no analogy between A_c and the coercive field in solid ferroelectrics. In fact, even if hysteresis cycles are found, nothing exists similar to a limit hysteresis cycle either in a L-A plane or L-V plane. Furthermore no attempt has ever been made to define A_c without making reference to particular waveforms applied, or to translate the above statement into a mathematical system model for addressing.

In a sense, matrix addressing is made possible by second order properties of the cell. In contrast, matrix addressing for nematics depends on first order properties, such as the voltage-square dependence of the transmitted light. A simple theory for matrix addressing nematic displays was presented some years after their first introduction.[29] It has yet to be formulated for the more complicated case of FLC displays.

Let me only observe that the simplest (inaccurate) system model for which latching for pulses exceeding a critical area is found is suggested by the drawings in Ayliffe[25] and corresponds to the following equations:

$$L(t)=f(S) \quad (1)$$

$$S'(t) = (S_2 - S_1)V(t)/(2A_c)$$
$$\text{for } S_1<S<S_2 \text{ or } V>0 \text{ and } S=S_1 \text{ or } V<0 \text{ and } S=S_2 \text{ ;} \quad (2)$$
$$\text{being otherwise } S'(t) = 0$$

in which f(S) is a non linear function relating the optical transmission L(t) to a state variable S(t), whose time derivative is S'(t). From a physical point of view, S could be eventually identified as an average along the cell thickness of a function of the azimuthal angle that describes the rotation of the director around the SmC cone.

What is interesting here is that the earlier and simplest addressing schemes can be described in accordance with this rough model and that, in my work at LETI, new addressing schemes were derived from it, before finding them experimentally.[16] In the model, no state latching is defined. In its place, memory of the past applied voltages is suddenly and completely lost when a saturated state S_1 or S_2 is reached. This was an oversimplification. In fact surviving memory effects were immediately found and tentatively attributed to ionic charges or to changing smectic layers.

The model fails at high voltages where it is unable to predict leading pulse latching for bipolar pulses[16] and the phenomena related to the square-voltage dependent dielectric torques.[30] Performing addressing modes based on such phenomena have been found.[31-33] One can distinguish between "normal modes", qualitatively operating in accordance with the model above, as the one in Figure 3, and "fast modes" or "high voltage modes" and "hf stabilized modes", for which a more complicated system model is necessary.

The simple dynamic equations used in Refs. 26-27, in the assumption of a uniform director, don't predict hf stabilization. They must be corrected in the light of the recent explanation of the hf stabilization in terms of biaxial dielectric tensor.[34,35] In the simplest case, by neglecting the ordinary dielectric anisotropy with respect to the difference of the components normal to the director and by including an empiric expression for the elastic torques, as in Ref. 27, the following empirical system model results:

$$L(t)=f(S) \quad (3)$$

$$S'(t) = \frac{V(t)}{A_c} \cos S(t) + \frac{1}{T_r} \sin 2S(t) \left(1 + \frac{V^2(t)}{V_c^2} - \frac{\cos S_0}{\cos S(t)} \right) \quad (4)$$

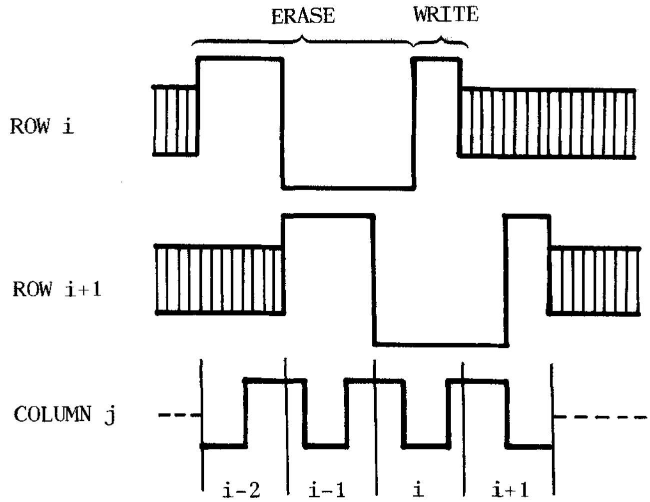

FIGURE 3
Example of "normal" addressing scheme in which long erase sequences are applied to the rows in overlapping times. Grey level control is obtained by the time-shift of the data pulse in the time-window corresponding to the write pulse and the last part of the erase sequence. The data voltage shown is such to obtain four decreasing shades at the four intersections of the column j with the rows from i+1 to i-2. The use of hf stabilization to improve bistability is also shown (LETI and Bari Univ, Refs. 38,16).

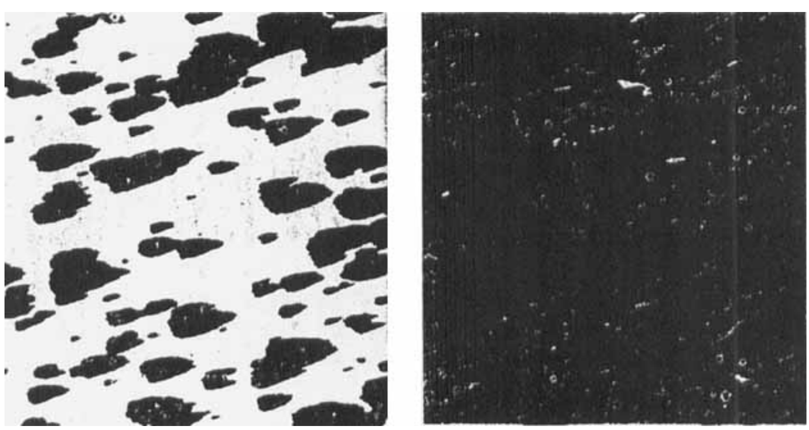

FIGURE 4
Micro-multidomain textures obtained by analog control in a cell presenting two uniform states, visible in the left or right texture, and one intermediate twisted state, visible in both (Citizen, Ref. 37).

in which A_c is a critical area; a relaxation time T_r and a critical voltage V_c have been introduced to model the elastic and dielectric torques and $+/- S_o$ are the stable states.

The author feels that a useful addressing theory can be derived from this model in which a minimal duration for latching with monopolar pulses exists and where both trailing pulse latching and leading pulse latching can be found for bipolar pulses. At the University of Bari, we are now undertaking numerical and analytical studies to investigate this point.

Important results in terms of addressing speed, brightness and contrast, have been obtained in the past by the development of better addressing modes and others are expected in the future when matrix-addressing is better understood. Major factors will be the tolerance to variations in cell thickness and temperature as claimed but not disclosed by Thorn-EMI[12] and the development of contrasted crosstalk-free modes such as the one from LETI.[36]

GREY SCALE

The SSFLC cell is able to memorize intermediate states, for intermediate phases or amplitudes of the voltage waveform across it. Such intermediate states can be non-uniform director states, but are usually only mixtures of two different domains. This is well shown in Figure 4, where mixtures of one twisted and two opposite uniform domains were obtained at Citizen in a low-duty-ratio matrix-addressing scheme for a printer bar.[37] As was reported by LETI and the University of Bari,[38,16] similar results can be also obtained without the intermediate state and under high-duty multiplexing conditions if a special drive scheme with enhanced blanking is used. However, the real problem is how to achieve reproducible levels in the presence of temperature and thickness non-uniformities. Thus, the actual choice used by LETI to obtain nine grey shades in their TV demonstrator was a combined spatial and temporal dithering technique.[6]

A simple but expensive solution was found in charge control.[39,40] If the pixel capacitance is charged through an electronic switch and then disconnected, this charge will redistribute in the cell and control the percentage of switched area in a way insensitive to the temperature variations of viscosity and to the thickness dependence of the internal electric field. Smooth curves result (Figure 5) and analog control is possible but an active matrix is required for addressing.[41]

Another solution has been recently proposed by the Philips researchers. Low frequency voltage treatments reduce the tilt of the layers and produce a dense net of defects: the result in terms of transmitted light versus a matrix-addressing data voltage, in a scheme using enhanced blanking, is shown in Figure 6.[22] Moreover, a stronger electric field treatment results in the thinner areas, compensating in part for the variations in A_c. Figure 7 shows an image displayed on a 5x5 cm display in texture III.[42]

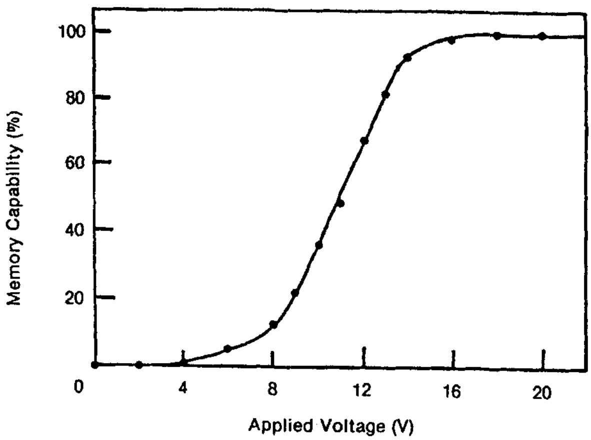

FIGURE 5
Charge control of grey shades (Tokyo Univ, Ref. 40).
Soc. for Information Display, *Proc. SID 31*, p. 139, with permission

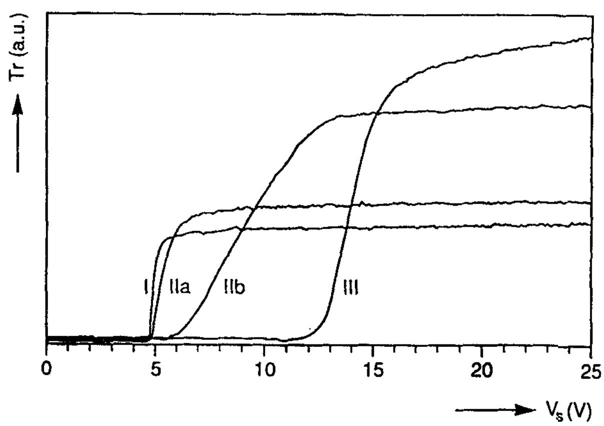

FIGURE 6
Effect of low-frequency voltage treatment on the modulation transfer characteristic of the cell (Philips, Ref. 42).
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FIGURE 7
Gradation image obtained by analog modulation in a directly addressed FLC matrix (Philips, Ref. 42).
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This approach is very attractive. A delicate point, however, is the ability of the layer structure obtained to survive mechanical and voltage stresses as well as to reform after damage by applying the required thermal and electrical treatment, without removing the display from its operating environment. Moreover, it is not clear that the necessary uniformity can be obtained over large surfaces.

Spatial and temporal dither have the advantage that very precise intermediate tones can be reproduced by a non-uniform liquid crystal panel. They can be easily demonstrated but both put considerable stress on the driving electronics if implemented in a real size and resolution display. The first requires very fine stripes for the electrodes in the matrix and many more connections and drivers. The second and the mixed approaches require a much shorter access time for writing a line in the display, because the refresh rate must be fast enough to avoid the perception of flicker.[43]

If a mosaic of microfilters is used for colour, the requirements for the photolithographic processes and for the connections to the drivers become difficult to meet. Unlike the nematic displays, colour can be also obtained sequentially, with the aid of pulsed fluorescent lamps for the three primary colours as the backlight. This was proposed by Thorn EMI,[44] who however preferred to employ microfilters and fully temporal dither in their latest TV demonstrator.[12] As in the case of LETI,[6] this is in fact a mixed approach, which turns out to be feasible with the available addressing speed, connector pitch and photolithography.

It is clear that an analog gradation technique would have large cost advantages if uniform enough panels can be manufactured. A further possibility is that of combining analog control with precise area subdivisions obtained by photolithography.[43,45] This is possible if voltage partitions are provided inside the display, as shown in the simpler version by Matsushita in Figure 8, in which three grey levels are obtained by splitting the rows into two parts, without increasing the number of external connections and drivers.

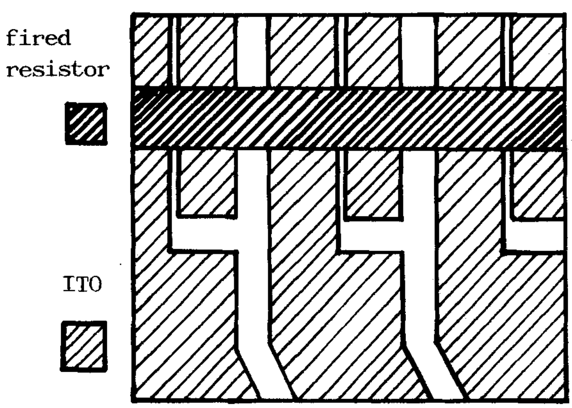

FIGURE 8
Voltage partition technique by an integrated resistor to drive splitted rows by a single external connection (Matsushita Ref. 45).

SYSTEM PROBLEMS

From a system point of view many basic problems arise, such as the choice of the liquid crystal operating temperature range, display refresh rate, and order in which the rows are addressed.

An example of temperature dependence of A_c is shown in Figure 9.[43] To work in a reduced temperature range of only 20 °C, the times or the amplitudes in the addressing waveforms must be varied by a factor of 3 to track the temperature variations. Changes in all frequencies is the simplest solution used up to now in most prototypes. However, it cannot be used for a large display in a large temperature range, due to the speed limitations in the electronics and from the resistivity of the electrodes, and due to the increase in power dissipation at high temperatures.[5]

A fixed refresh rate is highly desirable for electronic interfacing to avoid artifacts which appear for moving images generated at a refresh rate different from the one in the display, even if a frame memory and motion interpolation are used. The refresh rate should be as low as possible to reduce bandwidth, currents and power dissipation in the electronics as well as in the display itself. This is compatible with fixed voltages and variations in the times in the addressing waveforms for temperature tracking, only if dead times of varying durations are used, i. e. varying time intervals in which all voltages are zeroed. This would involve large complications as well as additional power consumption in the drivers and turns out impossible with the ones currently available.

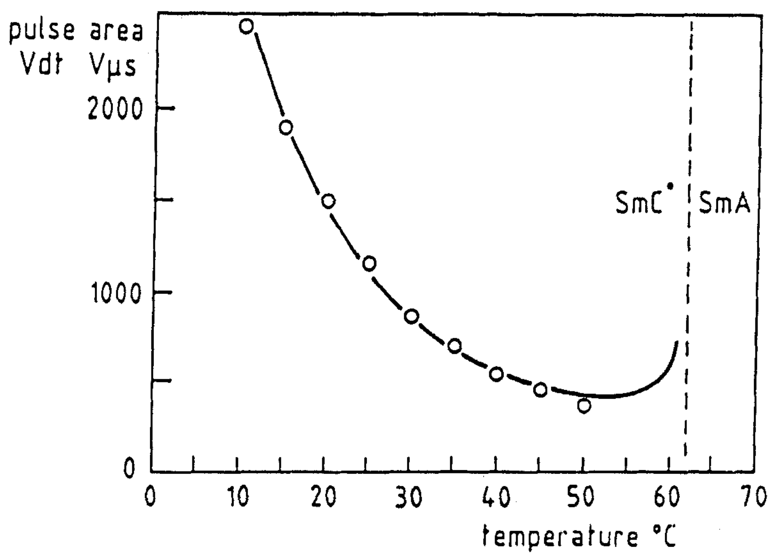

FIGURE 9 Temperature dependence of the Vt product for latching at high field in a 2 μm bistable cell (Bosch, Ref. 43).

Changing only the amplitudes allows fixed times, minimal power consumption and minimal requirements for the output resistances of the driving integrated circuits and for the internal resistance of the electrodes. However, this must be compatible with eventual high voltage effects in the addressing scheme chosen and with the internal architecture of the drivers. The required voltage range can be reduced by properly exploiting high voltage effects and the reduced slope at high temperatures of a curve like that in Figure 9, by making use of the heat from the backlight and of some thermal stabilization. Tolerance to temperature variations is now claimed by Thorn-EMI.[12]

For human interfacing, the refresh rate should be high enough to allow the perception of motion to be continuous and to avoid the perception of flicker. As known from cinematography, 15 Hz is the lowest limit for the first requirement.

An ideal FLC display gives no flicker even at much lower rates, if the latched optical states are stable between consecutive selections and if negligible light pulses are produced in the selections. In practice, the first condition can be met with the aid of strong enough bistabilities and the second by employing non-flashing addressing schemes.[31,37]

To avoid flicker at a basic 6 Hz refresh rate, in the first Canon display, scanning was 8 times interlaced and, to allow a good perception of motion, additional refreshing was made for the rows corresponding to moving parts of the image.[23]

Versatile testing electronics have recently been built in Seleco, to test arbitrary addressing schemes and interlace schemes in small FLC displays, while simulating the addressing of a full size screen. Tests made by the author and Seleco researchers make us confident that good motion reproduction without flicker can be obtained, with suitable FLC cells and addressing schemes, slightly above 15 Hz if progressive scanning is used. Interlacing was found to produce notched edges for laterally moving images, much more perceptible than with cathode ray tubes, in which the two half resolution images decay, so that they are never both present at the same time. Addressing schemes in which the image is written in two fields (such as the first one from Seiko I) also produce artifacts on moving images and should be avoided if substantially higher scan rates cannot be used.

If temporal dither is used to produce grey levels, complex interlacing becomes necessary. For instance, if eight grey levels are produced, one has to address the display three times, at different time intervals, corresponding to the binary weights 1,2,4. As shown in Figure 10, with progressive scanning of the entire display, four of the seven field times are unused. However, if the display is divided into two parts (for example odd and even rows) only one unused field time remains and the row access time allowed is doubled.

Better time allocations can be found at the price of dividing the display into more parts. Complications occur if the rows must be addressed twice to get the black and the white states. With temporal dither, to avoid flicker, both on steady images and on moving edges, and to avoid artifacts, at least 50 Hz must be used for the frame rate, in place of the standard 25 or 30 Hz used in television. This was indeed the approach followed by Thorn-EMI which continued the British JOERS/Alvey developments up to the recent demonstration of a colour gradation TV display.[12]

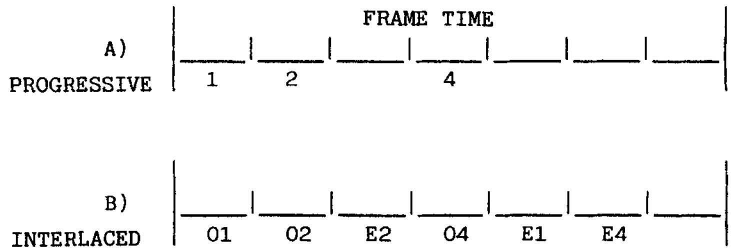

FIGURE 10 Examples of time allocations in seven fields (some of which unused), corresponding to the binary weigths 1,2,4, to obtain eight grey shades by pure temporal dither.

FINAL REMARKS

The development of FLC displays has turned out to be more difficult than expected and several important problems were simply left aside in the initial developments. In spite of this, important successes were achieved which have provided interest and funding for the required basic research activities. Even if few large prototypes have recently been presented, the basic understanding has greatly increased and this will lead to a new generation of much better prototypes. Major progress is still required with respect to temperature and cell thickness non-uniformities tolerance, light transmittance of the bright state, analog techniques for the control of intermediate tones and resistance to mechanical and voltage damage. Partial solutions to these problems are now being reported and will certainly be completed and combined in the next years.

Even though the Japanese laboratories, primarily Canon, dominate the scene, significant work and very good materials have been reported by European groups, especially in the recent years. The developments by the European project FELICITA started much later than those by LETI, the JOERS/Alvey project and PHILIPS. FELICITA's main target is a high resolution A4 colour gradation display and the present situation is promising.[46] Figure 11 shows an intermediate prototype under development at GEC.

The author would like to acknowledge his previous advanced experience with the LETI liquid crystal group; more recent joint work and stimulating discussions with F. Zuliani, S. T. Lagerwall, K.-F. Reinhart and all the partners in the ESPRIT II project FELICITA; photographs and references from N. A. Clark, J. Kanbe, S. Kobayashi, M. Matsugana, A. Mosley, A. Murayama, A. G. H. Verhulst and many others and finally funding from the EEC, mainly under ESPRIT II, and from the Italian CNR, mainly under the national project for telecommunications.

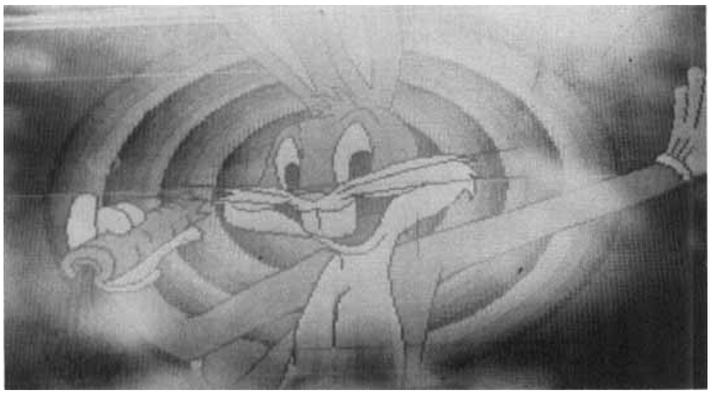

FIGURE 11 A 640x400 b/w 14" display under development in FELICITA (GEC, Ref. 43).
Society for Information Display, *SID Symposium Digest 91*, p. 404, with permission

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To help the reader, in these references the last published work describing consecutive developments by the same laboratory has been quoted. Reference to relevant previous papers will be found in it.

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