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Antiferroelectric liquid crystal displays

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In the last few years, the unique features of antiferroelectric liquid crystals (AFLCs) have been explored to develop high-end displays. A number of passive- and active-matrix prototypes have been presented. However, although their use in a number of application areas has been suggested, no commercial products have been announced yet. This work reviews the state of the art of AFLC displays, the reasons for their present low incidence in display markets, and the latest developments aiming to overcome the main shortcomings that hinder their development. V-shape smectic displays are also included in this study. Although not considered strictly antiferroelectrics nowadays, V-shape materials behaviour and scope are similar to traditional AFLCs.

Keywords: antiferroelectric, display, V-shape, LCOS, active matrix, waveform.

1. Introduction

The world market for displays amounts roughly 50.000 M per year, of which about 50% correspond to flat panel displays (FPDs) [1]. FPDs are ubiquitous nowadays, being employed in an increasingly large number of applications. A dozen emissive and non-emissive technologies were tested as FPDs during the last two decades of past century; at present, just a few of them are still considered [2] actual competitors for high volume consumer applications (Fig. 1). Even less are able to compete with the traditional cathode ray tubes (CRTs) for the high-end applications market, i.e., full-colour, high-resolution, and video-rate displays. Both, direct-view (e.g., plasma) and projection (e.g., digital micromirror) displays are currently available within this segment. In either case, an ever increasing number of these high-end displays are based on liquid crystals. In the 90s, liquid crystal displays (LCDs) extended their traditional simple applications as low-consumption, low-resolution displays for portable applications to highly sophisticated devices ranging from small to large (> 20") FPDs for video and computer applications [3], as well as high resolution miniature displays for video projection and spatial light modulators [4]. At present, LCDs are the natural choice not only for lap-top computers, but for desk-top computers, a traditional CRT market. Moreover, LCDs are becoming, in the last three years, the most serious candidate to FPD for consumer TV. Large size (40–60") direct-view FPDs, an exclusive arena for plasma display panels (PDPs) are currently being offered in LCD technology; prototypes up to 55" diagonal have been recently presented [5]. It is expected that the market of flat home TVs will soon be dominated by LCDs, with a marginal share for PDPs [6]. (A third candidate, organic LEDs or OLEDs, might eventually be a strong competitor of LCDs within this market, if it is able to unleash its potential performance [7]).

Most of high-end LCD realizations derive from active matrix (AM) displays, where the display performance is ultimately dictated by the device electronics. Active matrix LCDs are usually based on thin-film transistors (TFTs). Table 1 shows a comparison of active and passive LCD technologies. From the electrooptical point of view, AM-TFT LCDs are superior to passive matrix devices, for the LC material response can be made independent of the display electronic driving, and specifically of the multiplexing rate. This means that, unlike previous multiplexed passive displays like supertwist nematics, the device resolution (strictly, the product resolution frame rate) can be increased without impairing other display characteristics such as brightness. At present, regular nematic LCs employed in displays do not show any electrooptical effect that can be used to hold its information along the frametime. A constant voltage must be applied to every pixel for the transmission to be kept. In an active matrix, the active element controlling each pixel is responsible for holding the pixel information as sent during the corresponding slot, whereas in a passive matrix nematic LCD pixels must be either continuously driven (direct addressing) or allowed to lose their transmission through relaxation while the remaining rows are addressed (multiplexed addressing). High resolution displays are always multiplexed; as the multiplexing capabilities of passively addressed nematic LCDs are limited, manufacturers shifted towards active matrix-based displays as soon as reliable fabrication procedures for these devices became available.

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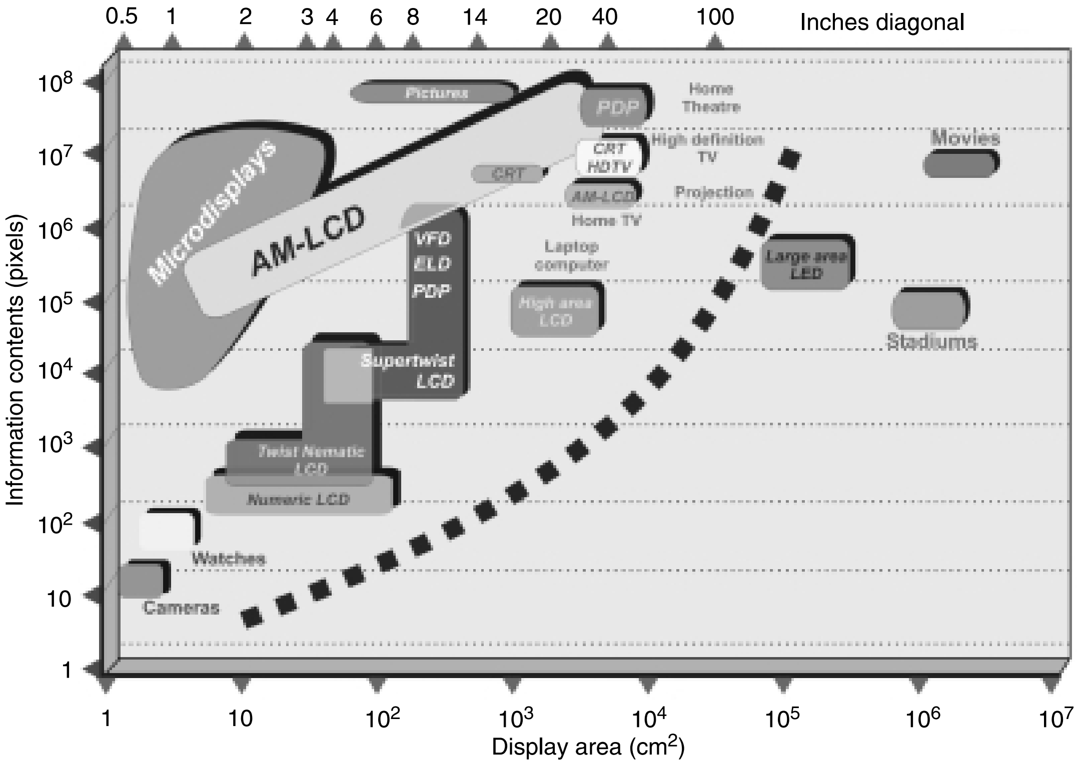

Fig. 1. Technologies and applications of displays. A trend for increasing size and resolution is highlighted.

At the same time as AM-TFT LCDs were developed, an alternative way to prepare high resolution LCDs arose from a different approach. Bistability was demonstrated in smectic LC phases, associated with ferroelectricity. Bistable LCs are able to hold pixel information in the absence of power supply. Therefore, they can be driven, in principle, by passive matrices. Since then, new ferroelectric families – antiferroelectrics, V-shape smectics, orthoconic materials – have widen the number of possible applications for these materials. In the last few years, ferroelectric-based display prototypes ranging from microdisplays to large direct-view displays have been created [8], demonstrating the feasibility of such technology. Development of these displays has been precluded by the lack of suitable materials

Table 1. Display capabilities of different LCD technologies.

Material/ technology	Multiplexability	Greyscale	Optical stability	Colour dithering	Switching type	Viewing angle	Dynamic response
Passive twisted nematic	Very limited	Analogue	Monostable	Spatial	Out-of-plane	Poor	10’s ms
Passive supertwisted nematic	Limited	Analogue	Monostable	Spatial	Out-of-plane	Very poor	10’s ms
Active matrix twisted nematic	Unlimited	Analogue	Monostable	Spatial	Out-of-plane	Good	10’s ms
Active matrix homogeneous nematic	Unlimited	Analogue	Monostable	Spatial	In-plane	Excellent	10’s ms
Passive ferroelectric	Unlimited	Spatial/ temporal dithering	Bistable	Temporal	In-plane	Excellent	10’s µs
Passive antiferroelectric	Unlimited	Analogue	Multistable	Spatial/ temporal	In-plane	Excellent	10’s µs
Active matrix V-shape smectic	Unlimited	Analogue	Monostable	Spatial/ temporal	In-plane	Excellent	10’s µs

and some difficulties in the manufacturing process. AM-TFTs, on the other hand, have experienced an extraordinary growth in many different applications areas [9].

In this work, the current state of the art and possible evolution of displays made of several ferroelectric kinds is reviewed. The work is focused on the above mentioned three families, whose electrooptic characteristics bestow good performance for high-end display applications.

2. Electrooptical behaviour of ferroelectric families

An increasingly growing number of smectic LC phases have been described [10]. A number of them show ferroelectricity. Depending on their spontaneous orientation in the absence of voltage, ferroelectric LC materials, similarly to solid ferroelectric materials, are classified in three different groups:

- regular ferroelectrics, in which all the molecular dipole moments are parallel to each other, and the macroscopic spontaneous polarization, therefore, is maximum,
- antiferroelectrics, in which the dipole moments are antiparallel, therefore the spontaneous polarization is cancelled out,
- ferroelectrics, intermediate phases with net spontaneous polarization lower than the corresponding ferroelectric material. No practical applications of these phases have been described yet.

In the last few years, other ferroelectric subfamilies have been included:

- V-shape smectics, a configuration showing thresholdless switching. Besides the controversy about the origin of this effect, and the involved smectic phase [11], their electrooptical (EO) behaviour seems quite appropriate for display applications.
- orthoconic smectics, tilted smectic phases like C phase (SmC) are characterized by the angle formed between the molecular director and the smectic layer normal. In orthoconic materials, this angle is 45°. Ferroelectric orthoconics switch between states located at 90° to each other. This confers unique EO properties to these materials [12], as commented below. Ferroelectric and antiferroelectric orthoconic materials have been found.

Displays made of ferroelectric LCs are usually prepared in thin (1.5–2 µm) cells with the LC material oriented in homogeneous configuration (i.e., parallel to the plates). These conditions lead to surface stabilization and bistability or multistability. Moreover, all the configurations achieved by the material upon switching are oriented parallel or nearly parallel to the outer plates. This feature is called in-plane switching (IPS) and results advantageous from the optical point of view. All kinds of ferroelectric displays show excellent optical performance as compared to twisted LCDs. The viewing angle is high, and colour degradation for oblique light incidence is less noticeable than in twisted nematic LCDs – not to mention supertwisted nematics. Some recent realizations on high-end displays include special arrangements of electrodes to achieve IPS with nematic LCs.

2.1. Switching ferroelectric displays

All ferroelectric families in surface-stabilized homogeneous configurations can be switched by DC signals. The simplest case is the bistable switching of regular FLCs. The orientation achieved upon the application of an electric field is kept in the absence of voltage. This intrinsic memory can be used to generate permanent images in displays with no power consumption, and to prepare high rate multiplexed displays with passive matrices.

The main disadvantage of FLC materials in high-end displays arises from its own bistability. Indeed, permanent orientation avoid the generation of intermediate transmission levels (i.e., grey levels). A full greyscale is required for the display to render full colour. High-end displays require at least 64 grey levels (256 kcolours); 256 grey levels (16.7 Mcolours) are customarily assumed in most applications. Although several alternatives have been proposed [13,14], regular FLC displays can only produce grey levels by spatial or temporal dithering, i.e., sharing either the pixel area between several subpixels or the frame time between ON and OFF states. These dithering techniques increase the number of addressed subpixels (spatial) or reduce the frame time (temporal). In either case the data rate required for any given application is substantially increased. Data rates as high as 2 Gbps may be required to provide true colour (24 bits) in a high definition (SXGA) video rate application.

2.2. Analogue switching

Several ferroelectric families, like antiferroelectrics and V-shape smectics, show intrinsic analogue greyscale. This is a decisive advantage for these materials to be employed in high-end displays. Figure 2 shows the electrooptical response of these two materials when driven by low frequency AC voltage signals of different amplitudes. V-shape smectics show thresholdless switching, the greyscale being developed at low voltages. Tristate antiferroelectrics develop greyscale above a voltage threshold. Grey levels can be stabilized by applying a constant DC voltage (bias voltage) below a threshold. Bias voltage is the same for any grey level, this is important because bias voltage is then compatible with passive multiplexing. The greyscale voltage range in both cases is just a few volts, therefore it can be generated with standard electronics.

As it can be seen in Fig. 2, V-shape smectics do not show hysteresis. Grey levels are kept as long as the correct voltage is applied to every pixel. As a consequence, multiplexing of these materials requires the use of active matrices. Tristate AFLCs, on the other hand, can be driven either with active or passive matrices, for grey levels can be maintained over the whole display with a constant DC voltage.

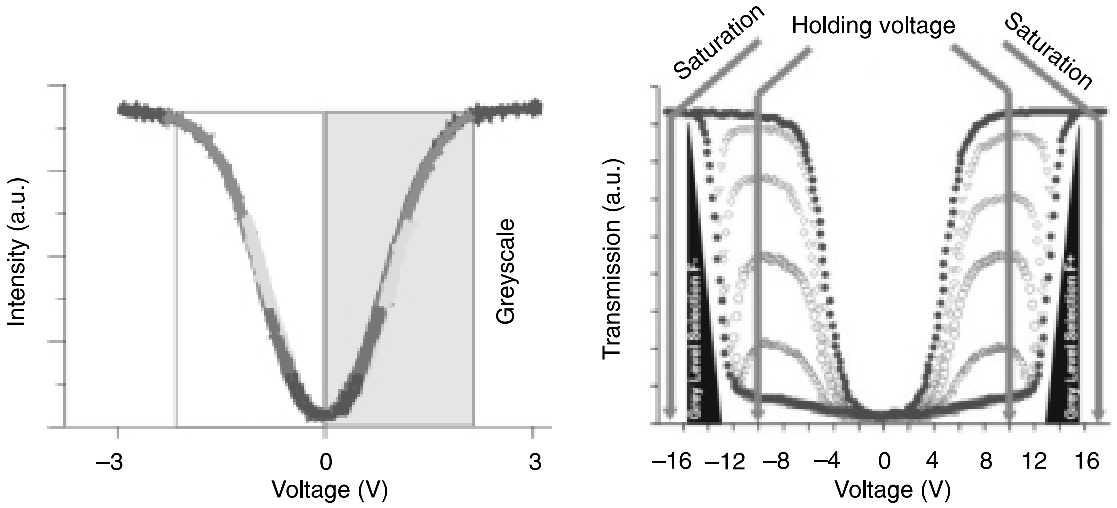

Fig. 2. Electrooptical responses of two ferroelectric families showing analogue greyscale: left, V-shape smectic; right, tristate antiferroelectric LC.

Switching time is another essential feature for any LC material to be used in high-end displays. Switching times of all kinds of surface-stabilized FLCs are significantly lower (5–50 μs typically) than nematic switching times. The V-shape and tristate AFLC cases are less straightforward. Indeed, their switching times are similar to other FLC families (regular FLCs, for example). However, achieving the 0-volt state requires the absence of external voltage. This relaxation process is significantly slower than switching. To overcome this problem, the driving waveform must include voltage signals performing forced relaxations of switched materials.

2.3. Contrast in V-shape and AFLC displays: the pretransitional effect

Contrast in V-shape smectics is excellent too (> 100:1), as in regular FLC displays. However, contrast in tristable AFLC displays is only fair (30:1–40:1 typically). The contrast ratio is impaired by light leakage in the dark state. This is in turn attributed to a phenomenon called pretransitional effect (PE, Ref. 15). The most noticeable consequence of PE is that the dark state transmission obtained in the AFLC → FLC voltage-induced phase transition is higher than the transmission at zero voltage as long as a bias voltage for grey level stabilization is employed. Although this leakage does not invalidate the tristable approach, it certainly limits its use in applications demanding high contrast. Two different solutions have been proposed to circumvent the problem: either using V-shape materials showing thresholdless switching or using orthoconic antiferroelectrics.

The first solution is equivalent, in practice, to an enhancement of PE; this enhancement, nevertheless, is used to generate the greyscale itself. V-shape smectics were formerly known as thresholdless antiferroelectrics [16]. Although much work has been done to demonstrate that V-shape materials cannot be ultimately considered regular AFLCs [17,18], the fact is that V-shape responses are found in AFLC materials when external parameters such as manufacturing conditions, frequency, and temperature are modified. Anyhow, the lack of hysteresis precludes passive multiplexing of V-shape smectics; as mentioned above, V-shape multiplexing requires an active matrix to address the display.

The second solution takes advantage of the excellent dark state shown by orthoconic materials. Passive and active multiplexings are possible, and waveforms are substantially the same as in regular antiferroelectric displays [19].

3. Multiplexing V-shape and antiferroelectric displays

3.1. Analogue greyscale in AFLC displays

The intrinsic bistability of regular FLC displays is a clear advantage for multiplex driving, but precludes the generation of grey levels. These are necessary to produce a full colour gamut, a must in high-end displays. Besides their arguable display quality, AFLCs show intrinsic analogue greyscale. This is one of the main advantages of these materials. The greyscale generation is compatible with passive multiplexed addressing. The use of an analogue greyscale, in principle, enhances the display performance as compared to dithering techniques. Moreover, the data rate is substantially reduced: the data rate of the display mentioned above would be brought from 2 Gbps down to 250 Mbps if analogue greys are used. Actual data rates depend on whether and how AD/DA converters are employed in driving electronics. The use of AD/DA conversion notwithstanding, the required rate of analogue data pulses for display columns is reduced down to the above mentioned figure.

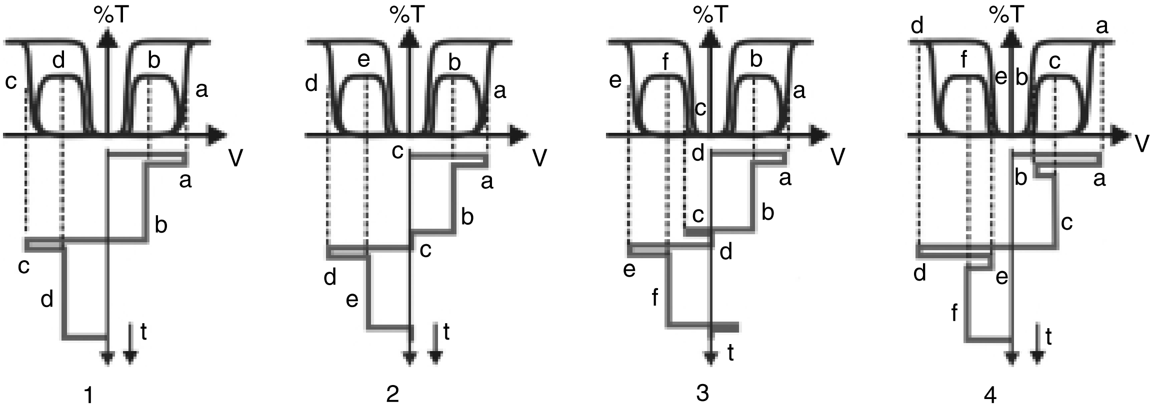

Fig. 3. Addressing waveforms for passive AFLC multiplexing. 1 – Simplest selection-bias waveform. 2 – Same as previous, including a reset time to allow the material to relax between frames. 3 – Waveform proposed by our group. It includes a well pulse (c) to force the relaxation. 4 – Waveform proposed by Okada group based on blanking through saturation.

Figure 3 shows several passive addressing schemes for AFLC multiplex driving. The hysteresis cycle is presented for reference, while time axis increases downwards. Waveform 3.1 is a simple selection-bias scheme. Grey levels are selected (a, c) and eventually stabilized by bias pulses (b, d) along the frametime. Selection is performed through AFLC → FLC voltage-induced phase transition. This scheme, however, shows memory effect, i.e., the grey level achieved in one frame depends on the grey level of the previous frame. To avoid memory effect, the pixel must be erased between consecutive frames. Waveform 3.2 includes a reset time (c) to allow relaxation of the pixel through an FLC → AFLC mechanism in the absence of applied voltage. This waveform can be used for low rate applications; however, it is not satisfactory for applications requiring high frame rates (e.g., video) ca. room temperature, since reset time must be extended several ms to allow full relaxation of the AFLC material. This problem can be circumvented by forcing the relaxation with a counter-pulse (well pulse) previous to reset time. The resulting waveform [20], proposed by our group, is shown in section 3.3. An alternative waveform, shown in section 3.4, was proposed by Okada *et al.* [21]. It is based on interframe saturation (a, d) of the pixels. This addressing scheme is faster than the previous ones, as it does not include any slow relaxation step. However, the achieved greyscale is less satisfactory.

Other waveforms have been recently proposed [22] to speed up further the AFLC response. This is specially important in orthoconic AFLC materials. The electrooptic behaviour of these materials is similar to the behaviour of any other AFLC, in particular, they can be addressed with the same driving schemes as regular AFLC materials. Orthoconics have been extensively studied in the last few years [23] to improve performance of AFLC displays taking advantage of their far superior contrast ratio. However, actual orthoconic materials usually show poor dynamic response. New waveforms allowing passive multiplexing of orthoconic displays at video rate are presently being developed.

Shortly after the advent of antiferroelectric materials, a number of prototypes were built. Nippondenso [24] developed a video-rate, full colour, 6” display for car navigation systems and a 17” full colour flat panel display for desk tops, while Citizen [25] showed a monochrome VGA 5.5” prototype. None of these became a commercial realization, mostly due to the poor contrast exhibited by regular AFLCs. Once orthoconic materials are available, it is expected that a renewed interest on development of passive AFLC displays will arise. At present, a helmet-mounted display prototype for enhanced reality and external data supervision is being developed for firefighters [26].

3.2. Analogue greyscale in V-shape smectic displays

V-shape smectics do not show hysteresis; any positive or negative voltage applied to a V-shape cell produces a transmission variation. Saturation is usually achieved in less than 5 volts. This thresholdless IPS switching arises the possibility of using V-shape materials as an alternative to standard nematics in high-end applications on active matrices. Indeed, their ferroelectric nature gives them an excellent dynamic response whereas their IPS switching yields a wide viewing angle. Several direct-view display prototypes have been presented [27,28], however, no commercial products have been presented yet, mostly due to the lack of suitable materials showing long-term electrical and chemical stability. Nematic displays, in the meantime, have remarkably reduced the advantage in dynamics and viewing angle.

Other possibilities for V-shape materials have been explored. Specifically, their use in photonic devices such as spatial light modulators (SLM) [29] has been proposed. V-shape microdisplays have also been proposed for projection applications [30]. In both cases, the devices employ liquid crystal on silicon (LCOS) active matrices, as opposed to TFT matrices. LCOS matrices are prepared in standard silicon wafers, and metallized to work in a reflective mode. V-shape LCOS devices can work over 250 Hz, i.e., four times the 60-Hz video frequency. As a conse-

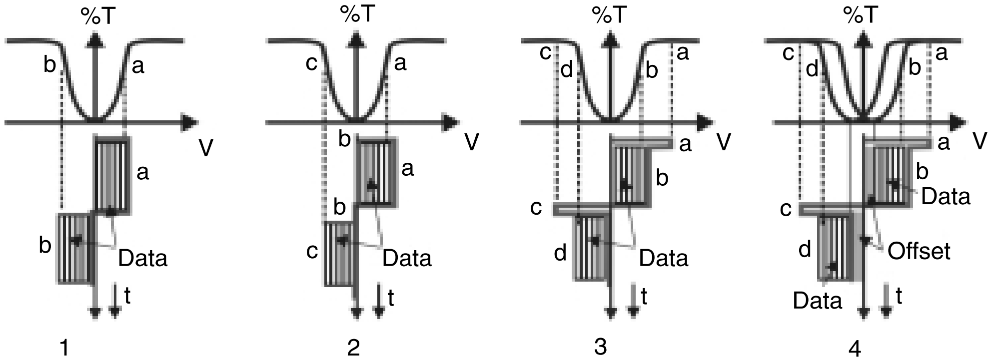

Fig. 4. Addressing waveforms for active V-shape multiplexing in LCOS matrix. Monopolar data and sequential colour are assumed. 1 – Simplest waveform, containing just data stored in the active matrix. 2 – Same as previous, including a reset time to allow the material to relax between frames. 3 – Waveform proposed by our group. It includes an erasing pulse (c) through saturation. 4 – Same as previous, including an offset voltage to compensate W-shape. Waveforms 3 and 4 can be used together if the material response varies from V to W.

quence, colour dithering can be applied: the LCOS microdisplay is sequentially illuminated with RGB lights arising from coloured flash lamps or a colour wheel. In this way, all pixels are used for every RGB subframe and the use of expensive colour masks is avoided.

Figure 4 shows a number of waveforms designed specifically for driving V-shape materials on LCOS devices employing colour dithering. Assuming monopolar data, waveform 4.1 simply compensates for polarity the positive and negative cycles. Waveform 4.2 merely adds a reset time (b) to allow interframe material relaxation. Waveforms 4.3 and 4.4, proposed by our group, deserve a more detailed explanation. It has been found that V-shape response may evolve to other electrooptical responses showing some residual hysteresis. The hysteresis becomes apparent by modifying the V-shape to a W-shape. This is a common feature of all V-shape materials, depending on manufacturing conditions, and external parameters such as temperature and frequency of the applied signals. Consequently, any driving scheme for actual devices must be able to cope with both, V-shape and W-shape responses, unless the display environment is carefully controlled. The last two waveforms of Fig. 4 are actually the same: waveform 4.3 is used for V-shape response and waveform 4.4 is used for W-shape response. A saturation peak (a, c) erases the pixel between frames, and allows migration from one branch to the other in the W case (otherwise the response remains in the same branch becoming non-symmetric). Both waveforms can be implemented together in the electronic drivers; an external feedback signal modifies the offset voltage, either manually or automatically, as required by the presence of residual hysteresis.

4. Conclusions

Both, tristable AFLC and V-shape smectic displays, are promising alternatives to existing products in the high-end segment of flat panel displays. At present, LCDs are experiencing a remarkable spread over a number of new applications, especially in consumer electronics products like large area LCD TV. The excellent dynamic response and viewing angle of ferroelectrics displays could be decisive to become the preferred option in a number of applications for which these materials could compete advantageously with current flat panel display technology. However, it is necessary to improve existing materials and some critical manufacturing steps, e.g., those related to material alignment. This issue is especially important in most recent antiferroelectric families such as orthoconic AFLCs.

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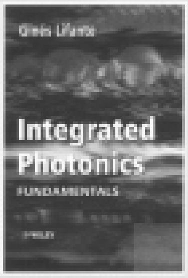

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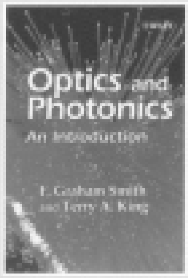

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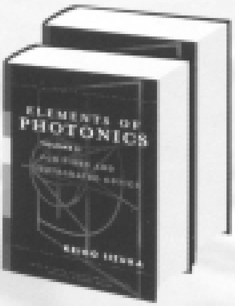

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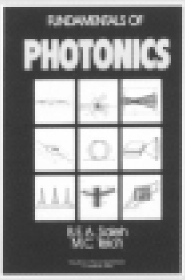

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