Future LC Technologies

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Abstract

Some nematic (NLC) and smectic based devices which have the potential to enable enhanced LCD performance are reviewed.

Introduction

Due to the extreme success of STN and TFT-TN many forget that it is possible to consider LC technology [1] as not fully matured, but to consider that these known LC technologies (and their commercialisation) are simply a proof of principle for the application of LCs to displays. If we start at this premise and then consider the available LC modes and phases, as well as the display-challenged areas of society then we soon realise the importance of continuing research into novel LC modes, but also the importance of identifying market needs and opportunities that these can create.

1. The Function of the System

There is not an end market for displays, the market is for systems that provide the customer with either a replacement for an existing function or with a function not previously available. For example once TFT-TN technology had developed to give high yields of high quality, full colour, small displays (3" to 6") they were incorporated into systems giving new functions to the customer and in turn realising an effective market. ViewCam is such a system, by replacing the viewfinder with a display of suitable size the video camera became a more flexible tool. Already we have experienced the symbiosis between medium size displays and the laptop market, a similar but less necessary effect may occur in the desktop market for medium-large displays, but in unrestricted spaces CRT may still dominate. One may then look for other single user desktop functions that can be built advantageously with LC panels; 3D capable displays[2] have one such function allowing specialised software for CAD, molecular modelling, medical imaging and perhaps simply overlaid windows to be used.

2. The Function of the LC Mode

There are perhaps three routes to improve LC modes over those already existing. The first is to identify a performance limitation of a mode and to add this function (i.e. solution) into the display module to circumvent it (e.g. using film compensation to remove the chromaticity of STN). The second is the inverse of the first, to identify a cost limitation in a display module and remove it by transferring the function from the module into the LC mode (e.g. replacing TFTs with a bistable LC mode). The third is to build an enabling, creative function into the display module / LC mode (e.g. a flexible display).

Here we discuss a few liquid crystal technologies and modes which fall into the above three classes. For brevity most examples are applicable to the area of direct view LCD.

3. Potential Active Matrix Addressed LC Modes

(i) Non-Twisted Nematic Based LC Modes.

Early active matrix TN displays had quite poor viewing angle characteristics particularly for intermediate greys. One of the major contributions to this poor performance is the zenithal (out-of-plane) switching that these devices yield under the application of transverse fields. In a similar way to the achromatic function being added to STN panels, the function of wide viewing was incorporated into TFT-TN panels by the use of additional, often complex, retardation films between the TN and the polarisers. In the Sharp SuperView technology this approach has led to excellent viewing characteristics of +/-70° horizontal. Of course such technology adds expense to panel production, an alternative is to look for NLC modes that are intrinsically wide viewing angle. One suggestion [3)] was to use an electrode structure to give lateral (in-plane) fields, this has recently been demonstrated in the N-IPS [4)], giving similar viewing characteristics with an added advantage of a flat transmittance verses off-axis angle. Unfortunately this device not only leads to a reduced aperture ratio but also has a typical time constant of

$$\tau_{off} \approx \frac{\gamma_1 L^2 d^2}{\left(L^2 + d^2\right) K_{22} \pi^2} \approx \frac{\gamma_1 \ d^2}{K_{22} \pi^2}$$

where L,d are the inter-electrode gap and the cell thickness and K_{22} is the twist elastic constant, typically 50% lower than the splay and bend constants that govern the relaxation of the TN (though flow coupling is reduced.) However with careful optimisation reasonable brightness and switching might be achieved [5)]. Further issues are associated with running the device normally black compromised with threshold behaviour, AR, off-axis colour shift and suitable materials for TFT driving. Though the N-IPS is potentially a beautiful wide-viewing angle mode, other IPS modes remain interesting.

A more tentative option is the flexoelectrooptic effect in short (c.f. the wavelength of light) pitch cholesterics [6)], the helical axis of which is aligned to lie unidirectionally parallel to the walls of a cell. On application of a transverse applied E-field the local directors undergo a rotation perpendicular to the field giving a periodic distortion with resulting flexoelectric polarisation parallel to the E-field. Associated with this is a rotation of the macroscopic optic axis, again in the plane of the cell. The sign of the field clearly defines the direction of rotation whilst the magnitude of the field defines the size of the rotation φ[6]

$$\varphi = \frac{e_s + e_b}{(K_{11} + K_{22})q} E$$

e_s, e_b are the flexoelectric coefficients, K_{ii} the elastic constants, q the helical wavevector and E the applied field. This leads to a quite temperature independent induced tilt of the optic axis (since both K_{ii} and e ~ S^2, whilst pitch can be compensated by mixing), but maintaining an in-plane helical axis ($\Delta\varepsilon$=0) and obtaining low voltage switching (high flexoelectric coefficients) make the material requirements here somewhat difficult. However similar analogue in-plane switching to transverse fields can be found in a variety of smectic devices and these are discussed later.

The colour function is added to most existing panels spatially i.e. a mosaic of filters is placed in front of the LC. This has the disadvantage of reducing resolution (/increasing driver and/or TFT number), increasing cost and reducing brightness. An alternative is to introduce the colour function temporally. To do this effectively requires fast modes which can switch between greylevels faster than 10ms and preferably faster than 1ms. Nematic devices in which the majority of director reorientation under field occurs in thin regions near the boundary plates (so called surface mode devices) can show such high speed switching [7)]. One particular case is the pi-cell [8)], comprising an NLC disposed between parallel rubbed polyimide alignment layers, sandwiched between crossed linear polarisers whose polarisation vectors are at 45° to the optic axes of the LC layer. The device is switched, in a bend or twist state, between two finite voltages giving some off-axis optical self compensation and millisecond order switching. At a lower voltage an unwanted H-state (splay) nucleates, but this can be avoided in display operation. The utilisation of pi-cells in field sequential full colour AMLCD has recently been developed [9)]. The fast switching (frame rate) function of this LC mode allows the colour function to be advantageously relocated to the temporal domain. Other fast surface mode devices may also be used, though, like the pi-cell, most will still require viewing angle compensation films.

(ii) Smectic Based LC Modes.

We have seen above examples in which at least either one of two cost limiting functions of an LC module (viewing angle compensation films & colour filters) can be alleviated by changing the NLC mode of operation. Of the three modes described, it is perhaps only the nematic flexoelectro-optic effect that has the potential to simultaneously satisfy both the wide viewing cone and fast switching criteria. However, in that device, the material difficulties associated with maintaining an in-plane helical axis and obtaining low voltage switching are clear. In smectic materials these issues are simply avoided. We discuss the deformed helielectric effect [10)] and thresholdless antiferroelectric LCs (TAFLCs).

In one embodiment of the helielectric effect a short-pitch chiral tilted smectic phase (typically Sc*) is aligned with its helical axis unidirectional and in the plane of the display, however unlike the equivalent N* device the helical axis is fixed by the layer normal, whilst the polarisation exists spontaneously and is easily tuned. On applying a transverse field the helix deforms giving an associated nominal change in effective birefringence and rotating the macroscopic optic axis by upto +/- the molecular tilt angle. Arranged between crossed polarisers this device then gives fast switching, wide viewing angle, low operating voltages (~5-10V), and repeatable analogue greylevels. Some difficulty can occur processing alignment layers to allow the helix to remain undistorted and hence the LC texture defect free @0V (to give high CR). A further disadvantage is the typical need for high spontaneous polarisation and resulting non-standard addressing architectures / methods.

The TAFLC is a recently discovered smectic phase [11)] showing tilted molecular alignment in each smectic layer, with intra-layer correlation but without interlayer correlation. This ordering has currently been described based on discrete layer models [12)], although other approaches (e.g. [13)]) remain to be investigated. Similar to the helielectric device it is possible to configure this phase such that the smectic layer normal (and hence the effective optic axis) is unidirectionally aligned in the plane of the cell. Again applying a transverse field rotates the optic axis about the field direction. Such a display has already been reported [14)]. Due to the presently limited knowledge of this phase it is unclear whether it can overcome some of the difficulties inherent in the helielectric phase (e.g. what Ps is required for suitable modulation, process tolerant alignment etc), however it is clear that both these in-plane smectic modes exhibit many possibilities.

4. Potential Passive Matrix Addressed LC Modes

(i) Non-Supertwisted Nematic Based Modes.

STN LCs intrinsically have the function of a non-linear response, the possibiltity of avoiding the use of TFTs and building a switch functionality into the LC mode occurs in multi- or bi-stable devices. Recently many such nematic based devices have been discussed and some of these demonstrated, with additional benefits.

In 1980 Berreman and Heffner described the 360° Bistable Twisted Nematic device [15)]. Typically in this device two substrates are arranged in an antiparallel rubbed geometry and chirally doped to favour ~180° twist, this twisted state then would cost splay energy. Two metastable states of 0° and 360° twist also exist and switching between these two is used in the display. The Δnd and orientation of the device between substantially crossed polarisers are chosen such that the 360° state appears black and the 0° state appears white. When a large voltage is applied a homeotropic 0° state is energetically favoured, on removing the voltage the director at the cell centre couples to the backflow (this dominates elastic torques as the director in the bulk of the cell was essentially uniform under high voltage) which can act to rotate the director beyond the homeotropic condition allowing relaxation into the 360° state. As indicated by Berreman by controlling the voltage pulse occurring after the blank to 0° relaxation into either of the two states is possible. A demonstrator panel based on this effect has recently been shown by Seiko-Epson [16)]. Interesting physics questions remain related to the device performance. These include the optimum elastic constants, pitch and boundary conditions for tuning the lifetime of the 0° and 360° (or ϕ° and ϕ° +360°) states, design and optimisation of temperature insensitive waveforms (at the simplest the position of the address pulse with respect to the blank) and perhaps most intriguingly the anisotropy as well as the magnitude of the viscosities may for the first time be important. Comparison with the recently suggested 0° to 180° BTN [17] also remains to be made, though unlike the previous device this requires unequal anchoring strengths at the two surfaces.

For both of these volume bistable devices the two switched configurations have distinct twist profiles, these may therefore be classed as azimuthally bistable. It is also possible to produce azimuthally bistable devices through surface bistability [18]. These devices typically have two uniform states to lead to considerably better optical performance than that available from the twisted devices above. Flexoelectric, chiral ion and others [19] have been used to select between these states. One major difficulty in fabricating such devices is the production of surfaces that support such bistable states (+/-φ_0) , by noting that the azimuthal energy of a bigrating surface

$$E \propto \left\{ \sqrt{\left(1 + k\cos^2\phi\right)}\cos^2\phi + A\sqrt{\left(1 + k\sin^2\phi\right)}\sin^2\phi \right\}$$

can be tuned by varying the relative energy, A, of the two basis gratings, it has recently been demonstrated [20] that topologically defined surfaces can fulfil this role. These surfaces give the required elastic characteristic to the surface energy, but finding a surface without a plastic [21] constraint has proved difficult [22], currently limiting the possibility of displays based on this technology.

Zenithally bistable devices (i.e. those in which the two switched states have a different tilt profile) have also previously been reported [23) 24] and more recently one that builds upon the topological alignment techniques above and earlier [25]. In this ZBD [26], one surface is flat whilst the other is typically a blazed grating, both being coated with a homeotropic alignment agent. For certain depth-pitch ratios this leads to two stable states, one is substantially homeotropic, whilst the other is a splay-bend state similar to that of a HAN. Selection can again be affected by flexoelectric coupling achieving millisecond line times for about 20V. Storage stability of the two states compared with that of the 360° BTN is aided by the formation and creation of defect lines in switching between the two states, thus introducing a new enabling function (of image storage) to the display. The opportunity to model the dynamics of sytems including disclinations using a modification of the Ginzburg-Landau equation

$$\gamma\frac{\partial\psi}{\partial t} + \nabla^2\psi + k\psi\left[|\psi|^2 - \left(|\psi_u| + |\psi_b|\right)|\psi| + |\psi_u||\psi_b|\right] = 0$$

(where $\psi=\sqrt{3}Se^{i\phi\sqrt{3}}$ and S is the order parameter and f the director orientation) has recently been suggested [27], but still remains to be applied to such devices.

(ii) Smectic Based LC Modes.

The potential of the myriad of bistable nematic configurations for application to storage or high definition, non-video rate displays is obvious. However, by definition bistable devices are digital and therefore can only display greylevel images by dither techniques. This necessitates the requirement for fast response (i.e. microsecond line address times) or the potential to induce a temperature insensitive multidomain structure to achieve high definition video rate displays. The first of these options can be achieved with surface stabilised ferroelectric liquid crystals (SSFLC) [28]. A combination of the first and second may be achieved with hysteretic AFLCD [29].

Some of the device aspects of SSFLC are discussed in detail elsewhere in this journal [30], however it is worth recalling some of the important physics problems, particularly for SSFLC, which still remain to be completed. These include the role of material parameters on the relative stability of the two possible chevron states [31], domain nucleation control [32] and shape [33], domain wall dynamics[34] and appropriate continuum theory [35]. All of these could have a direct bearing on display optimisation, performance and durability.

In hysteretic AFLCD the molecules in one smectic layer all tend to tilt in one direction, the tilt alternating sign from one layer to the next to give a macroscopic optic axis parallel to the layer normal. On applying a DC voltage greater than some threshold all the molecules tilt towards the same direction, at an intermediate voltage both the alternating tilt (AF) and uniform tilt (F) orderings are stable. Furthermore multidomain states are also stable at this intermediate voltage allowing some analogue greyscale to be introduced.

Both these passive smectic technologies then offer advantages over their nematic counterparts, particularly when applied to complex, video rate, full colour displays.

5. Hybrid Technologies

LC on a-Si TFT has been a successful hybrid between semiconductor and liquid crystal materials, the required addressing functionality of the panel being shared between the characteristics of the two materials. These possibilities are already being extended by changing the semiconductor to single crystal or poly- Si, allowing e.g the potential integration of functions such as memory, voice and optical IO onto the panel itself. More interestingly other display hybridisation is also occurring, one example is the plasma addressed LC (PALC) display.

Tektronix demonstrated the potential of plasma addressed liquid crystal displays [36], more recently taken up by Sharp, Sony and Philips. In this, ionised gas channels replace the TFT matrix as the functional active element allowing the possibility of very large area NLCs to be achieved. In the ionised state the gas is typically ten orders of magnitude more conducting than in the deionised state, and when used in conjuction with a three electrode geometry a plasma switch is readily fabricated, and simply applied to large area panels. In essence most LC modes which are compatible with standard TFT matrix structures can be applied to large area plasma addressed panels.

Another fruitful approach is to consider what the advantages of competitor emissive technologies are over the optical shuttering approach of LCD and merge these together. For example photoluminescent LCDs [37)] use LC displays to modulate the amount of activating light falling on a phosphor screen. The phosphor emission gives a broad colour gamut and wide viewing angle, whilst the LC mode can be optimised for a narrower spectrum.

6. Future Challenges

Undoubtedly there remain LC display challenges still to be identified. Currently two of the hardest are flexible and video rate bright reflective colour displays. Limited progress has been made on the former [38)], whilst the latter is making some useful steps by considering dye-guest host with colour filters, multi-layer dye guest-host panels [39)] and single-polariser devices [40)]. However none of these options as yet satisfies the desire for a video photograph.

7. Predictions

LCD technology has proven itself using STN and aSi-TFT-TN technology; at the high image quality market- end enabling (and being sold through) products such as laptop computers, handheld and small area TV, ViewCams and LC projectors. All of these areas will continue to improve, function being added to laptops (e.g. accurate touch-sensitivity), improved efficiency to projection systems, overall image quality to ViewCams and handheld TV.

In the near future we can expect to see LCDs; reaching the markets of direct view large area TV and HDTV, beating CRT for the desktop market (including 3D capable), bright reflective multi-colour displays, digital HMDs and microprojectors. These markets will allow hybrid technologies other than αSi-LC to develop.

We will also see some of the above being manufactured using smectic LC phases, particularly antiferro- and ferro-electric Sc materials. At the same time more exploratory novel device structures based on nematic LCs may appear, including in-plane switching and multistable configurations. As outlined above these newer smectic and nematic devices still require further physics understanding for full optimisation.

In the medium and longer term video rate full colour bright reflective LCD and flexible LCDs remain to be developed and integrated. Though fundamentally very hard targets, with elevated scientific understanding, improved fabrication techniques and device hybridisation they will be achieved.

Conclusion

We have suggested that there are three routes to improve LC technology / products over those existing

(i) add a function (i.e. solution) to an LC module to circumvent a performance limitation of the LC mode

(ii) replace a function of the module by a function in the LC mode so reducing cost

(iii) introduce a new enabling function into the module / LC mode.

By considering examples **(Fig. 1)** of each of these we have shown that, although we must respect that which the simple twisted nematic mode has allowed to be achieved (particularly when coupled to the astonishing fabrication levels of STN and aSi TFT production), when we view the breadth of other existing and theoretically predicted LC modes and phases it is inevitable that many more display enabled products can and will be generated.

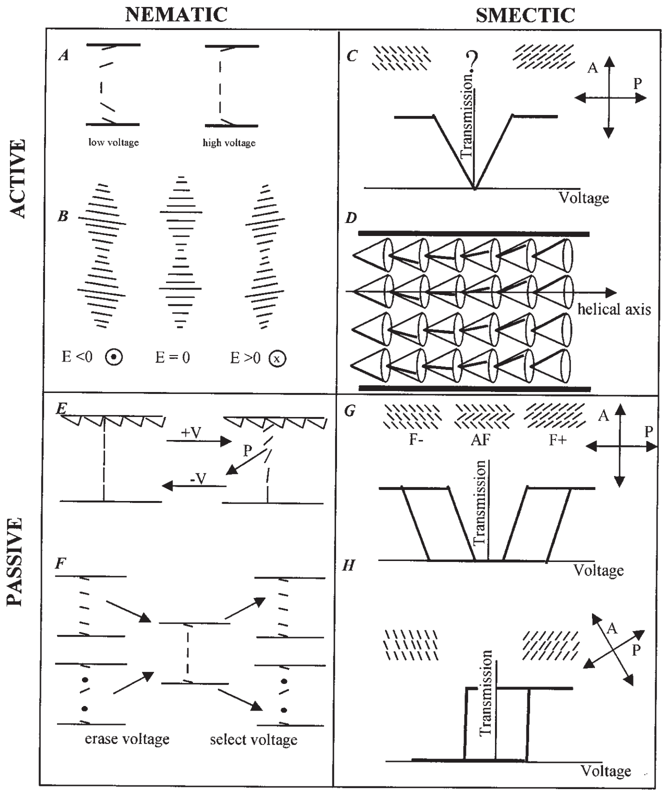

Fig. 1 ***A*** **Side view of pi-cell,** ***B*** **Plan view of flexoelectroopic Effect,** ***C*** **Plan view and optical response of thresholdless antiferroelectric LC,** ***D*** **Side view of 0V state of helielectric mode,** ***E*** **Side view of operation of zenithally bistable device,** ***F*** **Side view of operation of bistable twisted nematic,** ***G*** **Plan view and optical response of hysteretic antiferroerlectric LC,** ***H*** **Plan view and optical response of surface stabilised ferroelectric LC.**

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