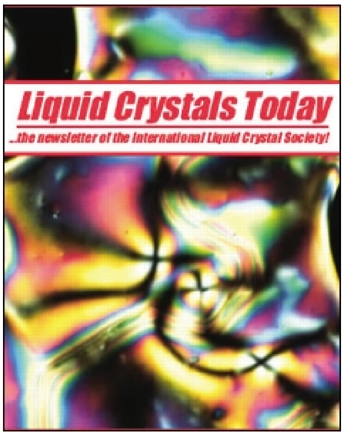

Liquid Crystals Today

Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713681230

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To cite this Article Lagerwall, Sven T.(1996) 'Ferroelectric Liquid Crystal Displays with Greyscale', Liquid Crystals Today, 6: 2, 5 — 7
To link to this Article: DOI: 10.1080/13583149608047641
URL: http://dx.doi.org/10.1080/13583149608047641

Ferroelectric Liquid Crystal Displays with Greyscale

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Having presented a range of powerful FLC display prototypes (among them a 24" monochrome, a 21" colour and several different 15" screens) Canon Inc. in Tokyo is now manufacturing their first commercial FLC product. It is a colour panel with 15" (38 cm) diagonal with a resolution of 1240 × 1024 picture elements. Each such element (230 μm × 230 μm) can produce 16 different colours due to its subdivision in four parts. When writing a picture a large number of hues can be simulated (32000 or 26000 are stated for the two different versions marketed) by a graphic so-called error diffusion technique. In general this gives a very good rendition of colour images but in certain cases the differently coloured single dots, which can be seen when the observer is very close to the screen, may be disturbing. The origin of this inconvenience is of course the fact that each subpixel only has two states; it cannot produce a continuous grey scale.

Although the Canon FLCD is not widely marketed yet outside Japan, I have it on my desk (it can be purchased for 4150 US$) and it is a delight to work with. It is bright and of excellent contrast but the outstanding quality is that the picture is absolutely calm: there is no trace of direct or indirect flicker (a result of bistability in FLC). This is so uncommon and striking that you cannot avoid noticing it after a few minutes in front of the screen. In Sweden where ergonomic factors are considered very important this is a definite asset. The operating temperature is from 10 to 35°C (50 to 95°F) and the storage is from –15 to 60°C (5 to 140°F). The power consumption lies in the range of 5–10 W, being maximum when you go from a completely white to a completely black screen or vice versa, because then the full polarization has to be reversed. This can be compared with the power consumption of the backlight, consisting of four fluorescent light tubes, lying in the range of 70–80 W.

Nevertheless, this screen is a result of a number of compromising considerations which had to be taken. For instance, already in 1989 Canon presented a monochrome panel of the same size which had the attractive hemispherical viewing angle connected with the fact that the optic axis when switched from one state to the other moved in a plane parallel to the screen surface. Nowadays this is called 'in-plane switching' and is a feature which is inherent in the original idea of the surface-stabilized (SSFLC) structure. This is not changed *per se* if the layers are in a chevron rather than a bookshelf configuration. However, in the first Canon prototype it turned out that the C1 chevron state became unstable and partly transformed to C2 at low temperatures. In order to avoid this, and also in order to increase the contrast sufficiently for colour, the zero pretilt surface condition was abandoned, and to stabilize the C1 state Canon had to go to extremely high pretilt values of more than 20 degrees.

Due to the high pretilt, the viewing angle of the FLCD, though very good, is no longer hemispherical, and in order to have the C1 configuration stable at any temperature, the intrinsic tilt angle of the material cannot be optimized but has to be kept as low as about 11 degrees (instead of 22.5 degrees matched to an ideal bookshelf structure). This limits the achievable transmission and contrast. In order to prevent ghost pictures at low temperatures the value of the spontaneous polarization has to be kept low (of the order of 10 nC cm^{-2}) which limits the achievable response speed. Hence, whereas the Canon FLCD in many respects represents the state of the art in today's LCDs, there is evidently quite a difference between its performance and the potentially available performance that the FLC materials would intrinsically permit. A further important point is whether FLC permits a true grey scale or not.

FLC is the GaAs among liquid crystals

When Robert B. Meyer in 1974 realized from symmetry reasons that a tilted chiral smectic would have a local polarization sterically connected to the director in each layer, and when subsequently such materials were synthesized by L. Liebert, L. Strzelecki and P. Keller [1], these were the first polar liquid crystals and as such something really new. Of course smectic C* materials had been synthesized 'accidentally' before, e.g. already in Vorländers' group in Halle, but no knowledge about their polar properties existed before 1974. Smectic C* materials are not automatically ferroelectric but they can always acquire this property in certain configurations (SSFLC). Ferroelectricity is, however, not a bulk property in liquid crystals. This fact, together with the intrinsic polarity and the low symmetry of the smectic C phase (it has for instance 9 elastic, 10 flexoelectric and 20 viscous coefficients) places this material on a completely different level of complexity than the nematic materials used in common displays. On the other hand it is clear that there is a considerable unexplored potential in the chiral smectics. The situation is somewhat reminiscent of the case of gallium arsenide and related materials among semiconductors, in relation to silicon. Silicon today completely dominates the scene although its limitations are well known, as is the potential of GaAs with its much higher mobility and corresponding higher frequency limits. But the processing of GaAs is complicated and the yield low. In fact, III–V compounds in principle offer the best solutions for almost all applications, nevertheless Si is used more than 93% of the time. The worldwide investments already made in silicon technology are enormous and most companies hesitate before investing in newer materials, whatever their future potential.

In liquid crystals the investments in TFT-addressed panels controlling twisted nematics have likewise been enormous and the technology is getting more and more refined, with special solutions for almost every minute problem. The dominance of this technology is based on a combination of high volumes of relatively low quality TFT-LCDs without true grey scale and low volumes of high-tech panels with grey scale. At the same time it is probable that in the long run, the FLC potential for much higher speed, higher resolution and better viewing angle will pay off, perhaps in the combination TFT-FLC. So far, however, the interest in FLC has been pursued in university research groups rather than in industry, though the number of patent applications – more than 2000 worldwide at the beginning of 1995 – reflects the awareness of future possibilities. If controlled by an active substrate, grey levels are certainly not incompatible with FLC, but more important they are not incompatible with passive driving either.

Amplitude-controlled grey levels

The natural approach to follow for grey scale FLC is the same as in magnetic materials: by controlling the switching of a large number of microdomains, a digital technology can be turned into analogue. If the fraction of switched to unswitched domains in a single pixel can be controlled this means a controlled level of grey. This could be achieved by varying the amplitude of the switching pulse, because of the somewhat smeared-out distribution of threshold for the small domains. In magnetic materials this is relatively easy thanks to the non-existence of magnetic charges. In the electric case, however, moving charges will tend to compensate and stabilize any written picture, which results in an asymmetric hysteresis behaviour, in which the result of an applied pulse depends on the previous state.

Time-controlled grey levels

Time modulation is a second fairly natural way of introducing grey tones, but not so easy to implement except in the case of active driving. Excellent full colour miniature FLC displays have recently been demonstrated using this technique by Displaytech Inc. in Boulder, Colorado [2]. In this case the FLC layer is placed on a reflective backplane which is a CMOS VSLI chip providing ± 2.5 V across each picture element. A transistor can in principle be used for implementing microdomain grey level by charge control (a method pioneered by the Philips Eindhoven group) but in this case it is only used to write one of two states. Video colour pictures are produced at a frame rate of 76 Hz. Each frame is, however, subdivided in three pictures, one for each colour – so the actual frame rate is 228 Hz – under the synchronous illumination from red, green and blue LEDs. (The LEDs are GaN for blue and green and AlInGaP for red.) During each of the 4.38 ms long colour sequences (corresponding to 228 Hz) a grey level is now defined for every pixel by rapidly repeating the scanning of the FLC matrix a number of times with a pixel being on or off for the fraction of time corresponding to the desired level. For instance, if the matrix is scanned $2^5 = 32$ times during illumination of one colour, then 5 bits of grey per colour is achieved. This requires a scanning time (basic frame rate) of a little less than 150 μs for a matrix consisting of 1000 lines. Displaytech has presented several versions of this miniature screen, for instance one 7.7 mm × 7.7 mm with 256 × 256 picture elements and aperture ratio of 90% and some with higher resolution, up to 1280 × 1024. In the latter case the dimensions are 9.7 mm × 7.8 mm with individual pixel size of 7.5 μm × 7.5 μm. The display is viewed through a magnifying glass and may be headmounted. Obvious applications are virtual reality, high resolution viewers but also projection displays. It is estimated that the FLC/VLSI will permit 8 bits of grey in the next design of the display.

Large-area FLC screens

The method used by Displaytech can evidently be used independently of the size of the screen, when there is an active substrate. The important question is, however, whether we can implement grey levels in large screens which do not have an active substrate. Clearly the time domain is then no longer available. An interesting proposal was made some time ago by Steve Elston from Oxford [3] which has triggered this article. It turned out to be much easier to implement domain grey scale in the antiferroelectric liquid crystal (AFLC) than in the FLC, although it is exactly the same physical mechanism that is used. The attempts can be exemplified by Philips' 'texture method' in passive matrix FLC [4] and by Nippondenso's passive matrix AFLC [5] display prototypes. Both use a variation in switching pulse amplitude to control the fraction of microdomains being in the on and off state. The difference between the two cases lies primarily in the driving: in the AFLC case the display is driven by symmetrical waveforms of the same kind as in the nematic case, that is, the sign of the voltages are exactly reversed between alternate frames. In the AFLC screen this reversal has a frequency of typically 76 Hz. This is enough to substantially reduce the sticking (ghost pictures) – even for the very high P_s values of the order of 100 nC cm^{-2} typical for AFLC materials – because any polarity distribution of dipoles across the screen is not going to be locked in by ionic impurities. Elston's idea is now to drive the FLC in the same way, i.e. symmetrically, by reversing the polarity every frame. In the FLC case, however, a reversed polarity corresponds to an optically inverted picture, so every second frame must be suppressed optically, by stroboscope illumination. This loses a factor of two in both speed and brightness, but gives grey levels directly related to amplitude.

Let us now take a closer look at the use of stroboscopic illumination: why not be more radical and extend it to colour sequential backlighting, using red, green and blue. In addition to LEDs we could also implement this by colour fluorescent tubes, as originally proposed by Thorn EMI [6]. Although we lose a factor of six in time and brightness, there is no longer a need for the RGB filter which more than compensates us for the initial loss in luminosity. Moreover, there is a considerable economic gain in replacing the very costly internal RGB filter which indeed competes even with the active matrix in manufacturing costs. This also leads to a simpler cell technology (important when considering that the cell gap is 1–2 μm), to simpler electrode and spacer technology and to an invaluable increase by a factor of four in spatial resolution (cf. Canon's subdivision in four parts in every pixel). The loss in the time domain can also be compensated for, because with the symmetric driving much higher P_s values in our materials can be used without running into sticking problems. This means much faster switching. We also gain a factor of two in time when there are no subpixels: note that Canon actually has to scan 2048 rows in the 1280 × 1024 FLCD.

And there is more again. A high P_s material means that the display will work in the QBS (quasi-bookshelf) structure, because the chevrons will continually be straightened up by the addressing pulses. This is of course what happens with the chevrons in the typical antiferroelectric case. The QBS structure means that we can forget about C1 and C2 and work with a pretilt close to zero. It means that we are back to in-plane switching and the hemispheric viewing angle.

The QBS structure leads to further – quite substantial – increase in luminosity and contrast. This comes in two steps. The QBS first of all has a much higher transmission than the chevron structure. Then it is finally possible to use materials with tilt angle θ approximating to 22.5° and optimize birefringence and cell gap to correspond to the half-way condition, and thereby get a switching angle approximating 45 degrees. With these optimized materials we are also likely to be able to increase the cell gap slightly. It should be noticed that optimizations of this kind have never been possible to make so far and therefore that FLC prototypes so far have been working with effective switching around 20 degrees. The corresponding optimized materials will permit a very high transmission in the bright state. This kind of optimization on the other hand seems impossible to make in AFLCs because it would require a tilt angle of $\theta = 45°$.

Thus the symmetric driving in FLCs brings out important advantages not present in AFLCs. This is enhanced by the fact that in FLCs there is no holding voltage and no light leakage through black pixels. The excellent dark state is already a feature of present FLCDs, but combined with a much superior bright state, it will lead to considerably higher values of both brightness and of contrast (today 45:1 for Canon, 25:1 for Nippondenso).

FLC grey scale – a case for international cooperation?

Although there are several industrial projects being pursued with the hope of realizing on FLC grey scale, there is probably none so far working along the lines discussed above. This is a much more radical approach than those followed earlier. We would need new FLC materials with different parameters, and especially with much higher P_s values than those developed so far in an entirely different philosophy. The only company which to some extent has shown interest in reasonably high polarization materials is Hoechst and they have also put considerable effort into trying to understand the physics of charge transport in FLC, phenomena which will be of great importance for a development project of this kind. The non-necessity of mosaic colour filter in the design is a definite advantage in a project. A project to generate grey scale in FLC along the lines indicated could very well be set up on an international basis. It would be healthy as a balance to the TN-TFT technology without following the track of conventional FLC ideas.

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