P-26.3: Low Voltage Zenithal Bistable Devices with Wide Operating Windows

J. Cliff Jones, Steve Beldon, Peter Brett
ZBD Displays Limited, Malvern Hills Science Park, Malvern, Worcs. WR13 5SZ, UK
Matt Francis and Mark Goulding,
Merck Chemicals Ltd., NB-C, UK, Chilworth Science Park, Southampton, Hants, SO16 7QD, UK

Abstract

Key parameters for any bistable device are operating voltage and temperature range. The development of liquid crystal mixtures for use with grating aligned Zenithal Bistable Displays (ZBD™) is described for the first time. Latching at voltages less than 5V, with 20V addressing faster than 80μs per line and operation over a temperature range from -20°C to 80°C are all demonstrated in the same 4μm device.

1. Introduction

Optimisation of liquid crystal mixture properties has historically been central to the successful commercialisation of LCDs. Contemporary commercial mixtures enable higher complexity displays, either through choice of dielectric and elastic properties for passive matrix TN or STN modes, or control of the electrical properties for active matrix TFT displays.

Bistable nematic displays are no different, requiring the liquid crystal mixture to be optimised for the specific display mode. The present work outlines device improvement through mixture development for the Zenithal Bistable Device (ZBD™). A ZBD device uses a grating alignment layer [1] to give two or more stable pre-tilts of the liquid crystal director on one of the internal surfaces. The grating is readily fabricated using a simple embossing technique. All other aspects of device design are typical; from conventional drivers to cell gap. Commercially available liquid crystal mixtures have been used to date in all previous work, [e.g. 2]. In the present paper, significant improvements have been achieved, by formulating LC mixtures specifically for use with ZBD. Careful attention has been paid to reducing the operating voltages for the device, as well as decreasing the sensitivity to panel variations and increasing the operating temperature range. It will be shown that a number of key targets for operation in portable products have been surpassed.

2. Characterisation of ZBD Latching

The two states of the zenithal bistable device are termed the defect D and continuous C states, corresponding to the low pretilt and high pretilt configurations. Latching between these states occurs when an electric field of the appropriate electrical impulse (τV) and polarity is applied; a positive field applied to the electrode on the grating substrate latches to the low tilt defect state, whereas a negative field latches to the continuous state. These latching polarities are maintained for all liquid crystal materials studied, and regardless of the cell configuration (e.g. the alignment of the opposite surface) because the transitions are driven by the surface polarization associated with the grating.

When each line is addressed some pixels are required to change into the D state, others into the C state. A practical way of addressing ZBD, therefore, is to blank a line completely into one state, before selecting the other state discriminately in the line address period [3]. Results for both mono-polar and bi-polar pulse latching of the commercially available liquid crystal mixture Merck MLC-6204-000 are shown in Figure 1.

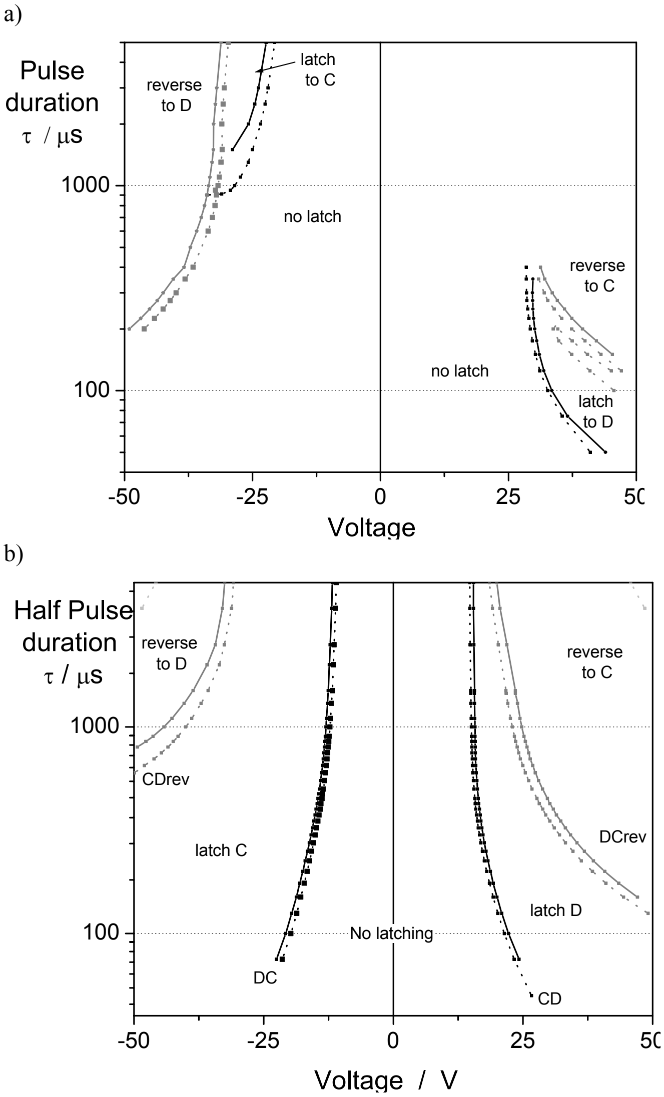

Figure 1 Latching behaviour of a commercial TN mixture (MLC -6204-000) in a 3.6μm HAN-VAN ZBD cell using a) monopolar pulses and b) bipolar pulses.

The latching behaviour is complicated by the effect of trace levels of mobile ions in the liquid crystal mixture. Both transitions from Defect state to Continuous (DC) and *vice–versa* (CD) undergo reverse latching if the pulse amplitude is too high, particularly at long pulse durations. The ions create a reverse field in response to the applied field that remains across the sample immediately after the pulse is removed. If the pulse had sufficient impulse (τV), the reverse field may be sufficiently great to latch back into the opposite state. Reverse latching sets an operating limit above which the desired image is not observed. Although the effect is not serious under normal operating conditions, it can limit performance both at high temperatures, or where low voltages and therefore longer operating pulses are used.

In the case of mono-polar pulses (figure 1a) the reverse latching may seriously impede device performance. With a bipolar pulse, however, the reverse field from the leading pulse acts to increase the effective field across the grating for the trailing part, thereby leading to significantly reduced latching voltages and wider operating windows, as observed in figure 1b). Bipolar pulses were used throughout the liquid crystal mixture development process described in this paper. This also ensures DC balance is maintained and prevents cross-talk.

It is also clear from Figure 1 that the latching characteristic can be considerably asymmetric, with $\tau V_{DC} < \tau V_{CD}$ as in this example, or *vice-versa,* depending on cell design. This asymmetry arises because of differences of the relative energies of the D and C states (which in turn depend on the grating shape [4]) and of the electric field distribution across the cell that occurs in the two states. In the case of black and white displays, the grating is designed to give asymmetric latching to maximize the blanking operating window and ensuring fast line-addressing [3]. For grey-scale and colour displays, the grating shaped is deliberately varied within each pixel to produce error-free levels, each with its individual operating window [4].

3. LC Mixture Characterisation for ZBD

Latching also depends on the liquid crystal mixture, the cell gap and the device geometry. With the original geometry of [1], the bistable grating is used opposite a monostable homeotropic surface. For a positive $\Delta\varepsilon$ material, this results in a high permittivity across the surface opposite the grating, and the electric field is concentrated towards the grating. Where a TN geometry is used [5], the opposite surface is planar, causing a slight waste of the applied field across the low permittivity boundary layer close to the monostable surface.

For these reasons, it is important to ensure that the cell geometry, grating shape and cell gap are fixed when comparing the performance of different liquid crystal mixtures. However, with small test cells, there can be large cell gap variations. Therefore, the latching results need to be corrected to allow direct mixture comparisons. Much of the electric field applied across the electrodes will be dropped across the dielectric of the grating structure itself. Approximating a typical grating, such as that shown in figure 2a, with a rectangular dielectric profile leads to the following expression for the applied field:

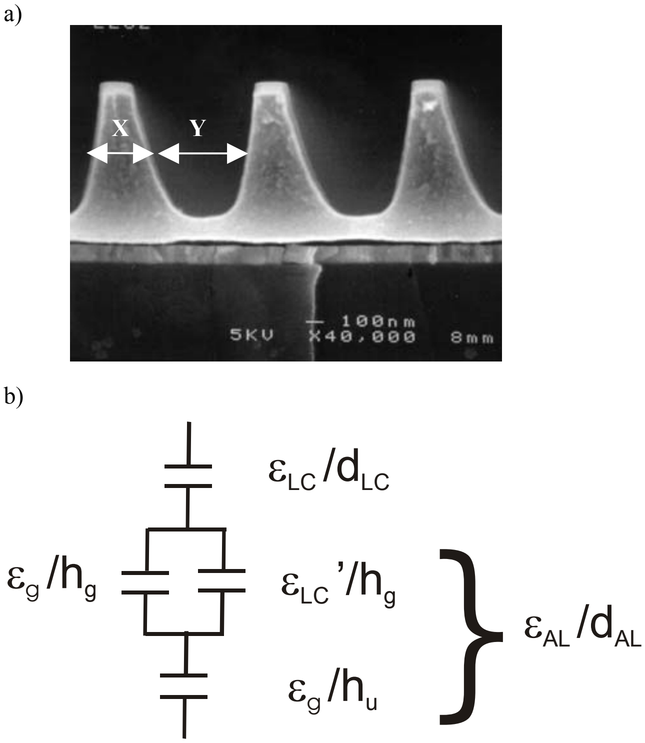

Figure 2 a) Typical grating alignment layer and b) its approximate electrical equivalent. The surface terms ε_{AL}/d_{AL} include an offset of height h_u and a rectangular grating of height h_g.

$$E_{LC} \approx \frac{V}{d_{LC} + \left(\frac{h_u}{\varepsilon_g} + \frac{h_g}{\varepsilon_g G + \varepsilon_{LC}(1-G)} \right) \varepsilon_{LC}} \qquad [1]$$

where G is the grating shape factor X/(X+Y), X and Y are the FWHM of the grating ridge and corresponding groove, respectively, as shown. Taking the factors for a typical grating and $\varepsilon_{LC} \approx 50$ then equation [1] is approximately $E_{LC} \approx V/(d_{TOT}+1.5\mu m)$, where d_{TOT} ($= d_{LC} + d_{AL}$) is the measured cell gap.

For simplicity, liquid crystal mixture performance is characterised using two parameters:

1. E_{CD}: the threshold field for the C to D transition at a given trailing pulse duration (taken to be $\tau = 100\mu s$ throughout this work);
2. ΔE_D the operating window for the defect state, taken as the difference between E_{CD} and the reverse latching E_{DCrev} (see figure 1b). This latter parameter is quoted for $\tau = 500\mu s$.

An important aim of the mixture development process is to ensure that E_{CD} is as low as possible whilst maximising ΔE_D.

4. ZBD LC Mixture Development

Satisfactory latching speeds had previously been achieved for the commercially available liquid crystal mixture Merck MLC-6204-000 (see figure 1). However, the clearing point of this mixture is 62.4°C; together with the limited operating window to reverse latching, this limits operation of the ZBD device to about 50°C. This is clearly not satisfactory for many potential applications. It was therefore important to develop new mixtures with the following characteristics:

- Increase of the nematic to isotropic transition temperature.
- Reduction of the latching field for a given pulse duration E_{CD}.
- Increase of the operating window (i.e. a higher reverse latching threshold) ΔE_D.
- Reduction of the latching temperature dependence.

An initial study was conducted using several commercial mixtures from Merck to help define a route for the material development programme. The pulse duration required for latching should follow the basic relationship:

$$\tau_{CD} \propto \frac{\gamma_1}{P_S E_{CD}} \qquad [2]$$

where γ_1 is the rotational viscosity and P_S is the surface polarisation associated with the grating. Several terms may contribute to the surface polarisation, including flexo-electric, ordo-electric, dielectric and ionic effects. Each of these terms is related to the liquid crystal dipole moment magnitude acting macroscopically. Thus, a rough trend between the latching field and the mixture dielectric anisotropy $\Delta\varepsilon$ is expected. Results for the latching field is plotted as a function of mixture $\Delta\varepsilon$ in figure 3. This shows that low voltage behaviour is possible using high Δe, polar mixtures. The correlation is incomplete because it ignores viscosity differences and other terms relevant to the latching. However, it provides a starting point for the mixture development programme.

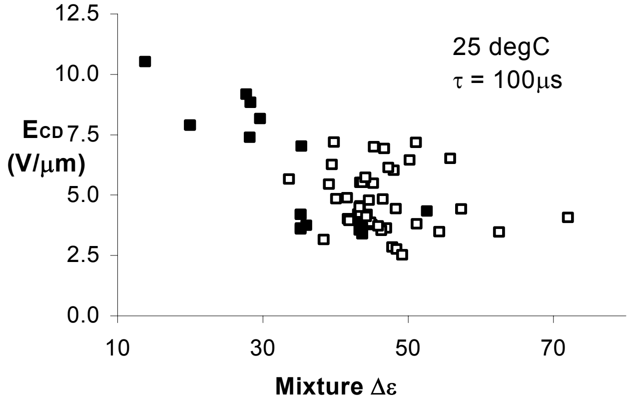

Figure 3 ZBD latching field versus dielectric anisotropy for a wide range of mixtures. Closed points represent initial results from commercial Merck TN mixtures, whereas the open points are for the newly developed mixtures.

A large number of new mixtures were formulated, as indicated by the open points of figure 3. Testing of each mixture was done using the same grating design and similar cell gaps (about 4.5μm). Component concentrations were carefully adjusted to give high clearing point (T_{NI}), low viscosity and low voltage latching of the final mixture. The improved nematic LC mixtures were formulated from typical components used in other LC mixtures commercially available from Merck. The properties for two new mixtures (labelled as A and B) are compared with those of MLC-6204-000 in table 1 below. These mixtures have birefringence values (Δn) ranging from 0.12 to 0.17. This allows the first minimum TN condition to be fulfilled for cell gaps in the range 3 < d < 5μm whilst retaining good optical properties. The 25°C latching characteristic is shown for mixtures A and B in figures 4a) and b), respectively.

Mixture	MLC - 6204-000	A	B
T_{NI} (°C)	62.4	88.7	93.6
Δn	0.148	0.171	0.120
E_{CD} (V/μm)	4.2	4.1	2.0
ΔE_D (V/μm)	2.7	3.3	8
Optimum cell gap d_{opt} (first minimum TN) (μm)	3.6	3.1	4.4
20V line-address time at d_{opt} (μs)	360	130	80
Lowest Voltage at d_{opt} (V)	15	7	<5
Temperature dependence for 400μs addressing (V/°C)	< 0.8	< 0.4	< 0.25

Table 1: Comparison of the electro-optic performance of two newly developed ZBD LC mixtures with the commercial TN mixture Merck MLC-6204-000.

5. Implications for Portable Products

The improved performance of mixtures A and B relative to Merck MLC-6204-000 has several implications for ZBD displays applied to different markets:

- The improved clearing points of these mixtures allows operation from -20°C to above 80°C, as demonstrated by the temperature dependence for mixture A shown in Figure 5. This permits the operation across the entire range necessary for many commercial products, from PDAs to mobile phones.
- The latching fields are up to two times lower than those demonstrated previously. This leads to very fast line-address-times for acceptable voltages. For example, with 20V bipolar pulses each line can be addressed in 80μs. Using the STN driver compatible addressing schemes described in [5] still faster addressing of 20μs per line is possible. For instance, a full page of a VGA eBook could theoretically be updated in 10ms. These addressing times are achieved despite the device cell gap being the conventional 4μm.
- Alternatively, the device may be addressed at a slower speed but using lower voltages. This leads to yet further reductions in the power consumption or to a reduced sensitivity to panel

variations.

- Applications such as smart watches, electronic shelf edge labels and smart cards require that much lower addressing voltages are utilised but the rate at which the devices are addressed is of secondary priority. Previously, latching was limited to above 15V, but with these new mixtures 5V has become accessible.

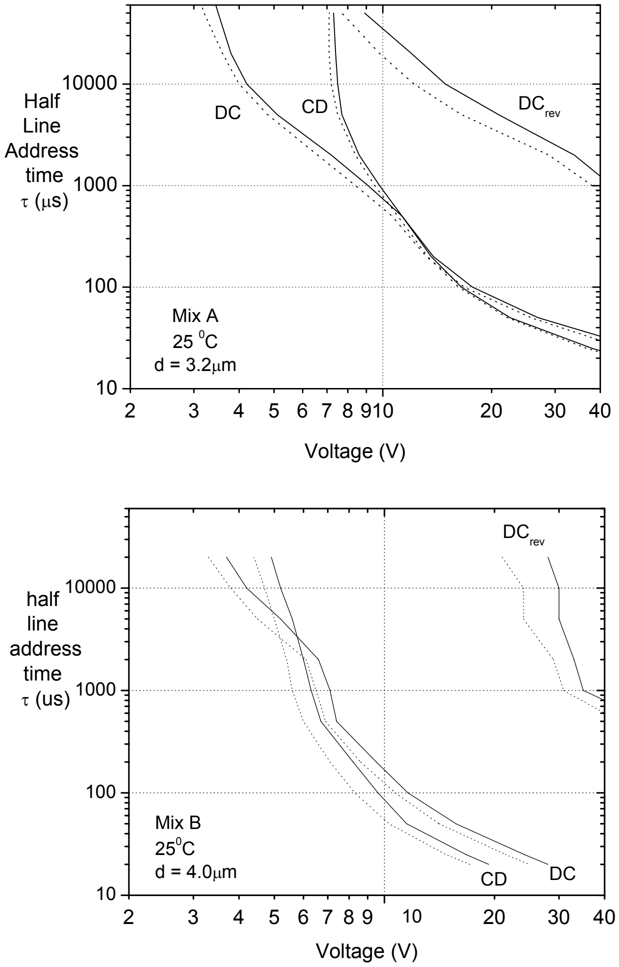

Figure 4 25°C Latching performance of two improved ZBD mixtures A and B corresponding to a) Δn = 0.17 taken in the TN-HAN ZBD geometry and b) Δn = 0.12 taken in the HAN - VAN ZBD geometry respectively.

6. Conclusions

One of the advantages of ZBD is that it is readily fabricated on a passive matrix LCD manufacturing line with few changes to the overall process flow. A ZBD device can be constructed using unpolished ITO coated TN glass spaced typically 4 to 5 microns apart. It uses standard STN drivers to address the panel, is combined with conventional TN polarisers and operated without need of compensation layers to give excellent optical characteristics. Although the device can be used with commercially available liquid crystal mixtures, significant improvements to the operating performance have been reported in this work through newly developed LC mixtures. Operation from -20°C to above 80°C, at voltages below 5V and at line address speeds of 20μs has been demonstrated. This combination of properties is unequalled in all previous bistable display technologies described previously.

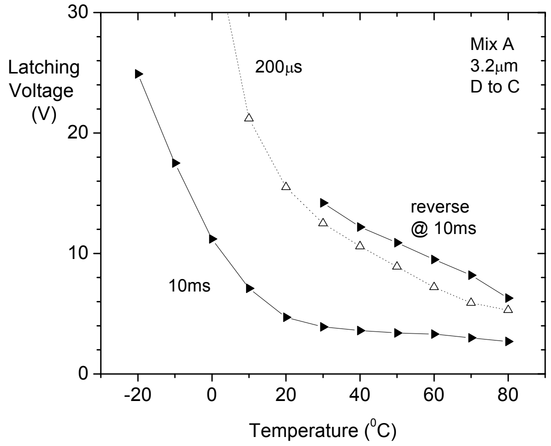

Figure 5 Temperature dependence of latching voltage for a 3.2μm cell containing mixture A for different line address times.

7. Acknowledgements

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8. References

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