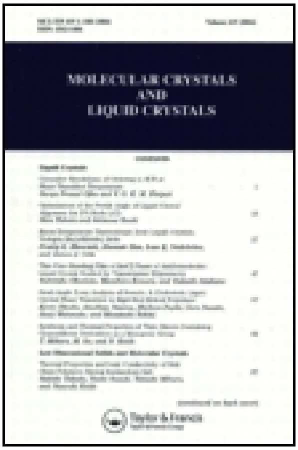

Molecular Crystals and Liquid Crystals

Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl16

Liquid Crystal Bistable Displays

R. N. Thurston [a]

[a] Bell Communications Research, Holmdel, NJ, 07733

To cite this article: R. N. Thurston (1985): Liquid Crystal Bistable Displays, Molecular Crystals and Liquid Crystals, 122:1, 1-24

To link to this article: http://dx.doi.org/10.1080/00268948508074738

Mol. Cryst. Liq. Cryst., 1985, Vol. 122, pp. 1–24
0026-8941/85/1224-0001/$25.00/0

Printed in the United States of America

Liquid Crystal Bistable Displays†

R. N. THURSTON

Bell Communications Research, Holmdel, NJ 07733

(Received August 28, 1984)

Bistability implies storage of information, which means *memory*. The practical significance of bistability is that it eliminates the need to refresh, which is a major obstacle to matrix-addressed displays that have a large number of elements.

We review displays based on bistable configurations of the director orientation. Two types of such displays are distinguished by whether the bistable configurations are topologically distinct, requiring disclination motion in switching, or not. The disclination-free type can operate at low voltages of about 5V, whereas a high voltage of 100V or more is required for rapid switching by disclination motion.

An example of the high voltage type is an electrically written, thermally erased display based on the topologically distinct vertical and horizontal states. A 20 row by 40 column model has been demonstrated.

Examples of the low voltage, disclination-free type are a cholesteric twist cell and a display based on bistable boundary layer configurations. The boundary layer display bistability is insensitive to variations in holding voltage, cell parameters, material properties, and temperature. Switching is simple: a short, low voltage dc pulse selects one or the other of the bistable states, depending on the polarity of the pulse.

1. INTRODUCTION

The need to refresh sets a major limitation on the number of elements of any matrix-addressed display that does not have memory. Bistability provides memory, and removes this limitation. This is the reason for interest in bistability, or storage effects, in displays.

The necessary ingredients of a bistable display are (1) two different states that are stable (or metastable but long-lived) under the same boundary conditions and voltage, (2) a method of obtaining optical

---

†Invited Lecture at the Tenth International Liquid Crystal Conference, York, U.K., July 15–21, 1984.

contrast between those states, (3) a method of switching between the two states, and, for displays of large information content, (4) a method of matrix addressing.

Most of the work on liquid crystal displays with memory uses bistabilities between phases or textures that have different optical properties. Among the storage effects of this type that have been considered for displays or "light valves" are the transitions between transparent and scattering textures in cholesterics[1-12] and smectics.[13-19] These effects involve order-disorder transitions.

The subject of the present review is a different class of bistability—a bistability between two ordered states that both have smooth configurations of the director. We call this *configurational* bistability to distinguish it from the *textural* bistability mentioned in the preceding paragraph. Configurational bistabilities are of two types, depending on whether or not the bistable states are topologically distinct, requiring disclination motion to switch from one to the other. Some ideas concerning the use of topologically distinct states in bistable displays, stabilized by the energy to detach disclinations, were given in Reference 20.

2. TOPOLOGICAL EQUIVALENCE AND THE UNIT SPHERE

The idea of topologically distinct or equivalent states can be understood very easily by picturing the director configuration as a path on a sphere. Picture the liquid crystal director as a unit vector from the center out to a point on the unit sphere. The point gives the orientation of the director, with the polar axis representing the direction normal to the cell surfaces. Consider configurations in which the orientation depends only on the z coordinate. Then, as the orientation changes with z, the point on the sphere traces out a path or graph that shows the director orientations in the configuration. The end points of the path on the sphere represent the boundary conditions at the upper and lower surfaces of the liquid crystal cell.

Figure 1 is an example of the use of the sphere in picturing configurations. The left part of the figure pictures the director as a circular cylinder with one end shaded, and shows two different configurations that satisfy the same boundary conditions: (a) a 180°-twisted state and (b) the planar vertical (V) state. The angle of tilt at the boundaries, α, has for simplicity been put to zero in the unit sphere description on the right. The boundary conditions at the cell

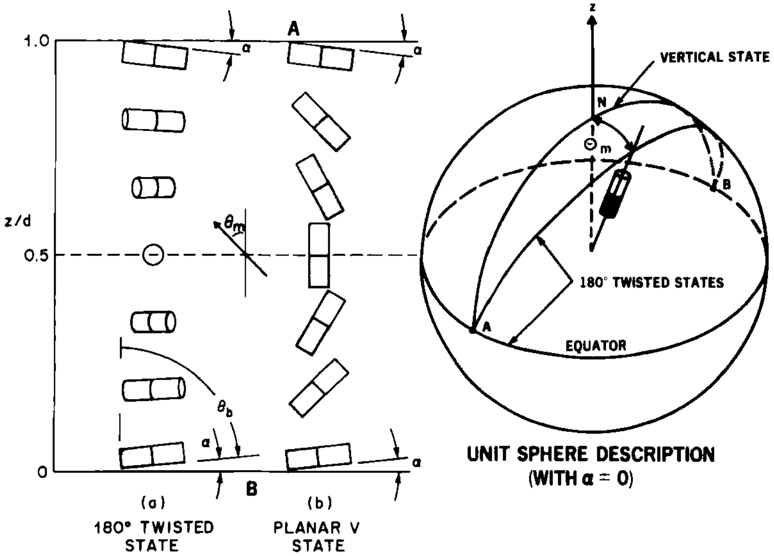

FIGURE 1 Director configurations (states) and their paths on the unit sphere. The pictorial representation on the left shows a boundary tilt bias angle α (reversely tilted on the two surfaces) that has been put to zero in the unit sphere representation on the right.

surfaces (with $\alpha = 0$) are represented by the points B and A. The configurations that satisfy these boundary conditions are represented by paths from B to A. The path along the equator represents a 180°-twisted state in which the director is everywhere parallel to the cell surfaces. The path over the pole represents the V state in which the director goes through vertical. The sphere picture shows a second 180°-twisted state in which the director tilts up to a minimum angle with the normal θ_m. States (configurations)[21] are topologically equivalent if the end points on the unit sphere are the same. Thus, all these states connecting B to A on the sphere are topologically equivalent, whether 180°-twisted or vertical. They have the property that the configurations can be deformed continuously from one to the other with no change in the boundary conditions.

The boundary conditions at the upper and lower surfaces of the cell may be established physically by rubbing or by oblique evaporation of some material such as SiO_x. Because of the equivalence of the director $\mathbf{n}$ and its negative $-\mathbf{n}$,[22] the same physically prepared surface can correspond to either of two diametrically opposite points on the unit sphere. For example, the *physical* boundary conditions of Figure

1 also support (with $\alpha = 0$) a uniform state in which the director orientation is constant throughout the cell. In this case, the path of the entire state degenerates to a single point on the sphere, either A or B. The uniform state that stays at B, or any state that goes from B to B is topologically distinct from the 180°-twisted and vertical states that go from A to B.

If we picture what happens when α in Figure 1 grows to a much larger angle, we see the topologically distinct horizontal (H) and vertical (V) states in a cell with oppositely tilted boundary conditions on the upper and lower surfaces, as sketched in Figure 2.[23] In the upper part of the figure, the lines are director lines—lines whose tangent at each point has the direction of the liquid crystal director. In the horizontal (H) state, in going from the lower surface to the upper, the director goes through horizontal at the middle of the cell, as shown at the top left of Figure 2. We can imagine the H state developing from the homogeneous state as the tilt angle at the surface changes. In the vertical (V) state, the director goes through vertical, as shown in the top right of Figure 2. The bottom section of Figure 2 shows the paths of the two configurations on the unit sphere. At the lower surface, the director angle, measured from the surface normal, is θ_b, represented by the point A. θ_b is typically 50° to 60°. (However, because of the equivalence of $\mathbf{n}$ and $-\mathbf{n}$, it could equally well be

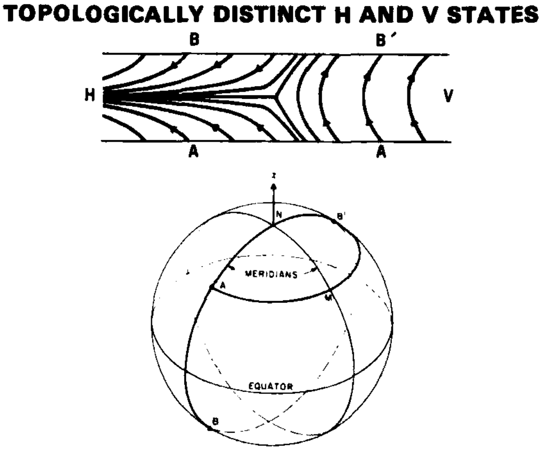

FIGURE 2 Director lines of topologically distinct horizontal (H) and vertical (V) states and their unit sphere representations in a cell with reversely tilted boundary conditions on the two surfaces. The sphere picture also shows a 180°-twisted state AMB' that is topologically equivalent to the V state ANB', but topologically distinct from the H state AB.

represented by a point diametrically opposite to *A*. We arbitrarily chose *A*.) The boundary condition at the upper surface is represented by either *B* or its diametrically opposite point *B′*. The choice *B* gives the H state, and *B′* the V state. The V and H states are topologically distinct because the paths on the sphere have the different end points *B* and *B′*, which represent different *mathematical* boundary conditions, even though the physically prepared surface is the same. This difference in mathematical boundary conditions (or topology) can also be seen from the arrows on the director lines in the pictured H and V states. If the arrows are shown leaving the lower surface, then in the H state, they leave the upper surface also, but in the V state they enter it. To switch between the states requires the passage of a disclination line to switch the boundary conditions.

Saito, Shirakura, and Kamihara discussed some of the properties of the H and V states at the Eighth International Liquid Crystal Conference in Japan.[24]

The sphere in Figure 2 also shows the graph of a 180°-twisted stated *AMB′* that has the same topology as the V state *ANB′*.[23] Porte and Jadot[25] were the first to discuss the transition between the vertical and 180°-twisted states. In nematics, if the director at the boundaries lies close enough to the surface, i.e. if the points *A* and *B′* on the sphere lie close enough to the equator, then ordinarily the twisted state *AMB′* is stable, but if *A* and *B′* are close enough to the pole, then only the V state *ANB′* is stable. This raises the interesting question: is it possible to choose the boundary conditions such that *both* the 180°-twisted state and the V state are stable, and use the resulting bistability in a storage display? Study of this question showed that the bistability does exist for achievable (although uncommon) ratios of the elastic constants, but even so, the bistability exists over such a narrow range of boundary tilt angles that a storage display based on this bistability would not be practical.[26]

One may wonder whether the length of the path on the unit sphere has anything to do with the elastic energy of the state. A *uniform* state, represented by a single point, has no elastic energy, and the path length of other states seems to be some measure of the extent of their elastic deformation. It is easy to show that for pure nematics at zero voltage, the elastic energy is proportional to the square of the path length on the sphere if the elastic constants are all equal, $k_1 = k_2 = k_3$.[26] For other ratios of elastic constants, the sphere can be mapped to another surface of revolution, on which the squared path length is proportional to the energy, and hence stable equilibrium states correspond to shortest paths (geodesics) on the surface.[27,28]

3. DISPLAY BASED ON TOPOLOGICALLY DISTINCT H AND V STATES

Boyd, Cheng, and Ngo[23] proposed a bistable display based on the H and V states. Optical discrimination was obtained by the guest-host effect using a single polarizer oriented to restrict the polarization to the plane of the configuration. The guest pleochroic dye molecules, which tend to align themselves with the host liquid crystal molecules, have a much larger optical absorption coefficient α when the light wave is polarized parallel to their long axis than when perpendicular ($\alpha_{\|} \gg \alpha_{\perp}$). Therefore, the light transmitted through the H state is subjected to a large absorption from $\alpha_{\|}$, while light transmitted through the V state has a lesser absorption from $\alpha_{\perp}$. Therefore H appears dark and V bright.

Switching from H to V (writing) can be accomplished with a vertical electric field. The switching time depends on the voltage and the distance the disclinations have to move. To reduce the distance, and therefore the switching time, the pels were divided into subpels, separated by a neutral web of uniformly tilted alignment. The creation of the isolation regions requires the boundary tilt in the neutral regions to be reversed from that in the active regions on one of the surfaces, as sketched in Figure 3, where the reversal is shown on the upper surface. The reverse tilt at the boundary is obtained by a second SiO evaporation over the active regions. The disclination studies of Cheng et al. were most helpful in understanding and improving the switching time, threshold characteristics, and the stability of the bistable states.[29-35] With 100 to 125 volts, the write time can be as short as 1 or 2 ms per row.

The first models of this display accomplished V to H switching (erasure) by transverse electric fields applied by means of interdigital electrodes. This worked successfully, but the best device used resistive heating, accomplished by passing a current through the row electrodes.[36] If the boundary tilt bias is close enough to the horizontal, the

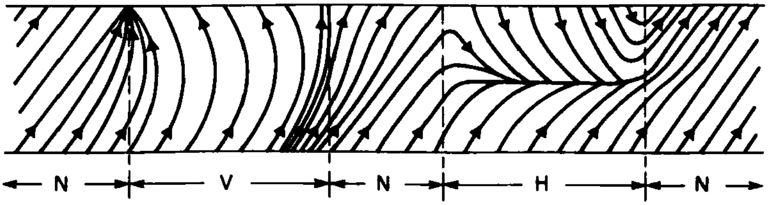

FIGURE 3 Director lines of the H and V states in active picture elements (pels) isolated by uniformly tilted neutral regions. (From Reference 36.)

H state will form spontaneously when the material cools from the isotropic phase. Figure 4 shows how the elastic energy of the vertical and horizontal states depends on the boundary angle measured from the normal. These curves were calculated using the elastic constants of E7 (Manufactured by BDH Chemicals, Ltd., Poole, Dorset, England. Available in the USA from EM Chemicals) as measured by Raynes, Tough, and Davies.[37] The curves show that the H state is favored for boundary angles greater than 42° from the normal. In our cells with SiO evaporation, the boundary angle is nearly 70° from the normal, and the H state forms quickly upon cooling from the E7 clearing point of about 60°C. With 1 W/mm^2, the time to heat the liquid crystal through the necessary 40°C temperature rise was about 30 ms. With adequate power available, the whole display can be erased at once, so that the total time to erase and rewrite a display of r rows is about $(30 + 2r)$ ms.

This electrically written, thermally erased bistable display is multiplexible, has good contrast, and can be built to operate in either

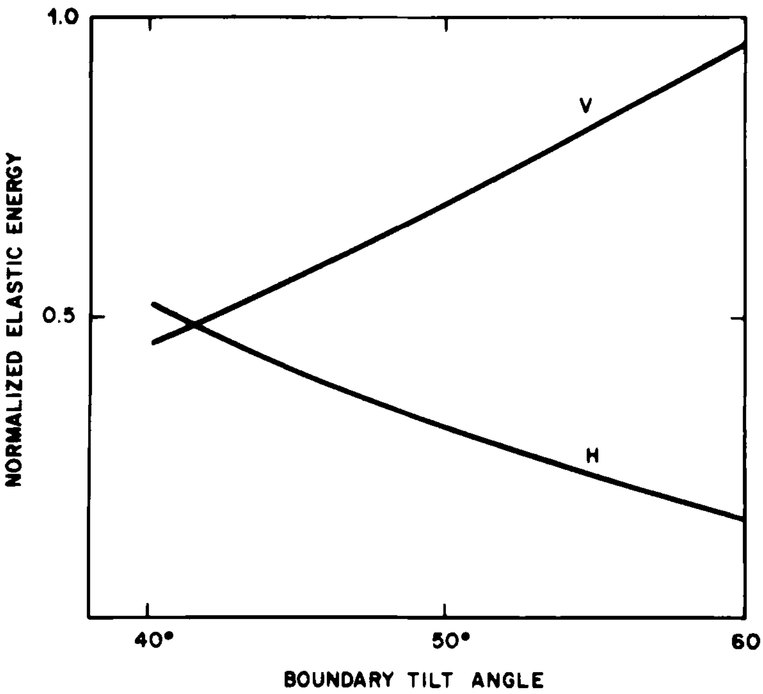

FIGURE 4 Elastic energy density of the H and V states versus boundary tilt angle. For E7 $(k_1/k_3 = 0.6)^{37}$ (From Reference 40.)

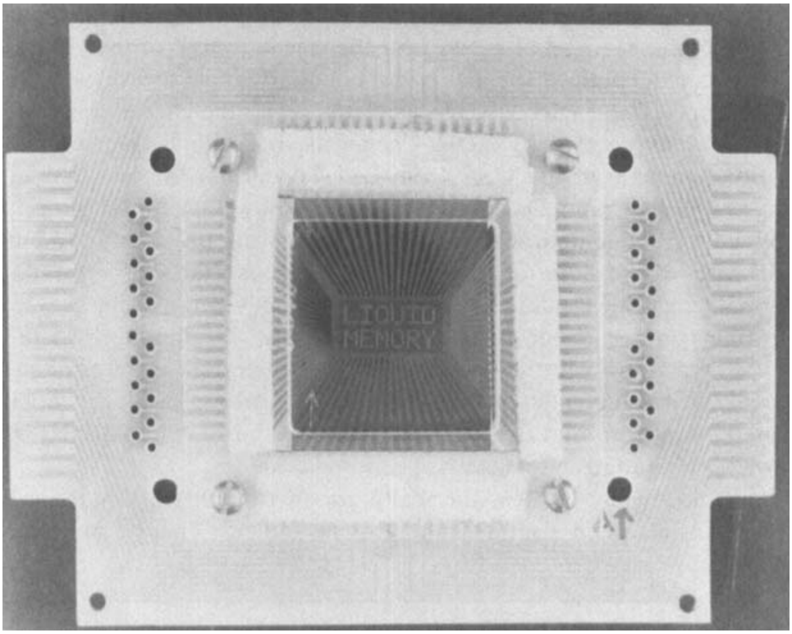

FIGURE 5 A 20 row by 40 column electrically written, thermally erased display based on the topologically distinct H and V states is shown in its printed circuit board. Connections to the transparent electrodes on the glass are made with elastomeric connectors. The permanent image, even when the board is unplugged, confirms the bistability. (From Reference 40.)

transmission or reflection. Measurements showed that the acceptable viewing angle is determined primarily by the character of the illumination provided, rather than by any intrinsic cutoff in the optical transmission properties of the H and V configurations.[38] A 20 row by 40 column multiplexed model has been demonstrated.[39,40] Figure 5 shows the display in its printed circuit board. This display stands as a possible alternative to other flat, large-information-content displays. Its chief disadvantage is the high voltage required for fast writing.

4. DISCLINATION-FREE BISTABLE DISPLAYS

The reason the above-described display requires a high voltage is that the two states are topologically distinct, requiring disclination motion for switching. Disclination motion entails a severe reorientation of the director in the immediate neighborhood of the disclination line. Since this rotation is opposed by the rotational viscosity, there is a significant effective drag, and the result is that a high electric field is required to accomplish rapid switching. The disclination motion necessary for switching will always impose a fundamental limitation on displays that use topologically distinct states. Therefore, bistabilities between topologically equivalent states have a possible advantage, and it is interesting to look for such bistabilities.

4.1. Cholesteric bistability of Berreman and Heffner

The first disclination-free bistability that held any promise for displays was discovered analytically by Berreman, and demonstrated experimentally by Berreman and Heffner in a cell with uniformly tilted boundary conditions on both surfaces.[41,42] The material is E7 with a fractional percent of cholesteryl nonanoate to give the mixture a cholesteric twist. Figure 6 illustrates four equilibrium configurations that can satisfy the boundary conditions. At the left (a) is a uniform untwisted state, which can be in equilibrium in spite of the cholesteric additive. The other topologically equivalent stable state is shown third from the left, at (c). This is a 360°-twisted, or full turn state, which means that the director makes one turn around the normal to the cell surfaces in going from one surface to the other. Between two valleys there has to be a hill, so between two topologically equivalent stable states, there has to be an unstable equilibrium barrier state. The barrier state is shown at (b), and it happens to be similar to a stable

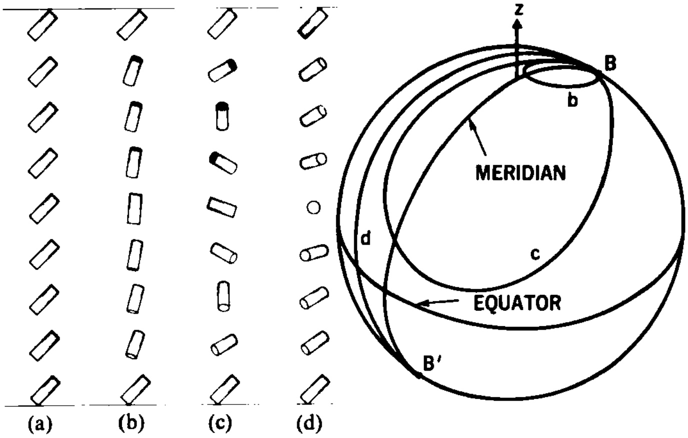

FIGURE 6 Director configurations in a cell with uniformly tilted boundary conditions. See discussion in text. (Adapted from Reference 41.)

state in a weak electric field. The state illustrated at (d) is a topologically distinct half turn state. The right hand part of this figure sketches qualitatively the paths of these states on the unit sphere. Let the point B on the sphere represent the liquid crystal orientation at the upper and lower surfaces of the cell. The path of the uniform state (a) degenerates into the point B. (With *nearly* uniform orientation, its path would be a very small loop through B.) The stable equilibrium state (c) has the director dip down towards horizontal at the midplane, so the path of its state sweeps down toward the equator in circling the pole to accomplish a full turn, as shown. The barrier state makes a smaller loop up towards the pole (vertical). The topologically distinct half turn state has the boundary condition at the upper surface changed to the point B' diametrically opposite to B, as shown for (d).

In a Berreman–Heffner cell of thickness to natural pitch ratio about 0.8, an applied voltage of about 2.5 V produces a state very similar to the barrier state (b), from which the configuration can fall either to the full turn state (c) or the no turn state (a), depending on small perturbations. If a smaller voltage, say 2 V is applied, and then gradually reduced, the configuration falls to the no turn state, but if 3 V or more is applied and turned off suddenly, the configuration falls to the full turn state.[42]

Optical discrimination of the bistable states in this cell is obtained with crossed polarizers. With the analyzer parallel to the plane of the directors in the untwisted state, that state appears dark. In the twisted state, the light is elliptically polarized and partially transmitted past the analyzer to appear bright.

With an appropriate ratio of cholesteric pitch to cell thickness, the states just described are bistable with no applied field. Shortly after this bistability was described, Berreman and Heffner announced an improved version of their display in which the states are bistable in the presence of a holding voltage.[43] With a holding voltage, one gives up the interesting but practically insignificant feature that the displayed information remains even when the power is turned off, but the chief advantage of bistability—elimination of the need to refresh —remains whether a holding voltage is used or not.

In a particular cell studied by Heffner and Berreman, with a cell thickness to pitch ratio of 1.0, the long-term bistability exists experimentally from about 1.65 V to 1.73 V.[44] The latest results are reported at this conference.[45]

Figure 7 shows some properties of the states in a holding voltage cell as calculated by Berreman.[46,47] The curve in the upper left shows

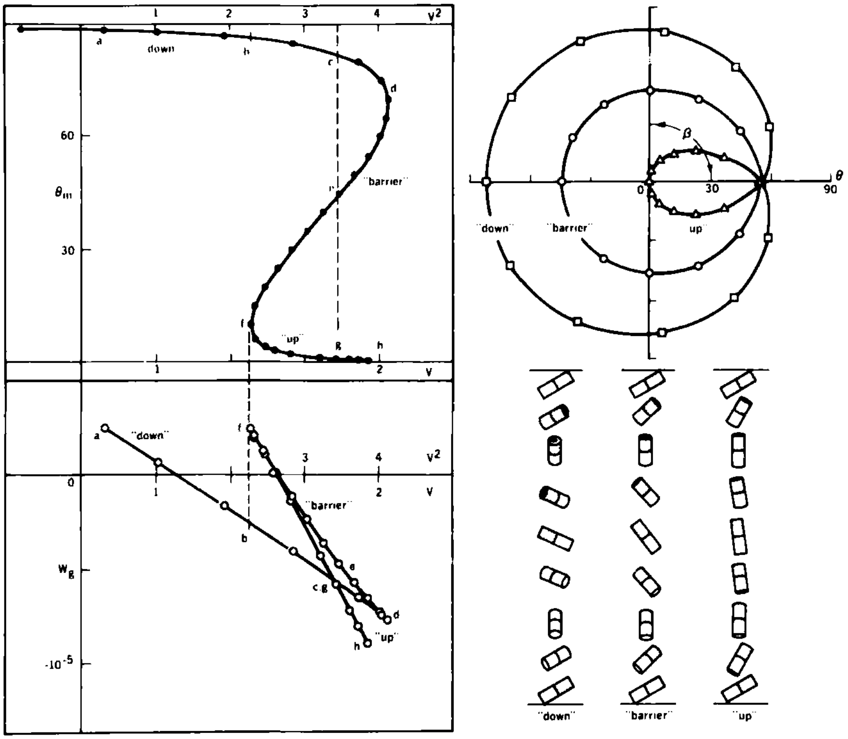

FIGURE 7 Properties of states in the holding voltage cell of Berreman and Heffner. Upper left, θ_m versus V^2; lower left, Gibbs free energy function versus V^2; right, polar plot and pictorial representation of the states at c, e, and g (1.86 volts). (Adapted from References 46 and 47.)

θ_m versus applied voltage squared for equilibrium states, where θ_m is the director angle at the midplane of the cell, measured from the normal to the surfaces. The director configuration is illustrated pictorially at the lower right and graphed in the polar plot at the upper right, where the common point to all the loops at $\theta = \theta_m = 55°$ represents the uniform boundary condition at the surfaces. At low voltages, a full turn state with the director nearly horizontal at the midplane, called the down state, is stable. As the voltage is increased, θ_m behaves normally, decreasing with increasing voltage, and the down state remains stable out to the point labeled d, where the slope of the curve changes sign. At higher voltages, only the up state is stable. Between points d and f where θ_m decreases with decreasing voltage, the curve represents unstable equilibrium barrier states. Between points f and h, and on to still higher voltages not plotted, θ_m

again behaves normally, decreasing with increasing voltage and the up state with the director nearly vertical at the midplane is stable. At any voltage between d and f, there are three equilibrium states, such as those represented by the points at c, e, and g at 1.86 V, $V^2 = 3.46$. These are the states graphed and pictured in the right half of the figure.

The lower left part of Figure 7 shows the electric Gibbs function for the equilibrium states represented by the curve in the upper left. States in equilibrium at the same voltage have stationary values of the Gibbs function, the stationary value being a minimum for stable states.[48] The illustrated calculations confirm that over the bistable range, the barrier state has a higher Gibbs function than the stable down and up states that it separates.

In considering the relation between stability and the equilibrium curve at the upper left of Figure 7, it is useful to think along the following lines.[49] Recognizing that a pair (θ_m, V^2) does not determine a state, we first conceive of the state that has the minimum possible Gibbs function for any fixed pair (θ_m, V^2), whether on the equilibrium curve or not. In the present case, one may introduce an imaginary surface at the midplane of the cell which fixes θ at θ_m and the director azimuth β at 180°, but which allows the derivatives $d\theta/dz$ and $d\beta/dz$ to jump at the midplane. Then the desired Gibbs function, say $G(\theta_m, V^2)$, is that of the *stable* equilibrium state at voltage V in such a cell. In other words, our $G(\theta_m, V^2)$ is twice the Gibbs function of the stable equilibrium state at voltage $V/2$ in a cell of half the thickness with $\theta = \theta_m$ on one surface and $\theta = \theta_b$ on the other, with the angle of twist of the cell specified as half that of the full state being investigated. For (θ_m, V^2) on an equilibrium curve, this G is precisely the Gibbs function of the full equilibrium state. Imagine this Gibbs function to be plotted as a surface over the (θ_m, V^2) plane at the upper left of Figure 7. *All* of the points where $\partial G/\partial\theta_m = 0$ must correspond to equilibrium states.[48] Therefore, the equilibrium curves such as that in Figure 7 divide the (θ_m, V^2) plane into regions of positive or negative $\partial G/\partial\theta_m$. The sign in any such region can be determined if it is known near any point on the boundary. Now it is certainly true that the down state is stable for at least part of the low voltage range. Therefore we know that $\partial G/\partial\theta_m < 0$ to the left of the curve and $\partial G/\partial\theta_m > 0$ to its right. This proves that points from a to d locate a valley of the G surface, d to f, a ridge, and f to h and beyond, another valley, all of which is consistent with what was just said about the stability of the corresponding equilibrium states.[50]

The voltage range between d and f sets a theoretical upper limit to the range of permanent bistability. The practical limit is less than the theoretical because three-dimensional effects, represented by domain walls, for example, serve to reduce the range of long-term stability from that indicated by the one-dimensional theory.[47]

4.2. Other disclination-free configurational bistabilities

Scheffer[51] set up general equations for investigating bistabilities between twisted states in pure nematics in the presence of a holding voltage, and studied thoroughly the case of 90° twist with zero tilt and also with a very small boundary tilt angle, measured from the surface. He concluded that the range of bistability is too narrow to be useful in 90° twist cells. Even if one grants the unlikely ratios of elastic constants needed to achieve bistability with zero tilt, a small tilt bias of the order of 0.2° destroys the bistability completely.

In the case of 180° twist, where one of the states can be the planar V state of Figure 1, the range of bistability is much wider.[49] For example, with the elastic constants of E7, but the dielectric anisotropy parameter $(\epsilon_\parallel - \epsilon_\perp)/\epsilon_\perp$ lowered to 0.05, the theoretical holding voltage range of the bistability with zero tilt and perfect alignment in azimuth is 7.3 percent. A boundary tilt bias of 1° lowers this range to 4.2 percent, while the combination of 1° boundary tilt and 2° misalignment in azimuth cuts it to 2.5 percent.[49] This bistability could probably be demonstrated experimentally but would not be practical in displays without materials innovation to widen the bistable range by lowering the elastic constant ratio k_1/k_3.

4.3. Boundary layer display

The most promising configurational bistability is the bistability between two asymmetric forms of the horizontal state that are both stable above a critical threshold voltage.[32,52] Here, the equal but reversely tilted boundary conditions are just like those of the horizontal-vertical bistability discussed earlier. The cell construction is much simpler, however, because no isolation regions are necessary. Figure 8 illustrates the bistable states. The upper left sketch illustrates the state at zero voltage. As the voltage is increased (with positive dielectric anisotropy) the director tilts up except in a boundary layer B at each surface and a director inversion layer I in the middle of the cell. It is not hard to see that the *symmetric* horizontal state becomes unstable above a certain voltage. Instability of the symmetric state occurs because one of the highly distorted, high-energy regions can be

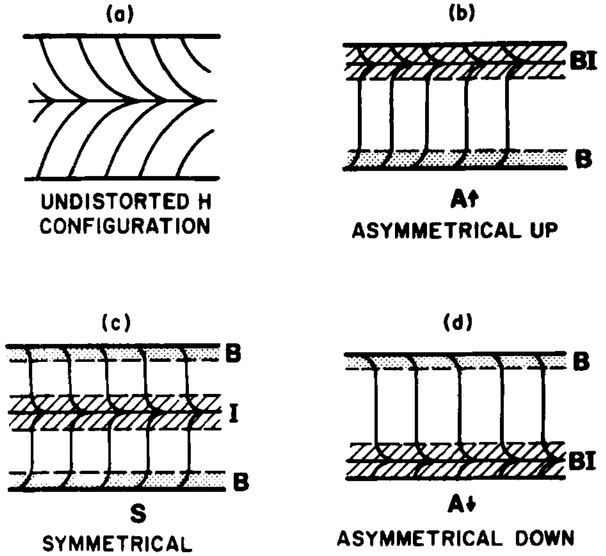

FIGURE 8 (a) H state at zero field. (b), (c), (d), distorted H states under a vertical electric field. S is stable below a critical threshold voltage V_{th}, and unstable above it. Above the threshold, the stable H states are the asymmetric ones in which the director inversion layer I has merged with one of the boundary layers B to form BI at one of the boundaries. (From Reference 53.)

eliminated if the director inversion layer I moves to the boundary to form a layer labeled BI.[32,53] The result is that as soon as the voltage reaches a critical value, the symmetric state becomes unstable, and we have the bistable states shown on the right—bistable in the presence of a holding voltage above the critical voltage.

The critical voltage above which the bistability exists is something like a Freedericksz voltage. Like the Freedericksz voltage, it depends on the elastic constants and dielectric anisotropy parameter. It also depends on the tilt angle at the boundary, and becomes identical with the Freedericksz voltage in the limiting case of alignment parallel to the surfaces.[32,54] In our cells with E7 the critical voltage is about 1.2 V.

An important feature of this bistability is that it does not go away if the voltage is too high. The bistability continues to exist above the critical holding voltage in spite of changes in voltage, cell parameters, liquid crystal material properties, or temperature.[53] This is an advantage over the cholesteric cell just described, in which both states are stable only over a limited range of voltage, and for a limited range of the ratio of cholesteric pitch to cell thickness.

Optical contrast in the boundary layer display is achieved by birefringence effects using two polarizers. The key to distinguishing the two states optically is to twist the director azimuth at the upper surface with respect to that at the lower.[53] In the simplest picture, suppose that all of the *director* twist takes place in the middle region of the cell where (because of the holding voltage) the director is so nearly vertical that its twist does not rotate the polarization of the light wave. Then each boundary layer is like a birefringent plate with the boundary-inversion layer BI thicker and more birefringent than the B layer. Switching between down and up interchanges the two layers, and has the same optical effect as rotating a birefringent plate between crossed polarizers.

The optical properties of the bistable states for light at normal incidence have been studied in detail, based on a boundary layer model of the configurations.[55]

At this point we have a good, highly stable bistability and a method of obtaining optical contrast between the bistable states. Now how can we control the selection of the states and switch between them? The problem is to make the director inversion layer move either up or down as we choose. What is needed is some controllable way to break the symmetry of the cell, in order to select either the down state or the up state. The first descriptions of this display recognized many of its advantages, but described a method of switching that is rather slow and difficult to control.[53,56]

The breakthrough that makes this display possibly practical is the discovery that it can be switched by a short, low-voltage dc pulse, which selects one or the other of the bistable states, depending on the polarity of the pulse.[57] Figure 9 illustrates the switching scheme. The top row shows the director lines for the key states. The next row is the envelope of an ac holding voltage applied to a row electrode, and next is the dc voltage applied to a column electrode. At the bottom of the figure, we see one of the pels of a matrix array sandwiched between row and column electrodes. In the held state, the holding voltage is applied to the row electrodes with the column electrodes grounded. Experiment shows that we cannot switch directly from one bistable state to the other, but the holding voltage must first be turned off to allow the pels to relax toward the symmetric configuration. (This is the price one pays for having such a good, stable bistability. But, it is also a tremendous advantage for line-at-a-time addressing because it means the already-written lines are locked in and immune to the pulses used to switch subsequent lines.) The dc pulse applied to a relaxed pel then biases the configuration toward the desired state, and

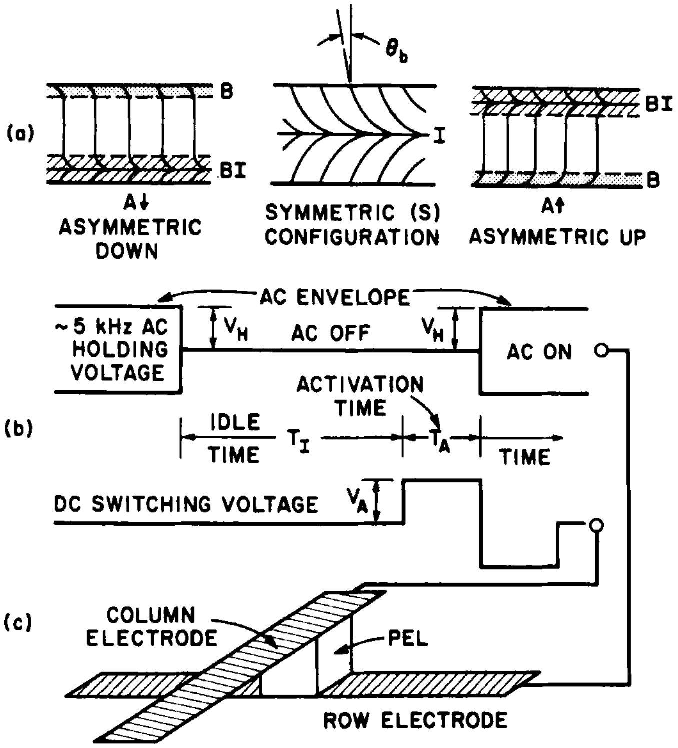

FIGURE 9 (a) Key states and (b), (c) switching scheme. The bistable asymmetric configurations are held by an ac holding voltage of rms amplitude V_H applied to the row electrodes with the column electrodes grounded. Before switching, the ac is turned off to permit relaxation toward the S state. Switching is activated by applying to the column electrodes a dc pulse whose polarity selects the up or down state. The second dc pulse of opposite polarity (second phase of bipolar switching pulse) allows faster multiplexing, as explained in the text. (From Reference 57.)

the holding voltage is turned on again to lock it in. The second pulse of opposite polarity allows faster multiplexing. Its function is to restore the not-yet-written lines to a neutral state so that they will respond properly when selected. In multiplexing, all columns are addressed in parallel and the rows are sequentially scanned. It takes about 40 ms for the pels to relax sufficiently to be switched, but this is no great hardship because the entire display can be relaxed at once. Once the entire display is relaxed, the rows can be written at an estimated 20 ms per row, so that the time to erase and rewrite a display of r rows is estimated as $(40 + 20r)$ ms.

To me the most exciting thing about this work was thinking about the switching mechanism. Let us first ask why the dc switching effect was not expected, when it is obvious that dc has a preferred direction.

Why should it be mysterious? The reason it is mysterious is that this effect is in a nematic liquid crystal, which has no permanent dipole moment. Therefore, the torque exerted by the electric field on the director is quadratic in the field, and independent of polarity. If the coupling of the director to the electric field is insensitive to the polarity, then how do we get a polarity effect? We concluded that the cause is an asymmetric distribution of electric field across the cell. When the field is higher near one wall than the other, the greater torque tending to align the molecules vertically in the higher field region biases the director inversion I layer toward the lower field region. We have suggested two possible mechanisms for an asymmetric distribution of electric field across the cell. One is an interface or double layer effect and the other an ion depletion effect.[57,58]

Figure 10 illustrates the interface effect. We suppose that for some electrochemical reason, ions of one sign, say negative, are stuck at the surface as illustrated on the left of Figure 10, leaving a net positive charge in the bulk. In the absence of an applied voltage, the field has a distribution which points toward the nearest wall. This means negative near one wall and positive near the other as in the solid curve showing D_z versus z. Here, D_z is the z component of electric displacement. Initially, before there is time for any ion movement, a suddenly applied field simply adds to this double layer field, produc-

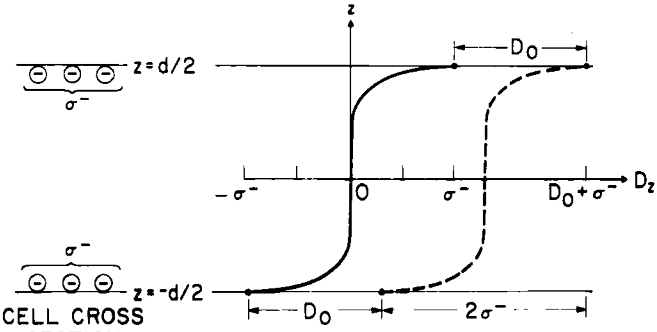

FIGURE 10 Sketch of the z component of electric displacement D_z versus z shows field asymmetry arising from double layers. Suppose, for example, that negative ions from the liquid crystal or from impurities in it are preferentially absorbed at the SiO surfaces of the cell, forming a layer of charge per unit area σ^- at each surface, as pictured at the left. With no applied voltage (solid curve) the electric field in the adjacent diffuse layer is directed toward the wall, the value of D_z being $-\sigma^-$ at one wall and $+\sigma^-$ at the other. The difference $2\sigma^-$ persists in the presence of an applied voltage (dashed curve). In the resulting asymmetry, the field is higher near the wall toward which the applied field is directed, and the stronger torque there, tending to align the molecules vertically, biases the director inversion (I) layer toward the opposite wall, i.e., in the direction opposite to the applied field. (From Reference 58.)

ing a higher magnitude near one wall than the other, and an asymmetry that could account for the dc effect.[58,59]

In the ion depletion effect, we suppose that one ion, say negative, has a higher mobility than the other. A dc field produces regions depleted of positive and negative ions at the positive and negative electrodes, respectively. As the voltage is maintained, the transient depletion region behind the faster (more mobile) ion thickens faster than the other one. The resulting transient charge distributions produce a higher field in the region depleted of the faster ion, as sketched in Figure 11.

To obtain faster switching, one would like to exploit the interface effect because it gives an immediate asymmetry as soon as the dc pulse is applied, whereas if the other mechanism acts alone, there is a delay before field asymmetry can build up from the differential drifting of the ions.[58] There is no direct experimental evidence for either of the suggested mechanisms.

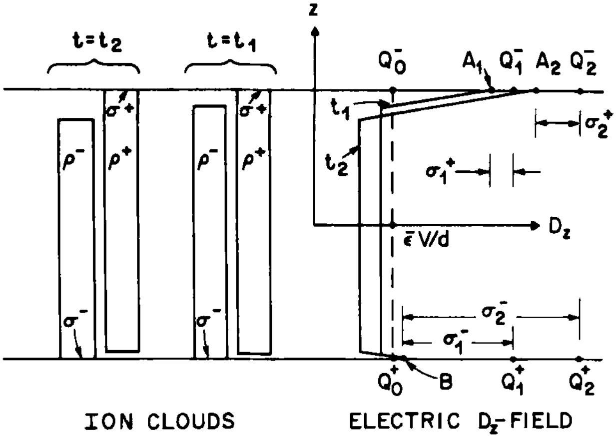

FIGURE 11 Transient asymmetry arising from a difference in mobility of the positive and negative ions. The mobility difference leads to an asymmetric distribution of ionic space charge, from which arises asymmetry of the electric field. The space charge is represented by ion clouds whose positions are shown at two times t_1 and t_2, both soon after the application of an applied voltage V. In this picture, the negative ions have the higher mobility, as shown by the wider depletion region behind the negative clouds. At the time t_1, the *electrode* charge $Q_1^+ = Q_1^-$ is screened by an accumulated ionic layer σ_1^- at the anode and σ_1^+ at the cathode to bring D_z on the liquid crystal side of the accumulated ion layers to the values shown by the points B and A_1. From Poisson's equation, D_z increases with z in the region depleted of negative charge, and decreases in the region depleted of positive charge. The sketches of D_z versus z show an asymmetry in which the field is higher in the region depleted of the more mobile ion. The stronger torque on the molecules in that region biases the I layer toward the opposite wall, i.e., toward the target wall of the faster ion. (From Reference 58.)

A study was made of the thickness dependence of the pulse duration ("switching time") needed to activate the desired state.[60] Not surprisingly, the results showed that the time increases drastically with thickness; therefore, fast switching requires a thin cell. The fundamental limitation on cell thickness, if not imposed by manufacturing considerations, is loss of contrast between the two states. The states were easily distinguished at our smallest thickness of 1.2 μm, where the needed activation time was less than 1.5 ms.

Figure 12 shows results of measurements[57] on the persistence of the activation when the holding voltage is delayed from its usual turn-on position, which is immediately after the first pulse. These are the results for two different experiments in the same cell. The right hand curve is with a unipolar switching pulse, and the other with a bipolar switching pulse. To interpret these curves, one must understand that the cell has a favored (F) state. Due to some accidental asymmetry, the boundary angles may be slightly different on the two surfaces. As a result, when the ac holding voltage is turned on without any switching pulse at all, the entire display goes to the favored state. However, an applied pulse of only 2 V and 5 ms duration activates

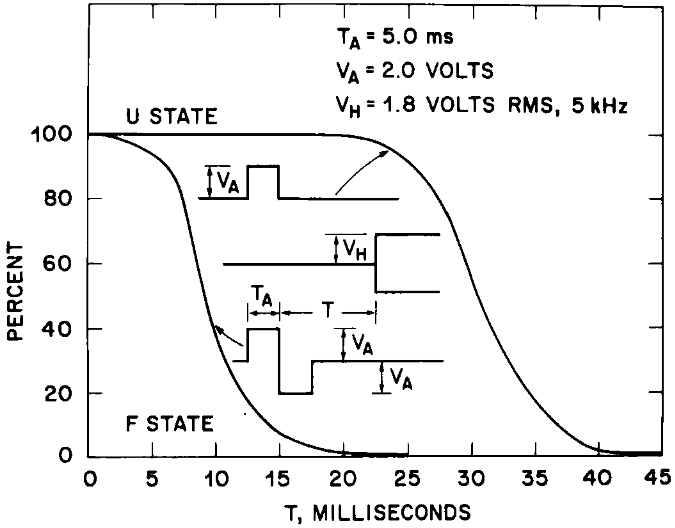

FIGURE 12 Effect of opposite-polarity pulse in shortening persistence of activation. Percent switched to U versus T. $T_f > 1$ s. A short persistence is desirable in order to do line-at-a-time switching (multiplexing) at a fast rate because the not-yet-selected pels must recover from the switching pulses for previous lines, in order to respond properly when selected. (From Reference 57.)

the unfavored (U) state. With the unipolar switching pulse, one can wait 25 ms before applying the ac holding voltage, and still get the U state. (For longer times, some pels of the display go to the favored state.) With the bipolar pulse, the activation loses its effect much faster, allowing faster multiplexing. For multiplexing, a short persistence is good, because one wants the not-yet-addressed lines to recover from all the previous pulses and be ready to switch properly when selected. These results are for a 5 μm cell. Reducing the cell thickness should reduce the persistence even further. From the results in Figure 12, the speed of line-at-a-time addressing has been estimated at 20 ms per line or faster. This allows 15 ms for the persistence to decay and 5 ms for the first phase of the bipolar pulse.

Since the switching pulses on the column electrodes are applied to all the rows, a possible limitation on the multiplexing rate occurs if the rms voltage of the switching pulses V_s exceeds the critical threshold voltage V_{th} for stability of the asymmetric states. In this case, the not-yet-addressed pels would be prevented from switching when selected because the switching pulses themselves would function as an effective holding voltage $> V_{th}$ that would keep the pels locked into one of the asymmetric states. This problem can be eliminated by using a dual-frequency material, in which the dielectric anisotropy $\epsilon_{\parallel} - \epsilon_{\perp}$ changes sign from positive to negative as the frequency is increased through a cross-over frequency f_c.[61] A signal at a frequency above f_c, applied to the not-yet-addressed rows can overcome the orienting effect of the switching pulses, whose effective frequency is below f_c.[62] An experiment simulating dual-frequency multiplexing showed that the principle is sound and confirmed that the display can be switched directly from the high-frequency held symmetric state.[63] However, because of the higher viscosity of the dual-frequency material used, there was no improvement over E7, even with $V_s > V_{th}$ in the dual-frequency case. This application needs a stable dual-frequency material with a higher dielectric anisotropy and a lower viscosity, a low cross-over frequency being of lesser importance. In the meantime, the results of Figure 12 suggest that useful multiplexing rates can be achieved by inserting a dead time between the switching pulses and using a material for single-frequency applications, such as E7.

The dc-switching effect is qualitatively repeatable, having been used successfully to switch every cell of about a dozen that were tested, including an insulated cell (cell with a 0.5 μm layer of polyimide between the metallic electrode and the SiO alignment layer) and cells filled with different liquid crystal materials. The results on the insulated cell[64] have been interpreted to mean that charge injection into the liquid crystal is not essential to the switching mechanism.

A possible disadvantage of the boundary layer display is that the holding voltage or switching pulses can conceivably trigger disclinations that bring in the topologically distinct V state of Figure 2, which, at the usual holding voltages, is likely to be the state with the lowest electric Gibbs function (most stable state). This has been observed to occur at the higher holding voltages in a few pels of the investigated displays. The V state then takes over the entire pel in which it originated, but does not go beyond the active area that has electrodes on both surfaces. Turning off the voltage for several seconds suffices to restore the H state. In the few pels that are prone to V state formation, the disclinations originate on the same surface imperfections each time they appear, and it is expected that better processing control will eliminate this problem.

5. CONCLUSION

Of all the displays based on configurational bistabilities of the director field, the boundary layer display is the most promising. It has the advantages of low power and low voltage operation, good contrast, an estimated addressing speed that is already fast enough to be useful for some applications, and a bistability that is relatively insensitive to changes in holding voltage, cell parameters, material properties, and temperature.

There are unanswered questions: the acceptable angle of view needs to be investigated; the estimated addressing speed should be confirmed by setting up the circuitry to actually do it; last not least, the polarity-dependent switching mechanism is not yet settled. Our conjectures[58] seem plausible, but they lack direct confirmation. Once the switching mechanism is understood to the point where the important parameters are known and can be controlled, it will surely be possible to improve the switching speed and multiplexing capability beyond the currently estimated 20 ms/line.

While the work that has been done is not complete enough to firmly appraise the potential of this display, everything that has been learned supports it as a practical, flat, matrix addressed display of large information content.

Acknowledgements

I had the privilege of participating in much of the work reviewed here while employed by Bell Laboratories (now called AT&T Bell Laboratories), and enjoyed the collaboration of many people without whom the described results could not have been achieved. It is a pleasure to thank especially Gary D. Boyd who provided constant encouragement, ideas, advice, and inspiration; Julian Cheng, who played a key role in generating workable ideas and who provided a depth of insight that proved indispensable to our progress; Robert B. Meyer of Brandeis University, whose stimulating, fruitful discussions and breadth of knowledge impacted tremendously on the work; Fred Storz, whose expert fabrication of the display models made the experimental work possible, and Eric Westerwick who designed and built the circuitry for the dc-switching experiments.

References

1. G. H. Heilmeier and J. E. Goldmacher, "A new electric field controlled reflective optical storage effect in mixed liquid crystal systems." *Proc. IEEE* **57**, 34–38 (1969).
2. W. Haas, J. Adams, and J. B. Flannery, "ac-field-induced Grandjean plane texture in mixtures of room-temperature nematics and cholesterics." *Phys. Rev. Lett.* **24**, 577–578 (1970).
3. W. Haas, J. Adams, G. Dir, and C. Mitchell, "Image storage panel based on cholesteric liquid crystals." 1973 *SID Digest*, pp. 44–45.
4. H. Melchior, F. J. Kahn, D. Maydan, and D. B. Fraser, "Thermally addressed electrically erased high-resolution liquid-crystal light valves." *Appl. Phys. Lett.* **21**, 392–394 (1972).
5. W. Greubel, "Bistability behavior of texture in cholesteric liquid crystals in an electric field." *Appl. Phys. Lett.* **25**, 5–7 (1974).
6. K. H. Walter and H. H. Krüger, "Speichereffekte in cholesterinischen Flüssigkeiten mit positiver DK-Anisotropie." *Berichte Bunsengesellschaft Physikalische Chemie* **78**, 912–914 (1974).
7. E. P. Raynes, "Cholesteric texture and phase change effects," pp. 25–43 in *Nonemissive Electrooptic Displays* A. R. Kmetz and F. K. von Willisen, Eds. New York, Plenum, 1976.
8. T. Uchida, C. Shishido, and M. Wada, "Liquid crystal color display devices with phase transition." *Mol. Cryst. Liq. Cryst.* **39**, 127–138 (1977).
9. M. Kawachi and O. Kogure, "Hysteresis behavior of texture in the-field-induced nematic-cholesteric relaxation." *Japanese J. Appl. Phys.* **16**, 1673–1678 (1977).
10. S. K. Kwok and Y. Liao, "Transient phenomena of relaxation from an electric-field-induced nematic phase to cholesteric phase." *J. Appl. Phys.* **49**, 3970–3975 (1978).
11. C. Tani, F. Ogawa, S. Naemura, T. Ueno, F. Saito, and O. Kogure, "Storage-type liquid crystal matrix display," in *Proc. 1979 SID Int. Symp.* pp. 114–115.
12. W. J. S. Blackburn, "On the exploitation of cholesteric-nematic phase-change effect for multiplexed liquid crystal displays." *J. Phys. D: Appl. Phys.* **13**, 1785–1799 (1980).
13. C. Tani, "Novel electro-optical storage effect in a certain smectic liquid crystal." *Appl. Phys. Lett.* **19**, 241–242 (1971).
14. F. J. Kahn, "ir-laser-addressed thermo-optic smectic liquid-crystal storage displays," *Appl. Phys. Lett.* **22**, 111–113 (1973).
15. M. Hareng and S. LeBerre, "Liquid crystal flat display" in *International Electron Devices Meeting Tech. Dig.* pp. 258–260, Dec. 1978.
16. S. LeBerre, M. Hareng, R. Hehlen, and J. N. Perbet, "A flat smectic liquid crystal display" in *SID Int. Symp. Dig. Tech. Papers* vol. **13**, pp. 252–253, May 1982.
17. S. Lu, D. H. Davies, R. Albert, D. Chung, A. Hochbaum, and C. Chung, "Thermally addressed pleochroic dye switching liquid crystal display," *SID Int. Symp. Dig. Tech. Papers* Vol. **13**, p. 238, May 1982.
18. S. Lu, D. H. Davies, C. H. Chung, D. Evanicky, R. Albert, and R. Traber, "High

information content large area liquid crystal displays utilizing thermally addressed dye switching." Conference Record of the 1982 Int. Display Res. Conf., pp. 132–135 (1982).

19. M. Hareng, S. LeBerre, B. Mourey, P. C. Moutou, J. N. Perbet, and L. Thirant, "The direct view matrix-addressed smectic-A LCD panel dynamic behavior," in *Conf. Record of the 1982 Int. Display Res. Conf.* Oct. 19, 1982, pp. 126–131. Also *IEEE Trans. Electron Devices*, vol. **ED-30**, 507–513 (1983).
20. R. N. Thurston, J. Cheng, and G. D. Boyd, "Mechanically bistable liquid-crystal display structures." *IEEE Trans. Electron-Devices* Vol. **ED-27**, 2069–2080 (1980).
21. We often use the shorter word "state" to refer to a configuration, or director field.
22. P. G. deGennes, *The Physics of Liquid Crystals* Oxford, England: Clarendon, reprinted 1975, p. 8.
23. G. D. Boyd, J. Cheng, and P. D. T. Ngo, "Liquid crystal orientation bistability and nematic storage effects." *Appl. Phys. Lett.* **36**, 556–558 (1980).
24. S. Saito, Y. Shirakura, and M. Kamihara, "Conformation of molecular orientation in a cell of nematic liquid crystal pretilted reversely on both electrode surfaces." Paper I-11P at the Eighth International Liquid Crystal Conference, Japan, 1980.
25. G. Porte and J. P. Jadot, "A phase transition-like instability in static samples of twisted nematic liquid crystal when the surfaces induce tilted alignments." *J. Phys.* **39**, 213–223 (1978).
26. R. N. Thurston, "Unit sphere description of liquid-crystal configurations." *J. Appl. Phys.* **52**, 3040–3052 (1981).
27. R. N. Thurston and F. J. Almgren, "Liquid crystals and geodesics." *J. Physique* **42**, 413–417 (1981).
28. R. N. Thurston, "Stability of nematic liquid crystal configurations." *J. Physique* **42**, 419–425 (1981).
29. J. Cheng, G. D. Boyd, P. L. Gould, and F. G. Storz, "Switching characteristics and threshold properties of electrically switched nematic liquid crystal bistable configuration devices." 1980 Biennial Display Research Conf., pp. 180–182, CH 1520-6/80/0000-0180 1980 IEEE.
30. J. Cheng and G. D. Boyd, "Threshold and switching characteristics of a bistable nematic liquid-crystal storage display." *Appl. Phys. Lett.* **37**, 1072–1074 (1980).
31. J. Cheng, "Surface pinning of disclinations and the stability of bistable nematic storage displays." *J. Appl. Phys.* **52**, 724–727 (1981).
32. J. Cheng, R. N. Thurston, and D. W. Berreman, "Boundary-layer model of field effects in a bistable liquid-crystal geometry." *J. Appl. Phys.* **52**, 2756–2765 (1981).
33. J. Cheng and R. N. Thurston, "The propagation of disclinations in bistable switching." *J. Appl. Phys.* **52**, 2766–2779 (1981).
34. J. Cheng and G. D. Boyd, "Reduction of threshold voltage for bistable liquid crystal switching using a priming voltage." *IEEE Electron Device Lett.* **29**, 1853–1856 (1982).
35. J. Cheng, "Homogeneous electric field threshold switching phenomena in a multiplexible bistable liquid crystal display." *J. Appl. Phys.* **53**, 5584–5595 (1982).
36. G. D. Boyd, J. Cheng, and R. N. Thurston, "A multiplexible bistable nematic liquid crystal display using thermal erasure." *Appl. Phys. Lett.* **40**, 936–938 (1982).
37. E. P. Raynes, R. J. A. Tough, and K. A. Davies, "Voltage dependence of the capacitance of a twisted nematic liquid crystal layer." *Mol. Cryst. Liq. Cryst. Letters* **56**, 63–68 (1979).
38. R. N. Thurston and G. D. Boyd, "Brightness and contrast of nematic liquid crystal bistable configuration displays." *Displays* **5**, No. 1, 15–20 (1984).
39. G. D. Boyd, T. Wilson, R. N. Thurston, J. Cheng, F. G. Storz, and E. H. Westerwick, "A 20 × 40 matrix addressed bistable nematic liquid crystal display using thermal erasure." Conference Record of the 1982 Int. Display Res. Conference, Cherry Hill, NJ, Oct. 19–22, 1982, pp. 136–139.
40. Tony Wilson, G. D. Boyd, R. N. Thurston, J. Cheng, F. G. Storz, and E. H. Westerwick, "A matrix addressable bistable nematic liquid-crystal display with electric field writing and thermal erasure." *IEEE Trans. Electron Devices* **ED-30**, 513–520 (1983).

41. D. W. Berreman and W. R. Heffner, "New bistable cholesteric liquid-crystal display." *Appl. Phys. Lett.* **37**, 109–111 (1980).
42. D. W. Berreman and W. R. Heffner, "New bistable liquid-crystal twist cell." *J. Appl. Phys.* **52**, 3032–3039 (1980).
43. D. W. Berreman and W. R. Heffner, "Disclination-free bistable twist cells." *Proc. SID* **22/3**, pp. 191–193 (1981).
44. W. R. Heffner and D. W. Berreman, "Switching characteristics of a bistable cholesteric twist cell." *J. Appl. Phys.* **53**, 8599–8606 (1982).
45. W. R. Heffner, D. W. Berreman, and G. Butler, "Effect of elastic constant ratio on the behavior of the bistable cholesteric twist cell," this conference.
46. D. W. Berreman, "Numerical modelling of twisted nematic devices." *Phil. Trans. R. Soc. Lond.* **A309**, 203–216 (1983).
47. D. W. Berreman, "Domain-wall tension allows bistability in imperfect laminar cholesteric twist cells." *J. Appl. Phys.* **55**, 806–809 (1984).
48. R. N. Thurston and D. W. Berreman, "Equilibrium and stability of liquid crystal configurations in an electric field." *J. Appl. Phys.* **52**, 508–509 (1981).
49. R. N. Thurston, "Bistabilities in twisted nematics with a holding voltage." *J. Physique* **43**, 117–128 (1982).
50. The essence of this argument was given in Reference 49 in connection with the voltage dependence of the stability of 180°-twisted states in pure nematics.
51. T. J. Scheffer, "Bistability effects in twisted nematic layers." pp. 1145–1153 in *Advances in Liquid Crystal Research and Applications* (L. Bata, editor) Oxford, Pergamon Press (1981). Paper given at the Third Liquid Crystal Conference of the Socialist Countries, held Aug. 27–31, 1979 in Budapest, Hungary.
52. The analogous bistability of the half turn state in a cell with uniformly tilted boundary conditions was described in Reference 42.
53. J. Cheng, R. N. Thurston, G. D. Boyd, and R. B. Meyer, "A nematic liquid crystal storage display based on bistable boundary layer configurations." *Appl. Phys. Lett.* **40**, 1007–1009 (1982).
54. R. N. Thurston, "Exact solutions for liquid crystal configurations and an improved boundary layer model." *J. Appl. Phys.* **54**, 4966–4988 (1983).
55. R. N. Thurston, J. Cheng, and G. D. Boyd, "Optical properties of a new bistable twisted nematic liquid crystal boundary layer display." *J. Appl. Phys.* **53**, 4463–4479 (1982).
56. J. Cheng, R. N. Thurston, G. D. Boyd, and R. B. Meyer, "A new low-voltage electrically-addressed bistable nematic liquid-crystal boundary-layer display." *IEEE Trans. Electron Devices* **ED-30**, 520–525 (1983). Reprinted in *Proc. SID* **24**, 180–185 (1983). Abbreviated version in 1982 Int. Display Res. Conf. Record, pp. 140–145 (Oct. 19, 1982).
57. R. B. Meyer and R. N. Thurston, "Discovery of dc switching of a bistable boundary layer liquid crystal display." *Appl. Phys. Lett.* **43**, 342–344 (1983).
58. R. N. Thurston, J. Cheng, R. B. Meyer, and G. D. Boyd, "Physical mechanisms of dc-switching in a liquid crystal bistable boundary layer display." *J. Appl. Phys.* **56**, 263–272 (1984).
59. R. N. Thurston, "Equilibrium distributions of electric field in a cell with adsorbed charge at the surfaces." *J. Appl. Phys.* **54**, 4154–4161 (1984).
60. R. N. Thurston, G. D. Boyd, and Donna Cowell Senft, "Thickness dependence of the switching time of the bistable boundary layer liquid crystal display." *Appl. Phys. Lett.* **44**, 813–815 (1984).
61. M. G. Clark, "Dual-frequency addressing of liquid crystal devices." *Microelectronics Journal* **12**, No. 3, 26–32 (1981).
62. R. N. Thurston, "Distribution of torque in a dual-frequency liquid crystal." *Mol. Cryst. Liq. Cryst.* **108**, 61–70 (1984).
63. D. Cowell Senft, G. D. Boyd, and R. N. Thurston, "Multiplexing the bistable boundary layer liquid crystal display." *Appl. Phys. Lett.* **44**, 655–657 (1984).
64. R. N. Thurston, G. D. Boyd, and Donna Cowell Senft, "Experiments in switching the bistable boundary layer liquid crystal display by the application of dc." *J. Appl. Phys.* **55**, 3846–3855 (1984).